Talandic Research Corporation

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FINAL REPORT

Purchase Order Number H001300

Submitted to

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INTRODUCTION

This report summarizes work performed for the Atomic Vapor Laser Isotope Separation (AVLIS) program from January through July, 1992. Each of the tasks assigned during this period is described, and result are presented. Section I details work on sensitivity matrices for the UDS relay telescope. These matrices show which combination of mirror motions may be performed in order to effect certain changes in beam parameters. In Section II, an analysis is given of transmission through a clipping aperture on the launch telescope deformable mirror. Observed large transmission losses could not be simulated in the analysis. An EXCEL spreadsheet program designed for *in situ* analysis of UDS optical systems is described in Section III. This spreadsheet permits analysis of changes in beam first-order characteristics due to changes in any optical system parameter, simple optimization to predict mirror motions needed to effect a combination of changes in beam parameters, and plotting of a variety of first-order data. Optical systems may be assembled directly from OSSD data. A CODE V nonsequential model of the UDS optical system is described in Section IV. This uses OSSD data to build the UDS model; mirror coordinates may thus be verified. Section V summarizes observations of relay telescope performance. Possible procedures which allow more accurate assessment of relay telescope performance are given.

I. RELAY TELESCOPE SENSITIVITY ANALYSIS

A discussion of U-AVLIS launch wall relay telescope sensitivity analysis is presented here. This is meant to aid in the alignment of this telescope

The relay telescope was designed to be a unit-magnification, five-mirror retro system. The laser beam passes through the five powered mirrors, emerges as a collimated magnified beam, reflects off a flat (although deformable) mirror, and passes through the five mirrors in reverse order. The beam emerges collimated and with the same diameter as when it entered the relay telescope. Thus, the telescope acts as two back to back five mirror systems, each of which is afocal and is similar to the launch telescope. Adjustments (similar to those performed on the launch telescope) in mirror positions may be used to influence collimation, beam diameter, and pupil position after the first pass through the relay telescope. Since the same mirrors are used for the exiting laser beam, no adjustment of the output collimation, beam diameter, or pupil position is possible. However, in the U-AVLIS implementation, the first mirror is split into two mirrors, one each for the entering and exiting beams. Thus, independent control of output collimation is possible. The output diameter is given by the input diameter multiplied by the ratio of the output mirror focal length to the input mirror focal length. So long as collimation is maintained on the deformable mirror, no independent control of the output beam diameter is possible. Possible relay telescope adjustments are discussed below.

The optical power ϕ of a five mirror telescope is given by

$$\phi = - \left\{ \frac{d_4 [f_3^2 d_1 - d_3 (d_1 d_2 - f_2^2)] + f_4^2 (d_1 d_2 - f_2^2)}{f_1 f_2 f_3 f_4 f_5} \right\}, \quad (1)$$

where f_n = focal length of nth mirror;
 d_n = separation of focal points of adjacent mirrors.
 If t_n = separation of mirrors, then
 $d_n = t_n - f_n - f_{n+1}$.

(2)

In an afocal system, the numerator equals zero.

A sketch of a five lens system is given below in order to clarify the definitions. This equation is useful in determining the change in beam collimation with changes in mirror positions and mirror focal lengths. The beam diameter afocal magnification M is given by

$$M = - \frac{f_1 f_2 f_3}{f_4 f_5} \cdot \frac{d_4}{f_2^2 - d_1 d_2} \quad (3)$$

Changes in magnification as functions of focal length and position changes may be calculated (for an afocal system) with equation (3) and its derivatives.

CODE V was used to calculate sensitivity tables for the relay telescope. Such sensitivity matrices may now also be calculated using the first-order spreadsheet described in Section III. Changes in beam diameter, collimation, and pupil positions as functions of mirror position and radius of curvature changes were determined. The results are given in Tables 1 and 2. In both tables the numbers give changes of the specified parameters for 1 mm changes in the mirror position or radius of curvature. The sensitivity tables may be used (1) to determine which mirrors are the most

effective in causing a desired parameter change, (2) as matrices to determine which telescope adjustments are permissible and how large the adjustments must be, and (3) to determine changes in parameters not being controlled. For example, Table 1 shows that all mirror positions have a large influence on beam collimation at the deformable mirror and at the system exit pupil, but only M16 and M22 affect the output beam diameter, and only M16 and M17 strongly affect the beam diameter at the deformable mirror. Radius of curvature sensitivities follow trends similar to those of the position sensitivities.

Five-lens system; adjacent focal points are shown.

A study was done to determine which parameters may be controlled using two, three, and four adjustable mirror positions. This was done by choosing a combination of parameters to be controlled and a combination of mirror position changes for controlling these parameters. A matrix containing numbers from Table 1 was assembled and then inverted. The inversion step solves the system of equations (represented by the matrix) for the position changes required to control the parameters. If the elements in the inverted matrix are large (compared to those in the original matrix), then a singular matrix is indicated and the desired control operation may not be performed. Results of this study are given in Table 3. Position adjustments of mirrors M16, M18, M20, and M22 only were considered. It is seen that, for example, maintaining collimation at the deformable mirror and at the exit pupil, while simultaneously changing the output beam diameter, is not possible. If collimation is to be maintained on the deformable mirror and at the exit pupil, then the output beam diameter is always given by the input beam diameter multiplied by the ratio of the radii of curvature of M22 to M16. If three mirrors before the deformable mirror are adjusted, then any combination of parameters may be obtained on the deformable mirror. However, only one parameter at the exit pupil may then be independently controlled (using adjustments of M22). Those mirror combinations which require the minimum position adjustments in order to achieve certain beam parameter changes are given in Table 4. These position adjustments do not necessarily result in minimum changes in those beam parameters which are not being controlled.

In a sample calculation, mirrors M16, M18, and M22 were used to maintain a 40 mm beam height on the deformable mirror, maintain output collimation, and change the output beam height by 3 mm. The system of equations to be solved is

	M16	M18	M22		
Def. beam height	0.2083	0.0402	0	δ_1	0
Output collimation	-0.7696	-0.7509	-0.7696	δ_2	= 0
Output beam height	0.1685	0	-0.1686	δ_3	3

The solution is given by

δ_1	=	7.941	0.4251	-1.941	0	-5.822 mm
δ_2	=	-16.27	-2.203	10.06	0	= 30.17 mm
δ_3	=	7.937	0.4249	-7.871	3	-23.61 mm

δ_1 , δ_2 , and δ_3 are the position changes of mirrors M16, M18, and M22. Actual adjustments given by CODE V are -5.730, 30.017, and -21.799 mm. Differences between CODE V and the calculations are caused by non-linearities in the dependence of beam parameters on mirror positions. These non-linearities occur predominantly for the output beam parameters. Because of the non-linearity, several iterations are needed in order to achieve the desired beam parameters both in CODE V and in actual relay telescope adjustments. After each adjustment, a calculation such as the one shown above must be performed using differences between actual and desired beam parameters. The process should converge in three to four iterations.

It has been suggested that differences between calculated and measured beam parameters, observed after a mirror adjustment, may be used to determine errors in the mirror radii of curvature. It is true that such mirror radius errors cause deviations of the actual from the calculated telescope performance. Estimates of these effects may be obtained by taking derivatives of equation (1), first with respect to mirror position (d_n), and then with respect to the focal lengths (f_n). Sample calculations show that the second derivatives (with respect to d_n and f_n) are two to three orders of magnitude smaller than the first derivatives (with respect to d_n). Effects due to the non-linearities mentioned above are, in some cases, only one order of magnitude smaller than the first derivatives. Thus, effects due to radius errors are unlikely to be observable. As an example, the above calculation was repeated (on CODE V) with a 0.1% change in the radius of M16. Mirror positions were adjusted initially such that a 40 mm beam height occurred at the deformable mirror, and a collimated output beam with nominal diameter occurred at the output. CODE V-derived changes in mirror positions needed to obtain the changes in beam parameters used in the above calculation were δ_1 , δ_2 , and $\delta_3 = 5.732$, 30.03, and -21.82 mm. Differences between these and the above CODE V values are seen to be far smaller than those between CODE V and calculated values. Only very large radius errors are likely to be observable.

It is recommended that the following steps be used in relay telescope alignment:

1. It should be verified that the input beam is collimated and has the proper diameter at the entrance pupil;
2. The relay telescope should be mounted according to design specifications;
3. Beam parameters at the deformable mirror should be measured;
4. Mirror adjustments should be calculated using either CODE V or the sensitivity matrices, such that the desired beam parameters on the deformable mirror are obtained.
5. Mirror M22 should be adjusted such that the beam is collimated at the exit pupil.
6. Further mirror adjustments should be performed such that the desired output beam diameter and pupil position are obtained.

It should be noted that an adjustment in the output diameter will always result in decollimation at the deformable mirror.

No mention has been made here of the effects of deformable mirror power variation and isolation window heating on beam parameters. These effects may be studied using the EXCEL spreadsheet (Section III). However, previous work in this area was performed in preparation for the 1989 critical design review (CDR) on UDS optics. Data from the CDR show that large pupil motion

(several passes in the special equipment) may result from window heating. Correspondingly large mirror motions may thus be required to correct the pupil location, and other beam parameters, as laser power causes heating of various UDS components.

Table 1.

Relay Telescope Position Sensitivities

Changes in beam parameters caused by +1mm change in mirror positions.
(See note below)

	M16	M17	M18	M19	M20	M22
<u>Deformable mirror</u>						
Focus (μ rad)	-0.6221	0.7500	-0.3036	1.1142	-0.9384	--
Focus (waves)	0.0207	-0.0250	0.0100	-0.0371	0.0313	--
Beam height (mm)	0.2083	-0.2364	0.0402	-0.0120	0.0000	--
Pupil pos. (meters)	-1.7450	1.9018	-0.1752	0.0207	0.0010	--
<u>Exit pupil</u>						
Focus (μ rad)	-0.7696	1.8750	-0.7509	2.7560	-2.3220	-0.7696
Focus (waves)	0.0207	-0.0500	0.0200	-0.0743	0.0625	0.0207
Beam height (mm)	0.1685	0.0000	0.0000	0.0000	0.0000	-0.1686
Pupil pos. (meters)	-1.1414	2.4834	-0.2291	0.0270	-0.0013	-1.1423

NOTE: For the north relay telescope, mirror displacements are positive to the south.

Table 2.

Relay Telescope Radius Sensitivities

Changes in beam parameters caused by 1mm increase in absolute values of mirror radii.

	M16	M17	M18	M19	M20	M22
<u>Deformable mirror</u>						
Focus (μ rad)	0.3100	0.6560	0.3010	0.9630	0.4690	--
Focus (waves)	-0.0100	-0.0220	-0.0100	-0.0320	-0.0156	--
Beam height (mm)	-0.1070	-0.1960	-0.0417	-0.0200	0.0031	--
Pupil pos. (meters)	-0.8940	-1.4500	0.1435	0.0103	0.0005	--
<u>Exit pupil</u>						
Focus (μ rad)	0.3900	1.6000	0.7430	2.3800	1.1600	0.3840
Focus (waves)	-0.0100	-0.0440	-0.0200	-0.0640	-0.0310	-0.0100
Beam height (mm)	-0.0840	0.0000	0.0000	0.0000	0.0000	0.0897
Pupil pos. (meters)	0.5844	1.9414	0.1889	0.0135	0.0007	0.6252

Table 3.
PERMITTED RELAY TELESCOPE ADJUSTMENTS

		Deformable Mirror			Exit Pupil		
		Beam Diam.	Beam Coll.	Pupil Pos.	Beam Diam.	Beam Coll.	Pupil Pos.
Four Mirrors (M16,M18,M20,M22)	1.	•	•	•		•	
	2.	•			•	•	•
	3.	•		•	•	•	
Three Mirror (M16,M18,M20)	4.	•			•	•	
	5.	•		•		•	
	6.	•	•			•	
(M16,M20,M22)	7.	•			•	•	
	8.	•				•	•
	9.	•	•			•	
(M18,M20,M22)	10.	•			•	•	
	11.	•				•	•
	12.	•	•			•	
(M16,M18,M22)	13.	•			•	•	
	14.	•				•	•
	15.	•		•		•	
Two Mirrors (M16,M18)	16.	•	•		•		
	17.				•	•	
	18.	•				•	
(M16,M20)	19.				•	•	
	20.	•				•	
	21.	•				•	
(M18,M20)	22.				•	•	
	23.	•				•	
	24.				•	•	
(M18,M22)	25.	•			•	•	
	26.				•	•	

Table 4.

BEST MIRROR COMBINATIONS FOR GIVEN ADJUSTMENTS

	<u>Deformable Mirror</u>			<u>Exit Pupil</u>			<u>Mirror Combinations</u>
	Beam Diam.	Beam Coll.	Pupil Pos.	Beam Diam.	Beam Coll.	Pupil Pos.	
1.	•	•	•		•		M16,M18,M20,M22
2.	•			•	•	•	"
3.	•		•	•	•		"
4.	•			•	•		M16,M20,M22
5.	•				•	•	"
6.	•		•		•		M16,M18,M20
7.	•	•			•		M16,M20,M22
8.				•	•		M16,M22
9.	•				•		M16,M20

II. CLIPPING-APERTURE TRANSMISSION

An ASAP/Rabet diffraction analysis of the launch telescope beam at the launch deformable mirror was performed. The purpose of the analysis was to determine (a) the transmission through a centered 50 x 90 clipping aperture, and (b) the amount of decentration of the clipping aperture needed to reduce the transmission to 80%. The observed transmission is 80%. Beams were traced from the relayed pupil (after the launch telescope) to the deformable mirror in order to properly simulate diffraction effects. 861 rays were used to define a beam having the nominal launch telescope exit beam dimensions. A wavelength of 0.6 μm was used. ASAP/Rabet assumes an irradiance, at the beam starting location, of 1 unit per unit area. This irradiance is summed over the window defined for diffraction analysis in order to give the total beam flux. Transmission through the clipping aperture was determined from the ratio of the flux with the aperture in place to that without the aperture (in the deformable mirror plane). The total flux without the aperture agreed well with that at the beam starting location. To determine the unclipped flux, the window size was increased until only insignificant changes in total flux were observed between successive window size changes. The transmission with the clipping aperture in place is 98.5%. The 80% transmission decentration was found to be 25 mm. Since the beam was not propagated beyond the aperture position, no edge effects were observed. It is recommended that such edge effects be analyzed with GLAD V if such analysis is needed.

In additional diffraction analysis, a beam consisting of 861 Gaussian beamlets was traced from the launch relayed pupil to the deformable mirror. In this new study, the beam intensity at the deformable mirror was synthesized over a 200 x 200 mm window so that all of the beam energy originating at the pupil would be included. The amount of energy transmitted by the clipping aperture was then taken to be the convolution of an appropriately sized (50 x 90 mm) window with this beam intensity profile. The 200 x 200 window further assured that no aliasing would take place in this convolution operation. Transmission through the clipping aperture was taken to be the fraction of the total energy in the 50 x 90 window when this window was centered on the beam intensity profile. Further analysis included the clipping aperture displacement needed to reduce the transmission to 80%. This displacement may be measured directly on convolution profiles generated by ASAP/Rabet. Displacements in both the x and y directions were found in this manner. The process was repeated for various beam sizes corresponding to various launch telescope magnifications. The results are summarized in Table 5.

Table 5.

Magnification		Transmission through clipping aperture	Displacement needed for 80% transmission	
x	y		x (mm)	y (mm)
0.81	0.81	0.986	25.6	16.1
0.75	0.875	0.980	27.1	15.4
0.81	0.875	0.976	25.5	15.4
0.875	0.875	0.979	24.1	15.4
0.93	0.875	0.978	22.8	15.4
0.81	0.81	0.987	26.7	15.9

Convolution profiles for each entry in the table are attached as Figures 1 through 6.

Figure 1. Magnification 0.81 x 0.81, f)at-top intensity profile.

Figure 2. Mag. 0.75 x 0.875, flat-top intensity profile.

Figure 3. Magnification 0.81 x 0.875, flat-top intensity profile.

Figure 4. Mag. 0.875 x 0.875, flat-top intensity profile.

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Figure 5. Magnification 0.93 x 0.875, flat-top intensity profile.

Figure 6. Magnification 0.81 x 0.81, clipped Gaussian intensity profile.

Figure 7. Intensity profile at pupil for clipped Gaussian.
BEAM AT PUPIL. $1/e$ AMPLITUDE POINT AT $X \approx 2.5 \times$ beam semi-width.

For the first five cases, a flat-top beam intensity profile at the pupil was assumed. In the last case, a clipped Gaussian profile was used. The $1/e$ amplitude point was taken to be approximately 2.5 times the beam long-axis semi-width. An intensity profile at the pupil is shown in Figure 7. It is evident from the table and the figures that the Gaussian shape has negligible effects on transmission, and only a small effect on the convolution profile. It should be noted that for all cases presented here, the 50 x 90 aperture is larger than the geometrical beam footprint. Thus, only diffraction effects cause beam energy to fall outside of the window and therefore, to be clipped. It is seen that only about 2% of the energy is clipped by the aperture. As was stated previously, it is recommended that this analysis be repeated with GLAD V for verification of the results.

It is seen that diffraction effects and clipping aperture decentration do not, by themselves, account for the observed transmission of 80%. It was stated by AVLIS personnel that laser energy may actually be observed outside of the clear portion of the clipping aperture. Expected aberrations in the launch telescope (about 0.25 waves of astigmatism) would cause a change in beam size at the deformable mirror of approximately 0.2 mm. Thus, aberrations are not likely to be the cause of the transmission loss. A more likely cause may be scattering due to defects in or large surface roughness of mirror coatings. BRDF measurements of the mirrors are recommended. ASAP/Rabet analysis of a launch telescope with the measured surface roughness will show whether the observed transmission loss then occurs.

III. FIRST-ORDER SPREADSHEET

A. INTRODUCTION

A series of macros was written for the Macintosh Excel spreadsheet software in order to permit *in situ* first-order analysis of launch-wall telescopes. The macros perform marginal and chief-ray traces of the telescopes so that the effects of changes in telescope mirror positions and powers may be studied. The geometrical optics conventions used, and details of the macros, are given below. Spreadsheets used for the first-order analysis are divided into three sections as follows:

1. OSSD; 2. optical system assembly; 3. optical system analysis. Each section is described separately below.

B. CONVENTIONS

The three sections, their functions, and the order in which they are used, are as follows:

1. **OSSD** - This section contains data taken directly from an OSSD spreadsheet. Changes in component coordinates and in other specifications may be entered here. Such changes will automatically be implemented in Section 2 of the spreadsheet. Surfaces in addition to those given on an OSSD may be entered here.
2. **Optical system assembly** - In this section OSSD data are converted into an optical system prescription. It is assumed that an experienced optical designer will use this section to add dummy surfaces, insert other additional surfaces, insert pickups and solves, and implement other changes. No optical analysis, raytracing, etc. is performed in this section.
3. **Optical system analysis** - This section takes data from Section 2 in order to assemble an optical system complete with marginal- and chief-ray traces. Effects of changes in system specifications, y-y bar and other plots, and changes needed to effect new output beam parameters may be observed and calculated here. It is expected that personnel with varying degrees of optical analysis experience will use this section.

Conventions used throughout the spreadsheet are as follows:

- Mirror radii:** convex surfaces take a positive radius of curvature; concave surfaces take a negative radius of curvature. Thus, both surfaces of a bi-convex lens take positive radii.
- Ray angles:** all ray angles are correct for an unfolded system. Thus, a ray from infinity incident on a positive-powered mirror (with positive ray height in a medium with positive index of refraction) attains a negative angle after reflection.
- Separations:** separations between optical components are correct for an unfolded system.
- Ray direction:** surfaces defined on the OSSD are given directions (N,S,E,W,U,D) appropriate to the coordinate system used on the UDS monolith. These directions are for rays incident on the surface in question. Thus, if a ray travels north on the launch wall before being incident on a mirror called, e.g., M1, then M1 is given the direction N. Positive component displacements are always in this designated direction.

Code: optical components throughout the spreadsheets are classified by codes, as follows:

<u>Code</u>	<u>Meaning</u>
-1	Mirror
0	Entity with focal length equal to entry in "radius" column (see below).
1	Dummy surface.
>1	Refractive surface with index of refraction = code.

The codes are used to properly calculate the optical power of components and determine refractive indices before, in, and after these components.

Detailed descriptions of the three spreadsheet sections are given below.

C. OSSD SPREADSHEET

This spreadsheet contains basic data from an OSSD. The following headings should appear in the first row:

(blank)	SN	X	Y	Z	Radius	Code
---------	----	---	---	---	--------	------

The columns are defined as follows:

(blank) = Component labels from OSSD. There should be no duplication of labels on this spreadsheet;

SN = Surface number (numbered consecutively from top);

X
Y
Z = Component coordinates in system units. All coordinates should be referenced to the same global coordinate system;

Radius = Radius of curvature for component. Enter 0 or a large number ($>10^{10}$) for a flat surface.

Code: = Code describing component type. See Section B above.

After all data have been entered, the entire used portion of the OSSD spreadsheet (columns 1-7, rows 1-last row containing data) should be selected. The command CREATE.NAME (formula menu), with both rows and columns selected, should be invoked. This is required for proper identification of individual cells on the spreadsheet. The selected area may contain blank lines, but again, should not contain duplicated labels. Rows may be inserted into the spreadsheet, but the CREATE.NAME command must be repeated after such insertions. "Label" cells may be left blank, but systems to be assembled on Section II of the spreadsheet may not begin with a blank cell. The OSSD section must be located on a spreadsheet named "OSSD".

D. OPTICAL SYSTEM ASSEMBLY

This section should be located on a spreadsheet named "YYBAR". A series of macros is implemented here in order to assemble an optical system from OSSD data. The assembly is automatic and always begins in column 25. The selected cell on "YYBAR" determines the beginning row number. Columns are automatically labeled as follows:

SN Label Separation Radius Power Nprime Code Dir Pickups Solves

where

SN	=	Surface number;
Label	=	Label from OSSD (or entered here by user);
Separation	=	Distance between OSSD components;
Radius	=	Component radius of curvature;
Power	=	Optical power of component;
Nprime	=	Index of refraction following component (in actual folded system);
Code	=	Component designation (see Section II above);
Dir.	=	Direction of ray incident on component (see Section II above);
Pickups	=	Column for defining separations or radii to be based on those of other surfaces;
Solves	=	Column for setting up separations or radii such that a given ray-based quantity remains constant.

Macros to be used in this section of the spreadsheet are as follows:

ASSEMBLE: This macro assembles an optical system from OSSD data. This asks for the labels of the beginning and ending components for the system being assembled. Thus, systems must consist of consecutive OSSD components, but may consist of any subset of such consecutive components. Any number of systems may be assembled in the optical system assembly section. Thus, if the OSSD contains data for the entire UDS system, then the entire system, in addition to separate launch and relay telescope systems, may be assembled. At the end of the macro, a name for the system is requested. A unique name not used for any other system should be used. This naming scheme will not be upset if rows are later added to or deleted from the system, so long as the first or last rows are not the ones in question. Links are established between this section of the spreadsheet and OSSD. Thus, any changes in OSSD parameters are automatically registered in the assembled optical systems. Such links remain in effect even if rows are inserted or deleted in either section.

DUMMY: This macro adds dummy surfaces before and after the surface designated by a selected cell. Pickups are inserted such that the surface may be displaced from its nominal position without changing the separations between subsequent pairs of surfaces. Subsequent surfaces are renumbered, but surface numbers used in

INS2: This macro inserts a new surface at the position of the currently selected cell. Information is requested by the macro and should be self-explanatory. The original surface at the selected cell location is moved to a position after the new surface. Again, surface numbers in column 25, but not in pickups and solves, are updated.

PT, sn, f1, f2 - pickup thickness
PF, sn, f1, f2 - pickup power

$$p = p_{sn} * f1 + f2$$

abc, n

b = u for control of ray angle after the surface
y for control of the ray height on the surface
(for $a = t$) or on the next surface (for $a = p$).

n = value to be assumed by $\bar{u}$ or y .

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E. OPTICAL SYSTEM ANALYSIS

In this section a series of macros is used to set up a complete optical system from any system assembled in Section 2 of the spreadsheet. These macros are as follows:

SETUP: This macro sets up an optical system starting in column 1 of the "YYBAR" spreadsheet and in the row in which a cell is selected. The name (from Section 2) of the desired system is requested. Equations needed for raytracing are inserted, and pickups and solves are activated. Starting marginal and chief-ray parameters are requested. The following column headings are inserted.

Surface No., Label, y, omega, sep., radius, ybar, omegabar, power, nprime, code, direction, pickup, solve, object, image, stop, pupil, label.

Headings different from Section 2 are

y	marginal ray height
omega	marginal ray angle
ybar	chief ray height
omegabar	chief ray angle
object	distance of local object from surface
image	distance of local image from surface
stop	distance from surface of preceding pupil
pupil	distance from surface of imaged pupil

CHANGE_RADIUS: The numbers in the "radius" column are calculated from numbers in the "power" and "nprime" columns. Thus, the radius values should never be changed directly. However, since radius values are typically more meaningful than power in the UDS system, they may be altered via this macro. The entered value may be either the actual radius of curvature or the departure, in waves, from a flat surface. Thus, deformable mirror shapes may be more easily handled.

PICKUP, SOLVE: These macros may be used to activate any pickups and solves inserted in this section of the spreadsheet. Rules for setting these up are the same as for the optical assembly portion of the spreadsheet (above). Pickups and solves are activated by selecting the respective cells and then calling either the PICKUP or SOLVE macro.

YYBAR PLT: This macro is used to create a yybar plot of the current optical system. The beginning and ending labels of the range of surfaces to be plotted, along with the plot title, are requested. The created plot may be reduced in size and left open as changes are made in the "YYBAR" spreadsheet. The changes will appear in the plot.

PLOT: This macro may be used to plot any parameter vs. another parameter, such as "y" vs. "label". The beginning and ending surface labels and the parameters to be plotted are requested. Again, changes in the "YYBAR" spreadsheet may be observed in this plot.

ITERATE: This macro constitutes a simple "optimization" routine for this section of the spreadsheet. System variables and operands may be defined. Changes in the variables needed to drive the operands to specified targets are calculated and implemented. ITERATE does not perform least squares; thus, the number of variables must equal the number of operands. The allowable variables are

SEP.
POWER
NPRIME

The allowable operands are

y
omega
ybar
omegabar
object
image
stop
pupil

Up to five variables/operands are permitted. However, running speed with more than three variables/operands may be agonizingly slow, and it is recommended that solves be used wherever possible to control operands. Operands are requested first by the macro. When the desired operands have been designated, the "cancel" button in the dialog box should be clicked. Variable names are then requested.

Surface designations from the "label" column should be used when requested. One should be sure to use variables which will affect the designated operands. ITERATE calculates a sensitivity matrix, then performs an LU decomposition on this in order to calculate the variable changes. These matrices and other appropriate data are given in rows following the ITERATE macro on the YYBAR_Macros worksheet. The merit function is displayed and updated after each iteration cycle. If this number does not decrease after two or three cycles, then the macro should be stopped (using command ____), and a new starting point or new variables and operands should be used.

DIRECT: *This is a subroutine called by SETUP to insert raytracing and other formulas into the appropriate cells. If such formulas are, for some reason, removed from cells, they may be reentered using this macro. The cell labeled "image" should first be cleared. The macro starts in the row in which a cell is selected and proceeds to the end of the system. This macro should not be started on the first surface of a system (surface number 0).*

CONJUGATE: This may be used to calculate points conjugate to an initial point. The initial point is specified by either its y, ybar coordinates, or by an existing surface label. Starting at the row in which a cell is selected, and proceeding to the end of the system, a table is generated giving distances of conjugate points after labeled surfaces. The distances are positive in the directions of light propagation after the surfaces.

ENTER: This macro may be used to enter individual surfaces on the "YYBAR" spreadsheet. All necessary information is requested by the macro. After all surfaces have been entered, the START and DIRECT macros should be called for proper insertion of raytracing equations.

No specific provision is made for inserting or deleting surfaces in this section of the spreadsheet; it is assumed that this is done in the assembly section. However, surfaces may be inserted manually. The proper equations may then be implemented by running the DIRECT macro.

F. CONCLUDING REMARKS

1. Caveats

The first-order spreadsheet is not as complete as was originally desired. Only one system at a time may be analyzed in Section 3 of the spreadsheet; the original intention was to provide means for appending additional systems, such as diagnostics packages, so that the output of such systems may be observed as changes in the main system are made. Ray angles in nominally collimated spaces are expressed only as the tangent of the angle rather than in fringes as was originally intended. In ITERATE, only absolute operand targets rather than changes from existing operand values may be specified. The spreadsheet was developed using version 1.5 of EXCEL rather than the later version in use at the AVLIS facilities. Thus, some macros may run differently on the later version of EXCEL. For example, the YYBAR PLT macro runs differently on the later version than on version 1.5; the resulting plot is not a y-y bar diagram. Thus, changes based on study of the manual for the later version of EXCEL may need to be implemented by AVLIS personnel. Examples of YYBAR and y vs. label plots, produced on version 1.5 of EXCEL, are attached as Figures 8 and 9. However, it is believed that the delivered macros will provide helpful means for analyzing UDS optical systems.

2. Running The First-Order Spreadsheet

The disk supplied with this documentation provides sample spreadsheets with a ready-to-analyze optical system. In order to run the macros, the following worksheets should be opened:

"OSSD"
"YYBAR"
"YYBAR_Macros"
"FCN_Macros"
"RESULTS"

The "YYBAR" spreadsheet should always be active when any of the macros is used. Macros may be started by selecting "run" from the "macro" menu, and then selecting the desired macro name from the displayed list. The results of an optimization run using ITERATE are stored on the "RESULTS" worksheet. New results are listed below any preceding results; thus, a running account of all telescope changes may be kept. The table generated by CONJUGATE is also placed on the "RESULTS" worksheet.

Figure 8. Y-ybar diagram generated by YYBARPLT macro. Surface range is 'stop' to 'pupil'.

Figure 9. Graph of marginal ray height vs. surface label generated with PLOT macro. The surface range is 'stop' to 'pupil'.

IV. UDS GLOBAL MODEL

A CODE V model of the UDS system, from the dye wall pupil to the special equipment exit, was developed. This model uses non-sequential surfaces for all optical components (flat and curved mirrors and isolation windows). All surfaces are defined in the monolith coordinate system. The model is meant to allow verification of mirror coordinates appearing on OSSD sheets, to assure that no beam clipping is caused by any components, and to perform tolerance analyses of component tilt angles.

The global model consists of two files for use with CODE V. The first file, UDSDATA(B).SEQ, contains the mirror coordinates. A and B stand for the south (north) half of the UDS system (south refers to the beam heading south after the launch telescope beamsplitter). The second file, UDSA(B).SEQ, contains the CODE V command sequence for setting up the model. Separation of the system into north and south halves was necessitated by CODE V memory limitations. All components in the UDSDAT files are defined by an array variable with at least three dimensions and using the OSSD name. For flat mirrors, the three dimensions contain the x,y, and z coordinates. Curved mirrors use five-dimensional arrays. Again, the first three dimensions are the x,y,z coordinates, the fourth dimension is the radius of curvature, and the fifth dimension is the distance to the next surface. Tilt angles are computed automatically as the UDS file is input into CODE V. The macro TILT.SEQ must reside in the local directory in order for the tilt computation to function. Mirror separations are computed from the coordinates. However, for curved mirrors, separations are constrained to those given in the UDSDAT file. In the case of launch wall mirrors, the z coordinate is adjusted such that this separation is achieved. The x and y coordinates are not changed. Special equipment mirror tilt angles are computed based on the desired number of passes. This number may be changed manually in the UDS file before entry into CODE V. Mirror aperture sizes must be entered manually in the UDS file. The macro TILT.SEQ uses mirror coordinates to compute tilt angles. All tilt angles, except those for the first and last relay telescope mirrors and the relay deformable mirror, may be computed in this manner. The latter tilt angles must be determined in a separate CODE V run and entered manually. Deformable mirror curvatures must also be entered manually.

In a CODE V run, the UDSDAT file should be input first, followed by the UDS file. Raytracing may then proceed with parameters appropriate for the dye wall.

Only the UDSA.SEQ and UDS DATA.SEQ files are currently (9/92) in the proper format. Preparation of the UDSB.SEQ file requires insertion of the launch telescope beamsplitter. The UDSDATB.SEQ file must be updated using the most recent OSSD spreadsheet. Many of the mirror coordinates here will differ from those in the UDSDATA file only in the sign of the z coordinate. The files may be found on TRITON in the ADISK2 : [STUHLINGER.UDS] directory.

V. OBSERVED RELAY TELESCOPE PERFORMANCE

During the visit to Lawrence Livermore Labs on July 27-29, 1992, the performance of the relay telescope was assessed. It was found, using the krypton local laser as a light source, that intermediate foci in the relay telescope are, to within the depth of focus, in the proper locations. Beam widths on the telescope mirror appear to be close to the design values, but these widths are difficult to measure due to diffraction effects. Diffraction patterns on M16, M17, and M18 appear to have the features expected for the krypton pupil location, although increasing effects of atmospheric turbulence cause these features to become less distinct as propagation distance increases. After M18, the intensity profile appears to be dominated by turbulence effects. The beam no longer contains distinct diffraction features, but appears to suffer from atmospheric "speckles". At the deformable mirror, shearing interferograms indicate that the beam is collimated to 1/2 wave or better, but due to turbulence/diffraction effects, the measurement of beam width is difficult. Thus, the true state of alignment of the telescope is difficult to assess.

The pupil distances in the relay telescope vary between plus and minus infinity inside the relay telescope. For the nominal pupil distance, the space between M19 and M20 is telecentric; for the krypton pupil, the space between M17 and M18 is telecentric (for the first pass). However, ASAP/Rabet simulations of the telecentric spaces and of other locations in the relay telescope show no unusual diffraction effects. These simulations are shown in Figures 10 and 11. Diffraction patterns on the mirrors bounding the telecentric space are given by the distances of the mirrors from their respective entrance/exit pupils. In the telecentric space, the patterns change from this to the far-field pattern at the focus between the mirrors and back to the near-field pattern. Thus, no unusual diffraction effects are to be expected in the telecentric spaces. Similar considerations apply to other spaces in the relay telescope. This is supported by the observation of a relatively intact beam profile on M18, after the telecentric space formed by the krypton pupil. It is believed that the deterioration of the beam intensity profile is more likely to be caused by thermal effects at the telescope intermediate foci. This explanation is more consistent with the observed rather abrupt deterioration between M18 and M19.

The following observations/adjustments are recommended in order to assess the validity of this explanation:

1. The krypton power should be reduced. An improvement of the intensity profile with decreasing power should be observed.
2. If no improvements are observed in step 1, the experiment should be repeated with the launch wall at vacuum. TV cameras should be mounted so that all relay telescope mirrors may be observed.
3. If no improvements are observed in step 2, then the relay telescope should be reconfigured so that a smaller number of intermediate foci occurs. In this case, only M16/22, M17, M18, and M21 would be used. The beam size on M18 and M21 would be smaller than the minimum specification, but this should not be a problem with the krypton beam. Again, the beam should be observed on all mirrors. This should show whether the number of intermediate foci in the nominal relay telescope design contributes to the problem.
4. If it has been established that thermal effects cause the beam deterioration, then the krypton/relay telescope system should be reconfigured so that the pupil is properly relayed onto the deformable mirror. This involves a reconfiguration of the krypton telescope and/or a reconfiguration of the relay telescope. Reconfiguration of the relay telescope was found to cause a substantial increase in beam size on M21. The following mirror motions result in a beam size on M21 twice the normal size, and cause the pupil to be relayed to M21.

80M PUPIL, AFTER MIRROR 2

After M17

PLX/AREA

① ASAP/robot

31-JUL-92 10:00

80M PUPIL, BEFORE MIRROR 3

Before M18

PLX/AREA

① ASAP/robot

31-JUL-92 10:50

200M PUPIL, AFTER MIRROR 2

After M17

PLX/AREA

① ASAP/robot

31-JUL-92 10:00

200M PUPIL, BEFORE MIRROR 3

Before M18

PLX/AREA

① ASAP/robot

31-JUL-92 10:00

Figure 10. Diffraction patterns for 200m (telocentric after M20) and 80m (telocentric after M17) pupils in relay telescope.

80M PUPIL, AFTER MIRROR 4

After M19

80M PUPIL, BEFORE MIRROR 5

Before M20

200M PUPIL, AFTER MIRROR 4

① ASAP/rabet

30-JUL-92 17:20

200M PUPIL, BEFORE MIRROR 5

① ASAP/rabet

30-JUL-92 17:23

After M19

FLX/AREA

① ASAP/rabet

30-JUL-92 17:13

Before M20

FLX/AREA

① ASAP/rabet

30-JUL-92 17:17

Figure 11. Diffraction patterns for 80m and 200m entrance pupil distances in relay telescope.

	<u>Motion</u>	<u>Beam Size</u>
M16:	322 mm South	Nominal
M18:	400 mm North	2x Nominal
M20:	12.1 mm South	2x Nominal
M21:	-----	2x Nominal

This will give an accurate indication of diffraction effects at the relay telescope exit and at the relayed pupil.

5. The relay telescope should be aligned so that the beam is collimated and has the expected size at the applicable mirrors. An object should be placed at the krypton stop; adjustments should be made so that this is imaged onto the deformable mirror. The actual image location may be determined by moving the object longitudinally; the large krypton to M21 magnification will result in a large image motion at M21 and should indicate what relay adjustments are needed for proper imaging.

6. The surface roughness of coated launch wall mirrors should be measured. This will permit the light scattering properties of these mirrors to be determined. It may then be determined whether stray light in the launch wall area might be caused by such surface scattering.

7. Sufficient time should be allowed for accurate assessment of relay telescope performance. One to two full days should be set aside to allow completion of the steps outlined above. The spreadsheet for determining telescope first-order properties should be implemented to permit the on-site calculation of adjustments.

It is hoped that the above steps will lead to the source of relay telescope problems. It seems important to carry out these steps before a final determination regarding relay telescope implementation is made.

VI. CONCLUSIONS

The preceding sections summarize various diffraction and first-order analysis results for the UDS launch wall optics. Tools for performing the first-order analysis are described. Sensitivity matrix studies show that only certain combinations of telescope adjustments may be used to effect certain beam parameter changes. Since beam first-order parameters are not exactly linear with mirror positions, it is suggested that changes be made incrementally. Diffraction studies were performed in an attempt to find the cause of a 20% transmission loss at the launch telescope deformable mirror. Several approaches were used in ASAP/Rabet, but no reasonable scenarios were found which reproduce the observed loss. It is suggested that light scattering at mirror surfaces may cause light to spread beyond the footprints predicted by diffraction.

A series of macros for performing telescope first-order analysis using the EXCEL spreadsheet was described. UDS telescopes may be assembled from OSSD data and then analyzed. Plots of a variety of beam parameters may be produced, and simple "optimization" may be performed to determine mirror motions needed for specified beam parameter changes. The analysis macros are designed to be operated by personnel without extensive optical design experience.

A CODE V nonsequential model of the UDS optics is described. This model is assembled from OSSD data, and may be used to verify mirror position coordinates, the absence of beam clipping, and other optical parameters.

Finally, observed relay telescope performance is discussed. Recommendations are made for improving the performance of this telescope, such as lowering local laser power to eliminate thermal blooming effects during operation in air. It is felt that no further computer modeling, with the exception of mirror scattering effects, should be performed at this point. Careful observations of actual telescope operation should be made; deviations from design performance should be understood and corrected. This should lead to the predicted performance of the UDS optical system.