2-22-77
5 to 7 TIS

MASTER

UCID-17381

Lawrence Livermore Laboratory

ARTEMIS: A DIFFRACTION MODEL FOR LASER LIGHT PROPAGATION*

P. A. Renard and J. T. Hunt

February 3, 1977

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ARTEMIS: A DIFFRACTION MODEL FOR LASER LIGHT PROPAGATION*

P. A. Renard and J. T. Hunt
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Introduction

Diffraction theory provides a convenient method for studying both the propagation and focusing properties of intense laser light passing through a chain of optical elements. Large scale phenomena such as gain amplification and whole beam aberrations are often addressed by conventional geometric ray tracing methods.⁽¹⁾ When optical path lengths become large and/or intensity profiles display severe gradients however, the geometric approach quickly breaks down. This is especially true within the focal region of a lens where it is desirable to understand detailed aspects of the light intensity profile.

The development, optimization, and understanding of large laser systems such as those constructed and utilized by the Laser Program at Lawrence Livermore Laboratory are dependent on a diffraction analysis of light propagation. Because of the high power yields associated with the laser systems at LLL, the analysis of such systems is dominated by the nonlinear effects upon the light - the result of passing intense fields through largely glass optical elements. Efforts to understand and combat these effects has resulted in the development of a computer-based simulation, employing diffraction theory, to model current and proposed glass laser systems.

*Work performed under the auspices of the U. S. Energy Research and Development Administration, contract No. W-7405-Eng-48.

The computer program, ARTEMIS, developed for the LLL-CDC 7600 computers, simulates the nonlinear propagation and focusing of laser light through a simplified chain of optical elements. Its specific capabilities include:

- Diffraction
- Spatial filter transmission
- Non-uniform gain
- Gain saturation
- Whole beam self-focusing
- Nonlinear propagation in both rod and disk-type amplifiers
- Focusing
- Thin lens combinations
- Nonlinear ripple growth
- "Soft" apertures
- Seidal aberrations

Currently, only radially symmetric beams are allowed, thus limiting the types of distortions; and of the basic Seidal aberrations, only spherical aberration is considered. The effects of astigmatism and coma have previously been studied⁽²⁾, and are assumed correctable for the purposes of ARTEMIS' simulation. In addition to the radial (spatial) profile of the laser pulse, it is possible to model the temporal dependence - the basis for encountering gain saturation.

Program Overview

The wave function for the initial beam injected into a laser system of optical components may be approximated by a generalized Fourier decomposition in which the basis functions are the familiar Laguerre-Gauss mode functions. The propagation of the beam in terms of its (Fourier) decomposition coefficients and modal phase is well understood⁽³⁾, and is defined in terms of a single complex propagation parameter, q , and an element transformation matrix, T . The temporal dependence of the wave function is accomplished by considering the (radial) wave function at a number of discrete planes of fixed t value in a time frame moving along with the wave form. For short pulses, typically only the zero position of the time envelope is modelled. For long pulses, the effect of gain saturation may be important and a time history is required. A set of decomposition coefficients is obtained for each time slice and propagation for each is effected.

The amplitude envelope of the initial wave function is typically Gaussian temporally and super-Gaussian ("top hat") spatially. Phase distortions may be present initially as well as a uniform intensity ripple. Once the initial profile is characterized by a set of decomposition coefficients, free space (vacuum passage) propagation is effected by a simple (diffraction) phase accumulation that is only dependent on propagation distance. The wave function may be reconstructed in any downstream position from its original coefficients and distance-dependent phase.

Optical elements placed in the path of the propagating beam are characterized by a transformation matrix.⁽³⁾ Passive elements are those

which serve only to alter the phase of the associated wave function, or specifically, the modal phases of each Laguerre-Gauss basis function used in decomposition. Typical passive elements are (thin) lens and free space propagation (here treated as an "optical element"). Active elements combine a phase change with an amplitude change and, to account for non-uniform spatial amplification and the subsequent remixing of the Laguerre-Gauss modal functions, the decomposition coefficients are actually altered. Both passive and active elements may have associated with them an incremental static distortion (Seidel aberration) or intensity dependent nonlinear distortion. The wave function is then reconstructed from its current decomposition, the additional distortions folded in, and a new set of modal coefficients obtained. In terms of program logic, beam propagation starts afresh at each decomposition, and only the relative diffraction-propagated phase between such decompositions is necessary to reconstruct the wave function at intermediary planes.

The most significant program output is a series of plots showing beam intensity profiles at various selected points in the laser chain of optical elements. Certain tabulated information is also provided.

Generalized Fitting Scheme⁽²⁾

The most crucial aspect to a successful propagation simulation is ARTEMIS' ability to suitably decompose a given wave function into a finite number of modal functions. Given a wave function, $\psi(r,z,t)$, it is necessary to form the approximation:

$$\bar{\psi}_i(r,z) \approx \psi(r,z,t_i)$$

It is assumed that the time variable, t , may be fixed at suitably placed coordinate positions and a vector of approximations is formed. For purposes of discussion, only one component of this vector will be expanded. The form chosen for $\bar{\psi}$ is:

$$\bar{\psi}(r, z) = \sum_{m=1}^N \gamma_m \Lambda_m e^{-i\phi_m} \quad (1)$$

where the basis functions are

$$\Lambda_m = \frac{\sqrt{2}}{w(z)} L_m \left[\left(\frac{r}{w(z)} \right)^2 \right] e^{-\frac{1}{2} \left(\frac{r}{w(z)} \right)^2},$$

and the modal phase is separated as:

$$\phi_m = (2m+1) \phi \quad ; \quad \phi = \tan^{-1} \left(\frac{-R(z)}{kw^2(z)} \right) \quad (1a)$$

L_m is the m^{th} order Laguerre polynomial, k is the wave number, and $R(z)$ (curvature radius) and $w(z)$ (Gaussian waist parameter) are obtained from the complex propagation parameter⁽³⁾, q :

$$\frac{1}{q} = \frac{1}{R(z)} - \frac{i}{kw^2(z)} \quad (2)$$

Elementary analysis provides the decomposition coefficients as

$$\gamma_m = e^{i\phi_m} \int_0^a \psi(r, z) \Lambda_m r dr \quad (3)$$

where a defines the aperture radius in a given decomposition plane.

Initially, $\psi(r, z)$ arises from an analytic expression of the general form:

$$\psi(r, z) = A(r) e^{-i\phi_0}$$

where $A(r)$ is some radial amplitude profile such as Gaussian, quadratic, super-Gaussian, etc; and ϕ_0 is an initial phase to be specified. At other decomposition planes, $\psi(r, z)$ itself arises from an expression like Eq. (1).

In order to accomodate gain amplification, incremental nonlinear distortion and incremental static (Seidel) aberrations, it is convenient to treat ϕ_m above as only providing the appropriate free-space phase change in the wave function as propagation proceeds; all other properties are absorbed by the coefficients, γ_m . It should be noted that each γ_m is really a function of the parameter $w(z)$. In the initial fitting procedure, $w(z)$ is chosen to minimize the power residual⁽²⁾. In all other decompositions $w(z)$ is obtained from the complex propagation parameter, q .

Phase and Amplitude Changes

The following discussion provides details of the methods ARTEMIS employs to model alterations to the wave function as it propagates through a chain of optical elements. At a fixed (r, z) position, let ψ be the wave function evaluated either analytically or from a prior decomposition. Let $\hat{\psi}$ be the wave function as it is modified to account for any amplitude or phase changes.

An attribute of laser amplifiers is that the gain they provide is typically non-uniform across the spatial dimensions of the amplifier. ARTEMIS

will allow a radially varying gain profile of the form:

$$G(r) = e^{(g_0 + g(r)) \ell} \quad (4)$$

where ℓ is the effective length of the gain medium, g_0 is the small signal gain coefficient, and $g(r)$ describes the radial non-uniformity. Thus, the first modification to the wave function to allow for gain amplification is simply:

$$\hat{\psi}(r, z) \sim \psi(r, z) e^{\frac{1}{2} (g_0 + g(r)) \ell}$$

Desiring to place any amount of static (Seidal) distortion on the beam requires a further change, in the form of a phase alteration. ARTEMIS will allow lumped phase alterations of the form:

$$\phi_s = f_1(r) + f_2(r) + \dots$$

where e.g.:

$$f_1(r) = \alpha \left(\frac{r}{a} \right)^2 \left(1 - \left(\frac{r}{a} \right)^2 \right)$$

a typical form for spherical aberration. This second modification results in:

$$\hat{\psi}(r, z) \sim \psi(r, z) e^{\frac{1}{2} (g_0 + g(r)) \ell} \cdot e^{i\phi_s}$$

Nonlinear phase distortion is similar to the static aberration, but is intensity (and therefore gain) dependent. It is characteristic of a glass medium and the phase alteration may be written as⁽⁴⁾:

$$\phi_B = \frac{\nu |X(r,z)| \left(\left(g_0 + g(r) \right)^\ell - 1 \right)}{g_0 + g(r)} \quad (5)$$

where ν is the nonlinear refractive index for the medium. Thus the final expression for $\hat{\psi}$ becomes:

$$\hat{\psi}(r,z) \sim \psi(r,z) e^{\frac{1}{2} \left(g_0 + g(r) \right)^\ell} \cdot e^{i\phi_S} \cdot e^{i\phi_B}$$

The phase alterations are all incremental distortions accumulated since the previous decomposition. ψ , itself, contains a history of all preceeding phase and amplitude modifications. New coefficients, $\hat{\gamma}_m$, can be calculated from an expression like Eq. 3, viz.:

$$\hat{\gamma}_m = e^{i\phi_m} \int_0^a \hat{\psi}(r,z) \Lambda_m r dr$$

Propagation in the region prior to the next decomposition plane is accomplished by keeping the $\hat{\gamma}_m$ fixed, evaluating new phase terms, ϕ_m , and calculating the new wave function as:

$$\psi(r,z) = \sum_{m=1}^N \hat{\gamma}_m \Lambda_m e^{-i\phi_m}$$

It is worthwhile to remark that the expression for gain (Eq. 4) and nonlinear distortion (Eq. 5) are valid only for unsaturated media.

Suitable expressions are utilized for expressing the phenomenon of gain saturation.⁽⁵⁾

Propagation

The propagation through space and/or certain passive elements can in general be described by a ray-transformation matrix, T:

$$T = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

If q_1 is the initial complex parameter (Eq. 2), then after propagation,

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D}$$

From q_2 the quantities $R(z)$, $w(z)$, and ϕ_m can be appropriately calculated (Eq. 1a, 2). ARTEMIS is originally intended for transformations of the more specific kind:

$$T = \begin{pmatrix} 1 & B \\ C & 1 \end{pmatrix}$$

where one of B or C is zero. $B \neq 0$ provides an incremental free space propagation distance. $C \neq 0$ provides a focal length for the appropriate (thin) lens transformation. For passive elements the only change effected to the wave function decomposition is a change in the modal phases, ϕ_m . If incremental distortions are also specified for the element, a redecomposition

also takes place. It has been unnecessary to associate distortions with every passive element traversed to successfully model existing systems at LLL. It is only necessary to lump distortions in strategic points along the optical chain.

Active elements are specifically gain media. The wave function is first propagated an appropriate free space distance (the amplifier length) to account for the correct diffraction-propagated phase change, ϕ_m , and then decomposed to account for the gain amplifications and nonlinear effects. Both the rod and disc-type amplifiers are conceptually the same, though care must be taken to so construe the model to prevent severely diverging or converging beams through an amplifier unit. Rod amplifiers may appear in segments or slices to meet this requirement as well as to apply the nonlinear effects in small increments. Disc amplifiers, whose individual discs are actually tilted, are always modeled as sequences of disc pairs to eliminate the need for considering steering effects.

All lengths specified for modeling purposes are not true physical lengths, but lengths modified to provide effective path lengths of the propagating beam. Components such as turning mirrors, Pockels cells, rotators, etc., are relatively unimportant for purposes of simulation; though ARTEMIS does provide a generalized "loss" element to account for any attenuation experienced when encountering such components.

Additional Features

ARTEMIS provides the ability for some specialized operations such as examining low frequency ripple growth. The initial wave function

may be modified by a sinusoidal intensity pattern. Focal volume sweeps similar to those depicted in Ref. 4 are available. Spatial filter pinholes may be accurately modeled. The input parameters described in the appendices offer the various simple elements allowed by ARTEMIS, and the sample output set actually used to model the ARGUS Laser System provides an example of the way these input parameters can be arranged to provide a powerful simulation.

Code Limitations

In a crude sense, the code handles "nearly perfect" laser system conditions and easily provides criteria for relative merit of alternatives to or variations of a given system. It is less useful in providing criteria for a "bad" system. The wave function may be decomposed several times during the propagation, and a "nearly perfect" laser system is defined as one where every such decomposition is successful. That is, the power residual obtained for the difference between an existing wave function and its subsequent fit should be relatively small. The errors tolerated are difficult to categorize, but experience has taught that when intensity plots are superimposed for the (original) wave function and its (re)fitted estimate, no discernible difference should be apparent. This customarily corresponds to a calculated percent residual of the order 10^{-5} . This criteria is often difficult to obtain with a finite number of basis functions and allowance is made by certain arm-waving arguments. Viz., since the physically real laser beam at any point is probably worse in terms of small scale structure as well as overall beam abnormalities, one asks if the decomposition is a

reasonable approximate to the beam in a nearby plane (often used when the initial fit is somewhat undesirable) or is it at least no worse than the beam prior to refitting (a smoothing process). In any event, effort can be directed towards minimizing these symptoms often by increasing the number of basis functions or choosing a more careful integration mesh. A "bad" system is defined as one where, during the propagation, a particular decomposition cannot be accepted as representing the beam. Percent power residuals of the order 10^{-4} or greater can usually be suspect. Propagation properties up to the position of the ill-fit may be acceptable, but following positions are clearly incorrect even though the fitting may be excellent. It is quite possible that a subsequent decomposition will fit a highly distorted beam arising from a bad prior decomposition.

Since numerical integration is crucial to the Laguerre-Gauss mode decomposition approach, and to the calculation of pertinent information such as energies and fill factors, several integration schemes are incorporated for different parts of the simulation, including simple Reiman sums as well as embellishments of the trapezoidal, Newton-Cotes formulae. Certain adaptive integration schemes have been tried, but the increase in execution time is prohibitive.

Program Verification

The basic diffraction methods of ARTEMIS have been applied and verified previously.⁽²⁾ Recent utilization of the code has involved the development of spatial filter relay chains,⁽⁶⁾ which have been experimentally tested on the LLL ARGUS laser system.

REFERENCES

1. SNORT - Annual Report (1974).
2. J. T. Hunt, P. A. Renard and R. G. Nelson, "Focusing Properties of an Aberrated Laser Beam", Applied Optics, Vol. 15, p. 1458, June 1976 and ZAXC unpublished.
3. Laser Physics, A. Maitland, M. H. Dunn, North Holland Publishing Co., Amsterdam - London, p. 154-158 (1969).
4. Laser Program Annual Report; Lawrence Livermore Laboratory, UCRL 50021-74.
5. (Memo: TDA 76-338 - Trenholme).
6. J. T. Hunt, P. A. Renard, Wm. W. Simmons, "Improved Performance of Fusion Lasers Using the Imaging Properties of Multiple Spatial Filters", submitted Applied Optics (Nov. 1976).
7. The so-called "Trenholme's Garrulous Input File" which liberally scatters comments among the actual input values.

APPENDIX A

Input and Output

The input to ARTEMIS comes from a disc file and is formatted as a modified TGIF file.⁽⁷⁾ The sample input file contained in Appendix D displays the basic structure. The name of the input file should contain a maximum of eight characters since the output files derive their names from this input name. Strict formatting must be followed (except where noted.) There are a few lines in the input file that actually contain no data and are present for readability. If the input file is called TEST, the code will echo the names TESTPP and DXTEST****. The first may be sent to HSP, the second to DD80 or other graphics devices.

Since the Fortran compiler used recognizes comma(,) as a field delimiter in a formatted READ statement, the appearance of comma in the sample data file should be noted. Normally, values should be right adjusted in their fields, but judicious use of comma can allow supressing of needless blanks.

Initialization Parameters:

This block consists of 70 character lines, the first 60 characters of each being a descriptive comment. The following is a listing of these parameters. (Fortran field lengths, and appropriate units are included in parenthesis).

ID (2A10) - 20 characters of identification to label the data set for later reference. This identification is duplicated into all output files.

NFIT (I10) - the number of Laguerre-Gauss mode functions to be used in the decomposition of the wave function in a given time plane. Maximum

value allowed is 100. No default is presumed.

NPROF (I10) - This flag indicates the type of input intensity profile desired (apodizer). A positive value is interpreted as the power of a (super) Gaussian profile. A negative value defaults to a quadratic profile.

APER (F10.2) - This is the aperture radius (cm) on which the initial beam is constructed. For super-Gaussian profiles, this radius will correspond to the point where the intensity is down by .001 from its peak (axial) point.

APER0 (F10.2) - This is the radius (cm) of the Gaussian source beam (e^{-2} point) that is folded into the apodizer profile. Since this value is subject to actual laser hardware considerations, it is data loaded internally.

PEAKIN (F10.2) - The (axial) peak intensity (watts/cm²) for initial beam.

BSPLICE (F10.2) - If NPROF indicates the quadratic choice for input profile, BSPLICE chooses the point where a parabolic tail is grafted. BSPLICE is normalized, and the actual splice will be chosen at BSPLICE*APER. The tail is so constructed that the intensity and its first derivative are continuous at the splice point, and smoothly decays to zero at APER.

Given the above information, a typical super Gaussian input profile is given by:

$$I(r) = \text{PEAKIN} \cdot \exp \left[-2 \left(\frac{r}{\text{APER0}} \right)^2 \right] \cdot (0.001) \left(\frac{r}{\text{APER}} \right)^{\text{NPROF}}$$

ABFNL (F10.2) - An initial nonlinear phase distortion (waves - cm^2/watt)

to be placed on the input wave function.

ABFSPH (F10.2) - An initial spherical aberration (waves).

ABFOTH (F10.2) - Some other distortion; controllee specific.

WMIN (F10.2) - The decomposition of the wave function performed throughout

WMAX (F10.2) the code is characterized by a fit parameter, w , chosen so as to minimize the power residual. A simple search is performed in the interval $(WMIN \cdot APER, WMAX \cdot APER)$ for this minimum. Typically, $WMIN=0$, and $WMAX=1$.

NSAMP (I10) - The number of sample points used in the minimization above.

Typically $NSAMP=50$ is a good choice in the interval $(0, APER)$. With experience, considerable time savings can be achieved by selecting $NSAMP=1$ and $WMIN=WMAX$. After the initial fit, w is appropriately calculated for the remainder of the problem and any subsequent re-decomposition. If $NSAMP$ is negative on input, the minimization search is conducted for other decompositions. This was mainly a debug tool.

FWHM (F10.2) - The full width, half-maximum (sec) for the Gaussian time variation of the initial pulse. Even if only a single time slice is modeled, this value is used in expressions for calculating energy.

TWINFAC (F10.2) - The time window factor. The time grid is initially constructed on a window width, $TWINFAC \cdot FWHM$, centered at $t=0$. It is often necessary to make the window initially wider so that if the pulse "walks off" the center line in the moving frame, or broadens significantly, it will not be prematurely truncated at the ends.

NDIMT (I10) - The number of time slices. If NDIMT=0, only the peak (center) of the time pulse is considered for the problem. Execution time is directly proportional to the number of time slices.

POLARITY (F10.2) - When NDIMT > .0, surface plots of the intensity, as well as psuedo grey level and contour plots are constructed.

POLARITY = 0 inhibits grey level pictures, POLARITY = +-1 merely switches the polarity of the display for grey levels.

ICONTRST (I10) - gives (approximately) the density relation between grey level and intensity value. ICONTRST = 1 gives a linear relationship, ICONTRST = 2 gives quadratic, etc.

XCONTR (F10.2) - Gives percent change in level contours for intensity plots.

Transformation matrix parameters - propagation, fitting, focusing:

The bulk of the remaining data contains parameters pertinent to the propagation of the laser beam through arbitrary optical elements. It was conceived that any optical element could be made up of a few elementary components juxtaposed. Thus, the elements considered are those in which the transformation matrix has precisely one non-zero off diagonal element. Aside from amplifier elements (special!) each optical element has one line containing parameters suitable for that element. Each line contains a four character key describing the element, five numerical values (5F10.2 field), plus a 20 character optional hollerith identification. The fields are blank (or comma) delimited. Usually only the first letter of the key is used in determining element types. Following is a list of typical elements and their interpretations. (Refer to the sample input file in Appendix D).

Passive elements - non-gain media.

E---: "E" signals a particular element, either a lens or a distance.

T12=distance $\neq 0$. The element is interpreted merely as free space, and the beam is propagated an incremental distance, T12(cm). T21 is ignored.

T21=focal length $\neq 0$. The element is interpreted as a lens with focal length, T21(cm). The wave function is appropriately transformed. T12 is ignored.

B, S, O - Incremental nonlinear phase distortion, spherical aberration, and "other" distortion to be accumulated by the wave function after the action prescribed by T12 or T21. If any of B, S, or O is non-zero, the wave function is re-decomposed to accommodate the incremental distortion.

H---: "H" signals an (artificial) aperture. ARTEMIS attempts to calculate an aperture radius throughout the propagation, but since it is based on theoretical considerations, it is often too large in a practical sense. T12 is used to temporarily override the calculated aperture and a re-decomposition occurs. T21 is ignored, but B, S, or O may be present. Typically "H---" will be used for a spatial filter pinhole, or to knowingly aperture the beam, or merely provide a smaller radius for a better integration during the fitting operation. If one specifies "HL--" and ARTEMIS is in the automatic plotting mode (see optional parameters below), then a logarithmic plot is generated for this fit plane.

L---: "L" signals a loss element. An empirical formula for generating energy loss is used. T12 and T21 are ignored, but B contains an empirical transmission coefficient. (Current usage has restricted the loss to also be dependent on the nonlinear distortion accumulated between successive spatial filter pinholes.)

S---: "S" signals a pause. The program temporarily suspends and is re-started by pushing linefeed. This is a useful debug tool.

PLOT: - If a key is undecipherable, a plot is made of the beam at the (or anything current propagation position. Normally plots are made not a legal option) after anything that requires a re-decomposition of the wave function (see optional flags below). Additional plots may be obtained via this key option. T12 may contain an overriding aperture for plotting purposes only. All other values on the line are ignored except for the descriptive comment.

F---: "F" signals a focal volume sweep in the manner of those in Ref. 4. T12 propagates the beam an incremental distance, and intensity contours are then swept from that position through an additional T21 distance. B may contain an overriding aperture for plotting, all other values on the line are ignored. Once the region has been swept with contours, ARTEMIS requests optional cross sectional plots directly from the teletype for specific z-positions within the region. The final propagation position is not allowed to go past the T21 position specification.

END---: merely a signal to end a given data set. Several complete data files may be concatenated.

Active elements - gain media.

A---: "A" signals a laser amplifier.

T12 is the effective gain length (cm) of the amplifier.

T21=APERG is the effective radius (cm) for the media, but is only used for non-uniform gain considerations.

NU is the nonlinear refractive index (cm^2/watt).

GC0 is the axial gain coefficient

ESAT is the saturation energy for the amplifier (J/cm^2).

Every "A" element requires a second line of input (possibly blank) containing parameters defining the gain nonuniformity.

T12 (I10) = GAINKEY points to the functional type of nonuniformity.

T21, B, -S, 0, 02 ($=G_1, G_2, \dots, G_5$) are five coefficients which may be used.

Currently, GAINKEY=1 is the only option allowed for non-zero nonuniformity, and corresponds to:

$$g = GC0 + \sum_{i=1}^5 G_i \left(\frac{r}{APERG} \right)^{2i}$$

and the overall gain is then $GAIN = e^{g \cdot T12}$

Optional input parameters:

The following is a list of data that may be changed dynamically prior to execution (they were data loaded at compile time). In most cases they are simply program control flags.

APERØ (see above)

IFITSW = 0 - Turn off all plots and tables resulting from re-decomposition of the wave function. This assumes that the data set includes a few "PLOT" keys at desired locations.

= 2 - All tables and plots are produced.

= 1 - Only tables are produced.

It should be noted that the plotting of output, especially the surface plots (when NDIMT .GT. 0) are very time consuming.

IRIPPLE = 0 No sinusoidal intensity variation is added to the initial beam.

= 1 Sinusoidal variation is added, and ARTEMIS requests from the teletype two additional parameters defining the amplitude of the variation, and the number of cycles to appear across the profile.

Since a sinusoidal variation often develops on the wave function due to normal diffraction effects, a special notice is sent to output files to indicate the presence of ripples on the initial beam.

APPENDIX B

Availability

The Fortran source code for ARTEMIS is extensively commented and should prove a valuable aid in understanding further the modeling methods employed. Since the author is fond of several cute options in LLL's CHAT compiler, non-standard Fortran is used throughout. Within the source listing there are alpha-numeric statement labels, lines longer than 72 characters, "parameter" statements, multiple statements per line, cliches, comments appearing on the same line as code, negative indexing, negative dimensioning, and perhaps other differences from a standard Fortran. These options made life easier for the author, and no responsibility is accepted for another's frustration in understanding the various idiosyncrasies which are, for the most part, "bookkeeping" in nature.

Source codes, controllee, and sample data files are available from the author, but not directly accessible by the casual user. For completeness, the pertinent photostore directories are included here, and may appear under the author's "take" directory at some future date.

- LASER:RAYTRACE:DIFRACTION:PROPAGATE:ARTEMIS (controllee)
- LASER:RAYTRACE:DIFRACTION:PROPAGATE:ARTEMIS\$ (source)
- LASER:RAYTRACE:DIFRACTION:PROPAGATE:PICTBIN (plotting routines)
- LASER:RAYTRACE:DIFRACTION:PROPAGATE:DATA:.....(various input files)

A CHAT compile line for generating a controllee is:

CHAT (PICTBIN\$ TV80LIB, ORDERLIB,) ARTEMIS\$ ARTEMIS BIN\$ MAP box LL / tv
PICTBIN is a binary file containing several plotting subroutines used but not contained in TV80LIB or ORDERLIB.

Given an input file, TEST, execution may proceed as follows:

ARTEMIS TEST / t v

⋮ (various TTY reports on progress of the code)

All done

The output files produced will be TESTPP, DXTEST****, and TIMINFO; the second of which is the interesting file to look at.

APPENDIX C

Timing information is available from the author, but it may be noted that the test problem indicated in Appendix D required about 90 seconds of 7600 computer time. This includes CPU and I/O time. For short pulses (single time slice), this execution time is dominated by the plotting routines. For long pulse simulation, the execution time, aside from plotting, goes linearly with the number of time slices used. An ARGUS simulation with full saturation effects (50 time slices) took 65 minutes of 7600 computer time. For such extended executions, ARTEMIS is conveniently run in a production mode under the LLL ORDER batch processor.

APPENDIX D

A Sample Input Set and Example Output

The following pages show an actual input set used to model the LLL ARGUS laser system. A few representative pictures from the output generated are also provided. Fig. 1 shows a typical radial intensity profile. For this particular simulation, it was deemed that saturation was unimportant, and so the 3-D projection and contour plots discussed earlier are not present. The "F" labels a curve arising from the newest Laguerre-Gauss decomposition, and superimposes the original decomposition. The fainter, dotted lines are merely a measure of the enclosed energy (vertical scale runs from 0 to 1). Fig. 2 is a similar picture produced further down in the laser chain simulation. It demonstrates a lack of fit between the labeled and unlabeled intensity curves, however, the power residual difference is negligible, so that this new fit is acceptable as per the previous discussion. Fig. 3 is still later in the chain. Examples of the 3-D, contour, and focal volume sweep pictures are available upon request.

```

PROGRAM ARTEMIS INPUT
INITIAL BEAM INFORMATION
NFIT - NO. OF LAG. GAUSS MODES
NPROF - POWER OF TOP HAT PROFILE (-2 GIVES QUAD)
APER - APERTURE RADIUS (CM)
PEAKIN - PEAK INPUT INTENSITY (WATTS/CM2)
BSPLICE (NPROF= 20 SPLICE POINT OF QUAD. TAIL
ABFNL - INITIAL NON-LINEAR DISTORTION (WAVES)
ABFSPH - INITIAL SPHERICAL ABBERRATION (WAVES)
ABFOTH - INITIAL OTHER DISTORTION
WMIN - INITIAL VALUE FOR -WFIT- SEARCH (.GE.0)
WMAX - FINAL VALUE FOR -WFIT- SEARCH (.LE.1)
NSAMP - NO. OF SAMPLE VALUES FOR SEARCH
FWHM - TIME PULSE (GAUSSIAN) WIDTH (SEC)
TWINFAC - TIME WINDOW FACTOR
NDIMT - NO. OF TIME SLICES
POLARITY - OF GRAY LEVEL (-1, 0, 1)
ICONTRST - OF GRAY LEVEL (1, 2, ...)
XCONTR - (%CONTOUR SPACING)
TRANSFORMATION MATRIX PARAMETERS - PROPAGATION, FITTING, FOCUSING
KEY /... T12.../...T21.../...B - NU.../...S -GCO.../...O - ESAT/...COMMENTS...

PLOT
E-1, 150.0,
E-1A, 300.0, 0.0,
E-1B, 150.0,
E-1C, 10.0,
E-1D, 16.0,
PLOT
A-1, 25.0, 0.0, 3.80E-16, 0.08480, 3.25, 1 INCH ROD-1
G=, 1, 0.0, 0.0, 0.0, 0.0, 0.0,
E-2, 25.0, 0.0, 3.80E-16, 0.08480, 3.25, 1 INCH ROD-2
A-2, 25.0, 0.0, 0.0, 0.0, 0.0,
G=, 1, 0.0, 0.0, 0.0, 0.0,
E-2, 27.0, 1.02E-11, 0.08480, 3.25, 1 INCH ROD-3
A-2A, 25.0, 0.0, 0.0, 0.0, 0.0,
G=, 1, 0.0, 0.0, 0.0, 0.0,
E-2A, 150.0, 3.53E-11,
HL-2, 1.25, -275.0,
E-3, 111.0, 386.00,
E-4, 25.0, 3.80E-16, 0.06050, 3.25, 40MM ROD
G=, 1, 0.0, 1.70E-2, 0.0, 0.0,
E-5A, 137.81, -386.0,
E-5B, 40.0,
E-6, 43.3071,
E-6A, 0.015,
HL-3, 85.0,
E-7, 85.0,
E-8, 85.0,
E-9, 158.0, 3.70E-11,
PLOT
A-4, 14.1, 4.25, 3.80E-16, 0.08535, 3.25, B AMP1
G=, 1, 0.0, 0.0, -2.36E-2, 0.0, 0.0,
E-10, 147.0, 3.80E-16, 0.08535, 3.25, B-AMP2
A-5, 14.1, 4.25, 0.0, -2.36E-2, 0.0, 0.0,
G=, 1, 0.0, 0.0, 0.0, 0.0,
E-11, 272.0, 2.17E-11,
E-12, 85.0,
E12A, 85.0,

```

HL-4,	0.0200,					SF PINHOLE
E12B,	85.0,					SPAT FILT
E-14,		85.0,				SPAT FILT, LENS2
E-15,	148.0,		2.11E-11,			PROP. TO B-A
A-6,	14.1,		3.80E-16,	0.08680,	3.25,	B-AMP3
G=	1,	4.25,	0.0,	-2.36E-2,	0.0,	0.0,
E-16,	174.0,					
PLOT						
E-17,		85.0,				SPAT FILT, LENS1
E-18,	84.93,					SPAT FILT
HL-6,	0.0200,					SF PINHOLE
PLOT						
E18A,	85.07,					SPAT FILT
E-19,		134.21,				SPAT FILT, LENS2
E-20,	300.0,					
E-21,		531.8181,				
E-22,	355.0,		6.22E-11,			
A-7,	9.0,		3.80E-16,	0.05840,	3.25,	C-AMP1
G=	1,	0.0,	0.0,	0.0,	0.0,	0.0,
PLOT						
E-23,	171.0,					
A-8,	9.0,		3.80E-16,	0.05840,	3.25,	C-AMP2
G=	1,	0.0,	0.0,	0.0,	0.0,	0.0,
E-24,	306.0,		1.22E-11,			
PLOT						
A-9,	9.0,		3.80E-16,	0.05840,	3.25,	C-AMP3
G=	1,	0.0,	0.0,	0.0,	0.0,	0.0,
E-25,	20.0,		0.00E-11,			
E-26,		195.0,				
E-27,	194.87,					SPAT FILT
HL-6,	0.0250,					SF PINHOLE
PLOT						
E27A,	195.13,					SPAT FILT
E-28,		195.0,				
E-29,	20.0,		1.39E-11,			
A-10,	9.0,		3.80E-16,	0.06530,	3.25,	C-AMP4
G=	1,	0.0,	0.0,	0.0,	0.0,	0.0,
E-30,	300.0,					
E-31,		195.0,				
E-32,	194.82,					SPAT FILT
HL-6,	0.0300,					SF PINHOLE
PLOT						
E32A,	195.18,					SPAT FILT
E-33,		195.0,				
E-34,	990.0,		1.40E-11,			
PLOT						
E-35,		20.0,	2.5E-11,	0.0,	0.0,	FINAL FOCUS
E-37,	19.97,					
PLOT						
E-38,	0.01,					
PLOT						
E-39,	0.01,					
PLOT						
END

***** OLD AND NEW FIT *****

BEAM CHARACTERISTICS AFTER A-6 B-AMP3 :

Z-POSITION (CM).....	1.942417E+03
APERATURE RADIUS (CM).....	4.243E+00
PEAK INTENSITY (WATTS/CM2)...	7.153E+09
OCCURS AT (R,T) = (8.487E-02, 0.)	
W(Z) (CM).....	3.395E-01
R(Z) (CM) CURVATURE RAD.....	1.658E+04
ERROR IN FIT.....	4.418E-07
ENERGY (JULLES).....	1.142E+02

FOR RADIAL PROFILE SHOWN:

FILL FACTOR.....	5.317E-01
POWER (WATTS).....	2.145E+11

TOTAL ACCUMULATED DISTORTIONS (WAVES):

NON LINEAR (ON AXIS).....	4.906E-01
SPHERICAL.....	0.
OTHER.....	0.

FIG. 1

***** OLD AND NEW FIT *****

BEAM CHARACTERISTICS AFTER E-35 FINAL FOCUS :

Z-POSITION (CM)..... 5.564417E+03
 APERTURE RADIUS (CM)..... 9.989E+00
 PEAK INTENSITY (WATTS/CM2)..... 1.216E+10
 OCCURS AT (R,T) = (3.995E-01, 0.)
 W(Z) (CM)..... 7.991E-01
 R(Z) (CM) CURVATURE RAD..... -2.001E+01

ERROR IN FIT..... 2.084E-05

ENERGY (JOULES)..... 9.943E+02

FOR RADIAL PROFILE SHOWN:

FILL FACTOR..... 5.269E-01
 POWER (WATTS)..... 1.868E+12

TOTAL ACCUMULATED DISTORTIONS (WAVES):

NON LINEAR (ON AXIS)..... 1.754E+00
 SPHERICAL..... 0.
 OTHER..... 0.

FIG. 2

BEAM CHARACTERISTICS AFTER E-37 FOCAL VOLUME
 Z-POSITION (CM)..... 5.584387E+03
 APERTURE RADIUS (CM)..... 1.830E-02
 PEAK INTENSITY (WATTS/CM2)..... 1.713E+16
 OCCURS AT (R,T) = (8.419E-03, 0.
 W(Z) (CM)..... 1.464E-03
 R(Z) (CM) CURVATURE RAD..... -3.829E-02

ERROR IN FIT..... 0.

ENERGY (JOULES)..... 9.946E+02

FOR RADIAL PROFILE SHOWN:

FILL FACTOR..... 1.654E-01
 POWER (WATTS)..... 1.869E+12

TOTAL ACCUMULATED DISTORTIONS (WAVES):

NON LINEAR (ON AXIS)..... 1.754E+00
 SPHERICAL..... 0.
 OTHER..... 0.

FIG. 3

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

NOTICE

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Printed in the United States of America

Available from

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

Price: Printed Copy \$: Microfiche \$3.00

Page Range	Domestic Price	Page Range	Domestic Price
001-025	\$ 3.50	326-350	10.00
026-050	4.00	351-375	10.50
051-075	4.50	376-400	10.75
076-100	5.00	401-425	11.00
101-125	5.50	426-450	11.75
126-150	6.00	451-475	12.00
151-175	6.75	476-500	12.50
176-200	7.50	501-525	12.75
201-225	7.75	526-550	13.00
226-250	8.00	551-575	13.50
251-275	9.00	576-600	13.75
276-300	9.25	601-up	*
301-325	9.75		

* Add \$2.50 for each additional 100 page increment from 601 to 1,000 pages, add \$4.50 for each additional 100 page increment over 1,000 pages.

Technical Information Department
LAWRENCE LIVERMORE LABORATORY
University of California | Livermore, California | 94550