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SYSTEM OPTICAL QUALITY USERS GUIDE. PART 1.(U)
MAR 80 J L FORGHAM, S S TOWNSEND F29601-77-C-0025
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# SYSTEM OPTICAL QUALITY USERS GUIDE.

## Part 1,[redacted]

(10) J.L./Forgham S. S. /Townsend J. L. /Campbell

United Technologies Corporation
West Palm Beach, FL 33402

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This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication

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## SOQ USER GUIDE UPDATES

June 1980 Updates to SOQ80128

## INTRODUCTION

This document defines the changes made to the SOQ code (SOQ80128) between January and June of 1980. The changes either correct shortcomings found in the code or, more usually, document the increased capability being continually built into the code. The SOQ code is maintained as SOQ80128 June PL,ID = AFLOJRA as a NOS/BE-1 CDC update format file.

## UPDATES

### 1. *ID FIXZRN

This update redefines the coeffiencets to be input to the Zernike subroutine. This new convention is more physically meaningful in that, at least for lower orders, the coefficients are in waves. For example, to impose one wave peak to peak of defocus ($P_4$) on a beam, one would input P(4)=1. The phase applied is now:

$$\phi(I,J) = \sum_k P_k \pi Z_k(I,J)$$

The subroutine affected is ZERN. This update does not effect the rest of the code.

### 2. *ID FIXJTR

This update ensures a correct definition of DF in subroutine JITRBG since when JITRBG is called from subroutine QUAL, the X-coordinate array contains R$\lambda$/D coordinates, not the spatial coordinates.

Only one line of the code is affected by this update.

### 3. *ID ROTZRN

Due to different coordinate system orientations for data, it became necessary to allow for this variation within subroutine ZERN.

Define the data x and y coordinates to be XROT and YROT, and the SOQ x and y coordinates to be XIN and YIN. The rotation angle is then defined to be $\theta$ (in radians).

COSROT = COS(θ)

SINROT = SIN(θ)

XROT = XIN x COSROT + YIN x SINROT

YROT = -XIN x SINROT + YIN x COSROT

Application of Zernike polynomials to and SOQ point located at (XIN, YIN) would then be calculated using Z(XROT, YROT). The possibility of axis flips are also accounted for and are flagged by FLIPX or FLIPY not equal to zero. Namelist ZERNS is modified to include FLIPX, FLIPY and the rotation angle (in degrees) ZTHETA. No common was modified. This update modified only subroutines GDL and ZERN.

```
.SDG9DUPDT,ID=ARLOSST + SDGBD128,ID=ARLOJRA                          PAGE    1

     *IDENT FIXZRN

        */  ZERN
          *DELETE ZRNIKE.115
                DEL = DEL*3.14159264
          *DELETE ZRNIKE.125
               C 20X,22H PHI(N) = PI*R(N)*Z(N)//

     *IDENT FIXJTR
        */  JITREG
          *DELETE JITTER.29,JITTER.30
                DF = 1./(FLOAT(NPTS)*DX)

     *IDENT ROTZRN
        */  SDL
          *DELETE ZRNINPC.3
                NAMELIST /ZERNS/ RO,R,RRANG,SIGMAY,NTERMZ,ZTHETA,FLIPX,FLIPY
          *INSERT ZRNIKE.9
          C           ZTHETA = THE CLOCKWISE ANGLE OF ROTATION OF THE DECOMPOSITIO
          C                    AXES ONTO THE SDG COORDINATE SYSTEM
          C                    BEFORE CALCULATION OF THE ZERNIKE POLYNOMIALS.
          C                    IT IS INPUT IN DEGREES.
          C           FLIPX = 1. RESULTS IN A FLIP ABOUT THE X AXIS BEFORE
          C                    ROTATION.
          C           FLIPY = 1. RESULTS IN A FLIP ABOUT THE Y AXIS BEFORE
          C                    ROTATION.
          *DELETE ZRNINPC.2
                DIMENSION PZ2SV(20,10)
          *INSERT ZRNINPC.7
                ZTHETA = 0.
                FLIPX = 0.
                FLIPY = 0.
          *INSERT ZRNINPC.9
                PZ2SV(IZERN,3) = ZTHETA*3.141593/180.
                PZ2SV(IZERN,4) = FLIPY
                PZ2SV(IZERN,5) = FLIPY
          *DELETE ZRNINPC.10,ZRNINPC.11
            244 CALL ZERN(PZ2SV(IZERN,1),PZ2SV(IZERN,2),PZ2SV(IZERN,3),
               X           PZ2SV(IZERN,4),PZ2SV(IZERN,5),
               X           PZSAVE(25,IZERN),PZSAVE(1,IZERN))
        */  ZERN
          *DELETE ZRNINPC.12
                SUBROUTINE ZERN(SIGMAY,XNTRMZ,THETA,FLIPX,FLIPY,RO,R)
          *INSERT ZRNIKE.72
                COSROT = COS(THETA)
                SINROT = SIN(THETA)
          *DELETE ZRNIKE.75
          *DELETE ZRNIKE.77
                XIN = X(IX)
                YIN = X(IY)
                IF(FLIPX.GT..5) YIN=-YIN
                IF(FLIPY.GT..5) XIN=-XIN
                XROT =  XIN*COSROT + YIN*SINROT
                YROT = -XIN*SINROT + YIN*COSROT
                IF(FLIPX.LT.-.5) YROT=-YROT
                IF(FLIPY.LT.-.5) XROT=-YROT
                XSQ = XROT**2
                YSQ = YROT**2
          *DELETE ZRNIKE.80
                THET = ATAN2(YROT,XROT)
```

```
*IDENT MCRSUM
      *INSERT SUMMRY.515
      C
      C   **** COPY TAPE(50) TO OUTPUT:
      C
            END FILE 50
      C
            WRITE(6,3035)
            REWIND 50
       7000 READ(50,4005) IC1,C2
       4005 FORMAT(I1,21A4)
            IF(EOF(50).NE.0.) GO TO 7015
      C     IF(IC1.EQ.1) WRITE(6,3035)
            WRITE(6,4040) C2
       4040 FORMAT(10X,21A4)
            GO TO 7000
       7015 REWIND 50
            WRITE(6,3035)
      C
            REWIND 57
       4000 READ(57,4005) IC1,C2
            IF(EOF(57).NE.0.) GO TO 4015
            IF(IC1.EQ.1) WRITE(6,3035)
            WRITE(6,4040) C2
            GO TO 4000
       4015 REWIND 57
            WRITE(6,3035)
      C
            REWIND 57
       6000 READ(57,4005) IC1,C2
            IF(EOF(57).NE.0.) GO TO 6015
            IF(IC1.EQ.1) WRITE(6,3035)
            WRITE(6,4040) C2
            GO TO 6000
       6015 REWIND 57
            WRITE(6,3035)
      C
      C   **** COPY TAPE(ISUMRY) TO OUTPUT:
      C
            REWIND ISUMRY
       5000 READ(ISUMRY,3005) IC1,C2,C3
            IF(EOF(ISUMRY).NE.0.) GO TO 5015
            IF(IC1.EQ.1) WRITE(6,3035)
            WRITE(6,3040) C2,C3
            GO TO 5000
       5015 REWIND ISUMRY
            WRITE(6,3035)
      C
      C   **** COPY TAPE(50) TO OUTPUT:
      C
            WRITE(6,3035)
            REWIND 50
       8000 READ(50,4005) IC1,C2
            IF(EOF(50).NE.0.) GO TO 8015
      C     IF(IC1.EQ.1) WRITE(6,3035)
```

```
      WRITE(6,4040) C2
      GO TO 9000
 9015 REWIND 50
      WRITE(6,3035)
C
```

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18. SUPPLEMENTARY NOTES

This report is divided into three parts. Part 1 consists of the front matter and text pages 1-34. Part 2 consists of text pages 35-296 and the References. Part 3 consists of Appendices A and B and distribution list pages 297-360.

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

| | |
|---|---|
| Laser | Optical System |
| Code | High Power Laser |
| Optics | High Energy Laser |
| Optical Quality | |

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report describes the System Optical Quality (SOQ) code structure and the input to the code required for analyzing High Power Laser Optical Systems. The SOQ code provides the designer with a physical optics model of the system. The code traces the beam from its point of origin in the resonator through the optical train into the far field. This report is divided into three parts. Part 1 describes the general structure of the SOQ code and establishes a correlation between the usual optical elements encountered in the optical —

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20. ABSTRACT (Continued).

train/gas dynamic laser resonator and the appropriate SOQ models. Part 2 acquaints the user with the individual SOQ subroutines and their analytical formulations as manifested in Fortran within the SCQ framework. It also delineates the input required to exercise the subroutines, familiarizes the user with the operation of the SOQ model, and contains working input modules which carry the user through the usual calculations of the SOQ code from input generation to loaded cavity calculations. Part 3 contains Appendices describing SOQ updates.

# CONTENTS

## PART 1

## PART 2

CONTENTS (Continued)

PART 2

PART 3

## ILLUSTRATIONS

ILLUSTRATIONS (Concluded)

# SECTION I
# INTRODUCTION

As a prerequisite to the design and optical integration of high power laser systems, sophisticated analytical tools are needed to predict overall system performance and to perform design tradeoff studies. Without analytical guidance, the search for the highest level of safe system operation becomes an empirical trial-and-error process involving not only expensive and time-consuming hardware changes, but also risk to critical system components.

One useful analytical tool which has been developed for the design and integration of electro-optical systems is the system optical quality (SOQ) computer code. This code is designed to guide the optical designer in the comparison and assessment of system optical performance by providing a physical optics model of the system which traces the beam from its point of origin in the resonator through the optical train into the far field.

To predict overall system performance, detailed knowledge of the optical field (phase and amplitude distributions) is needed at every axial station in the optical train. A wave-optics theory is mandatory since the resonator mode structure, aperture losses, optical feedback, flux spillage, etc., are governed principally by diffraction. Moreover, system components cannot be analyzed independently since the beam distortions induced by each component depend on the shape and magnitude of the incident field distribution.

The purpose of this report is to provide a fundamental description of the SOQ code structure and a description of the input of the code as applied to gas dynamic laser systems. This description allows the optical designer to access and use the code to model a wide variety of resonator and pointer/tracker concepts. This report does not attempt to describe how the system analyst should lay out his optical design problem. Familiarity with the optical components and with the concepts of scalar wave theory and fundamental optics are assumed. Also assumed is a working knowledge of Fortran IV and the CDC NOS/BE operating system commands. Accurate use of the SOQ code requires familiarity with References 1 through 8.

This report is divided into four main sections. Section II describes the general structure of the SOQ code and establishes a correlation between the usual optical elements encountered in the optical train/gas dynamic laser resonator and the appropriate SOQ models. Section III acquaints the user with the individual SOQ subroutines and their analytical formulations as manifested in Fortran within the SOQ framework. This section also delineates the inputs required to excerise the subroutines. Section IV familiarizes the user with the operation of the SOQ model. This section contains working input modules which carry the user through the usual calculations of the SOQ code from input generation to loaded cavity calculations.

An additional section, Section V, has been included to show the user how to access and modify the code.

# SECTION II
# CODE DESCRIPTION

## 1. GENERAL CODE OVERVIEW

Section II provides a guide to the region of applicability of the SOQ code and a synopsis of the overall structure and accessibility procedures for the code. It is to acquaint the user with the way the computer code operates and with the subroutines supplied with the code.

It is assumed that the user has unfolded his optical system into an equivalent optical train in which each wavefront/medium interaction may be easily identified (Ref. 1). The following illustrates the concept: Figure 1 is a simplified diagram of a telescope. Figure 2 is a representation of the same telescope expressed as an equivalent optical train. The SOQ user must correlate the optical elements in the code (the equivalent system) with his optical system.

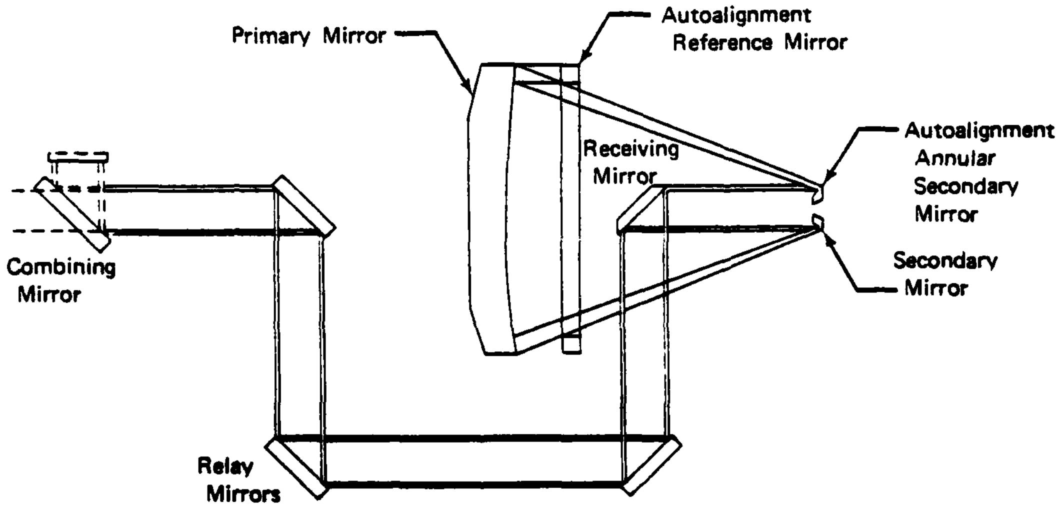

Figure 1. Simplified diagram of a telescope.

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1. Sziklas, E.A., et al., System Optical Quality Study Phase I -- Problem Definition, Pratt & Whitney Aircraft, AFWL-TR-73-231, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, June 1974.

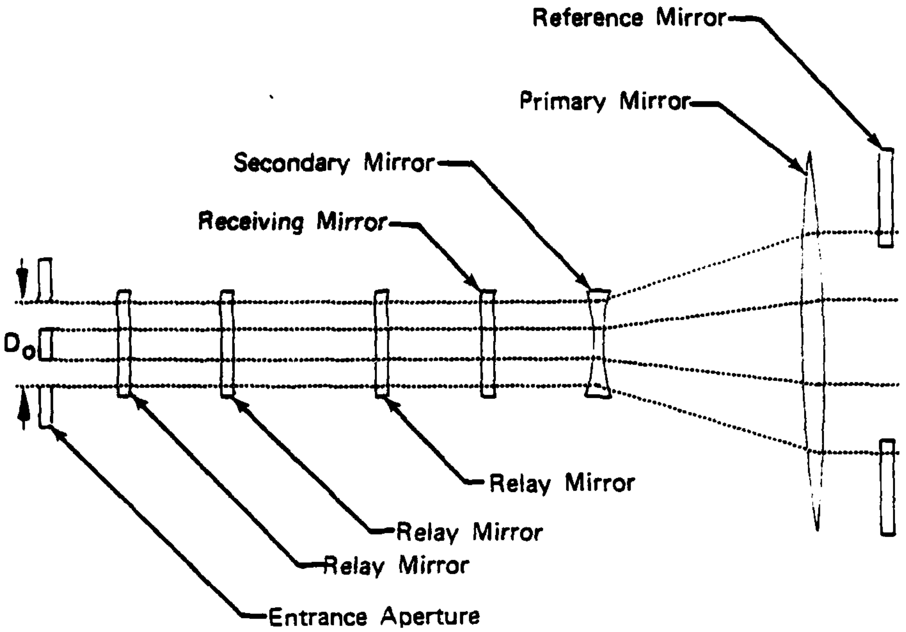

Figure 2. Equivalent optical train of a telescope.

In the equivalent system, the actual optical train is replaced by an equivalent optical transmission line which does not transmit the actual beam, but an effective unidirectional beam. In the wave propagation function the propagation algorithm replaces the actual beam with the effective unidirectional beam and propagates this beam through the entire equivalent optical train.

The optical train of the laser system under investigation is divided into a series of linked subsystems A, B, C . . . . etc., arranged in the sequence encountered by the beam (Figure 3). Laser systems employing feedback (e.g., oscillators) are viewed as a repetitive chain of subsystems in which the period constitutes one round trip pass through the resonator.

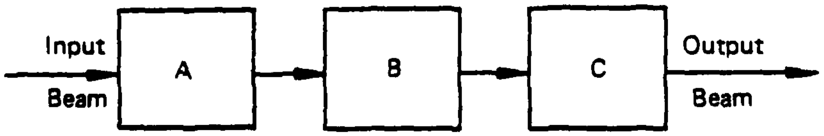

Figure 3. Optical train of the laser system.

Each subsystem A, B, C . . . is described by one or more library subroutines. Subroutines define a particular optical geometry in which all effects on the beam, including that of a transmitting inhomogeneous medium, are lumped at one or more discrete planes along the optical axis. Thus, each subroutine defines the position of a number of discrete optical elements (e.g., mirrors, apertures, gain/phase segments) along the optical axis. Free-space propagation is prescribed between the optical elements. Mirrors and apertures are described by a single optical element, while a transmitting medium is described generally by several optical elements. The number of optical elements needed is governed by the requirements that the continuous amplitude and phase changes across each element in the distributed "loss" system be replaced by a series of lumped "losses" whose amplitude and phase changes are small relative to unity and $2\pi$, respectively.

The input/output format of each subroutine is identical, viz., an $N \times N$ array of complex numbers representing the transverse phase-amplitude distribution of the input and output optical fields. In this discussion, $N$ is an integer defining the number of grid points used to specify the field in one transverse dimension.

Each optical element is characterized by a complex transmission function. Thus, if $u\ (I,J)$ denotes the field incident on a particular element and $u_+\ (I,J)$ the output field, then

$$u_+(I,J) = t(I,J,)\ u_-(I,J) \tag{1}$$

where the transmission function t which characterizes this optical element can be written in the general form

$$t(I,J) = A(I,J)\ \exp\left[i\Delta\phi(I,J)\right] \tag{2}$$

Here, $A(I,J)$ represents the amplitude change and $\Delta\phi(I,J)$ the phase distortion induced by the optical element. The integers $I,J = 1, 2, \ldots N$, define the two transverse grid coordinates. In general, a subroutine is constructed to define each transmission function and then stored in the subroutine library.

In the wave propagation function, an effective unidirectional collimated beam is generated and propagated along the equivalent optical transmission line. The beam is effectively unidirectional and collimated since linear and quadratic phase components (tilt and defocus) are normally analytically removed from the description. Care must be taken to properly account for the apparent transverse displacement of optical elements when tilt is analytically removed from the wave. The resultant collection of displaced optical elements defines the equivalent optical transmission line, as illustrated in Figure 4.

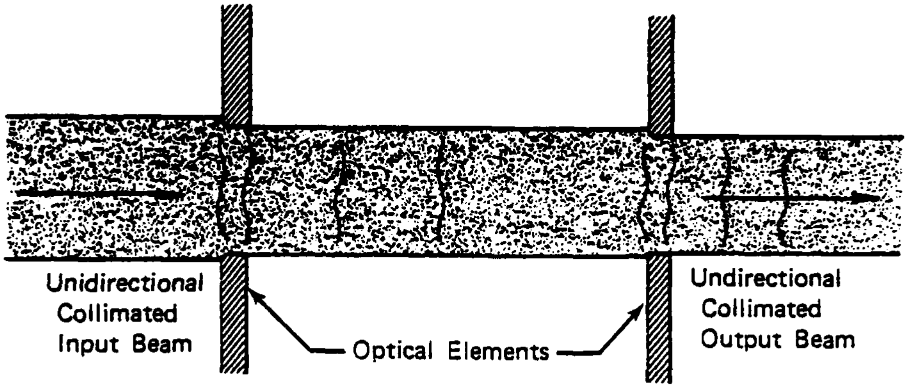

Figure 4. Equivalent optical transmission line.

The system performance (e.g., beam quality at various specified axial stations) is assessed in a performance evaluation function. This function also includes initiation of any desired parametric study (e.g., cost/performance tradeoff assessment) in which the wave propagation analysis is repeated for each specified value of the parameter.

## 2. REGION OF APPLICABILITY OF CODE

The SOQ code documented in this report is applicable to calculations which are resolved by the 128 x 128 point transverse description of the complex field behavior. The code is currently outfitted with those subroutines which describe a flowing, high Mach number $CO_2$-$N_2$ gas dynamic laser system and the appropriate optical elements, such as mirrors and apertures. A synopsis of the available models is included in Section II of this report and a full disclosure is included in Section III. The 128 x 128 point code is well suited to the description of problems characterized by collimated Fresnel numbers $\leq$ 15. Use of the 128 x 128 point code for propagation at higher Fresnel numbers has been shown to convolve away the higher spatial frequency information, while retaining the general character of the solution. Thus, the code can be used outside the Fresnel number region described above without totally erroneous results. Specific requirements are set in the following section which state the analytical relationship between beam geometric size, required calculation region size, and the number of sampling points.

Though currently limited to 128 x 128 points, the code can be expanded to 256 x 256 points for loaded cavity calculations on the Air Force Weapons Laboratory (AFWL's) current Control Data Corporation (CDC) Cyber 176 computer. The SOQ code currently uses about $225_8$K of small core memory (SCM) and $420_8$K of large capacity memory (LCM) to load and execute. The basic number of point requirements is specified in powers of 2 to achieve the most efficient use of Fast Fourier Transform (FFT) techniques, although the FFT algorithm employed for the propagation algorithm may be executed with any integer radix, but with some loss in efficiency.

The SOQ computer code installed at AFWL includes many optical transmission functions. However, the basic structure of the code allows the user to include whatever additional optical elements desired by appropriately updating the code. A detailed description of subroutine addition is included in Section V.

The computer program can now simulate the following numbers of optical elements. The code structure limits the user to 20 different optical elements, each of which can have up to 14 physical parameter input arguments. Each of these input arguments can be called up to 9 times within a system setup. Up to 98 optical elements may be included within one iterative resonator calculation with a maximum of 2 laser flow cavities containing 5 gain-phase segments per cavity. Each of these gain-phase segments represents a complex transmission function which couples the cavity kinetics and flow field inhomogeneities with the propagating optical field. Calculations outside an iterative loop limit the user to 9 calls to the same subroutine. All of the above constraints may be changed by the user, if he so desires, by redimensioning the deck. Presently the program also provides an automatic procedure for storing information from previous calculations and restarting subsequent calculations based on these results.

## 3. SAMPLING REQUIREMENTS

The fundamental SOQ propagation procedure uses a numerically efficient Fourier transform technique to obtain the solution to the scalar wave equation. When the problem is discretized, it becomes necessary to incorporate certain sampling theorems to ensure an accurate numerical result. Criteria have been derived (Ref. 2) which relate the accuracy of the scalar wave equation solutions for a desired propagation step (defined by a particular collimated Fresnel number) to the number of sampling points, and to the width of the discrete calculation region relative to the initial beam size.

To satisfy these requirements, the SOQ code user should describe the beam calculation region and number of points by simultaneously solving the following two inequalities. The width of the calculation region $D_{calc}$ required to model a propagating collimated beam with initial diameter 2a must be chosen to satisfy

$$G \geq 1 + \frac{1}{2\pi^2 N_c \varepsilon} \tag{3}$$

where $G = D_{calc}/2a$ is the guard band, $N_c = a^2/L\lambda$ is the collimated Fresnel number for the propagation step of length L, a is the radius of the geometric beam, $\lambda$ is the wavelength of the propagating wave, and $\varepsilon$ is the tolerance or fractional power spillover outside the calculation region. For general SOQ calculations, $\varepsilon$ is usually chosen to be 0.02. The number of sampling points $N_p$ in each transverse dimension must be chosen large enough to encompass the spatial frequency bandwidth of the propagating wave. In Reference 2, it is shown that

$$N_p \geq 4G (G + 1) N_c \tag{4}$$

where G is given by inequality (3) and $N_c$ is the Fresnel number defined above. For GDL SOQ calculations, the value of $N_p = 128$ is usually selected. As an additional precaution, a raised cosine data window is employed in a user specified region of $D_{calc}$ in both spatial frequency space and in real

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2. Sziklas, E.A., and Siegman, A.E., "Mode Calculations in Unstable Resonators With Flowing Saturable Gain. 2: Fast Fourier Transform Method," Applied Optics, Vol 14, pp. 1874-1899, August 1975.

space to avoid the errors introducted by aliasing and leakage. Both spatial frequency and real space windows are usually chosen as ten percent of the total calculation region in their respective spaces.

Since each propagation of the wave may be expressed in terms of the propagation of an equivalent collimated propagation step, the user has a means of determining the relevant numerical parameters to ensure numerical accuracy for the problem being simulated.

## 4. GENERAL SOQ CODE STRUCTURE

The SOQ code can be viewed as having several levels of program communication. Each level is associated with executive and/or computational responsibility. Executive routines denote those programs which, based on user input, select and integrate the appropriate subprograms to effect the desired computations. There are essentially four levels within this hierarchy which, macroscopically, describe the SOQ code structure. The lower the level number, the more executive is the routine. The higher the level number, the less executive and more computational the routine becomes. Care has been exercised in an effort to provide as little overlap as possible between the levels. The following diagram defines the hierarchy which exists within the SOQ code.

| | | | |
|---|---|---|---|
| Level I | SOQ | | |
| Level II | GDL | QUAL | LIST80 |
| Level III | AEROW | REGAIN | TILT |
| | APRTR | SPIDER | |
| | CAVITY | OUTPUT | |
| | MODER | | |
| | MIRROR | | |
| | STEP | SILVER | |
| | RGRD | | |
| | TBLOOM | | |
| | THERMAL | | |
| | BLUMIT | | |
| | IPLOT | | |

Level IV

GAINXY
DENSY
RANDU
FOURT
FUHS

KINET
INTERP
MIX
LINTERP
ROSN

ROSN6
POWWOW
POWR
ERF
ERFC

SPTAN
SIMPGG
BLUMIT

Routines in Level I are used primarily to set up the calculations at the initialization of a SOQ run and to provide flags for higher level computations and branching. The program at Level I communicates with Levels II through Level IV, and also with the user through his input job stream. At the single Level I routine "SOQ," the user decides, after specifying and constructing a complex input, whether far-field (QUAL) or optical train (GDL) calculations are to be performed.

Level II routines are primarily executive routines, although many computations are performed in this level. Subroutine GDL is used to communicate with the user's namelist input, to direct calls to Level III optical train routines, and to perform numerical computations. Subroutine QUAL, on the other hand, is used primarily to calculate the beam's far-field performance. Subroutine LIST80 appears at Level II since it primarily echoes the user input for a particular run, and can only be accessed through Level I.

Routines in Level III are the principle group of routines which a user may access and are the routines which make up the library of standard SOQ optical transmission functions. These normally are generally called from within GDL and, as such, receive their input primarily through the namelist input provided for subroutine GDL. Subroutine CAVITY is the only exception because it has its own namelist which is read from subroutine CAVITY the first time a particular cavity element is called.

Level IV routines are primarily numerical computation routines which are accessed by Level II and III routines. Level IV routines are used primarily to perform numerical calculations, with little executive responsibility.

System computations based on namelist input are primarily effected by transfer of data through named commons, with subsequent storage of input data in common to satisfy the need for program calculational memory when iterative calculations (resonator) are required.

To meet specific needs, additional optical element models may be constructed. The user usually incorporates the new model in the Level III library of routines. Subroutines called by the model are generally placed in Level IV, and modification of the Level II program is generally advised to provide input and complex field communication to the new Level III subprogram.

## 5. SYSTEM MACROSCOPIC FLOW CHART

The system macroscopic flow chart is the principal diagram used by the SOQ code. The structure acquaints the user with the way information is passed from input to each subroutine within the SOQ code along with a synopsis of the method used to store information for subsequent iterations. Figure 5 depicts the general SOQ flow of calculations.

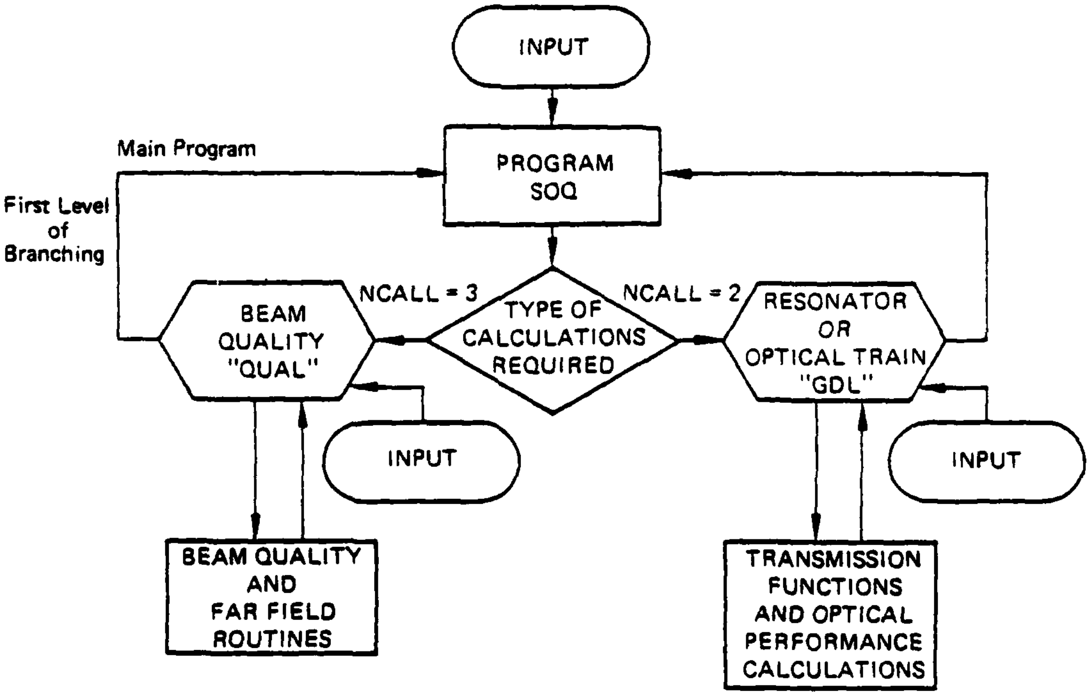


Figure 5. General SOQ flow of calculations with memory arrays associated with each subroutine.

At the main program level, input is provided which directs the SOQ code to either perform beam quality calculations or resonator and/or optical train performance calculations. The parameter, NCALL, in the SOQ main program input argument list specifies the branch to be followed. Within either subroutine GDL or QUAL the appropriate branches are taken based on input at these levels, which describe the input parameters for the requested optical transmission function element.

Since calculations may be of an iterative nature, the SOQ code within the GDL subroutine provides an array of information which stores the order and name of each optical element along with the appropriate input that characterizes that element. Correspondence between the equivalent optical train which the optical analyst has described is retained within the memory system of the SOQ code. Figure 5 depicts the structure of the SOQ code with the memory arrays associated with each subroutine.

For each GDL subroutine initially called, the model input is retained through the IGDL array shown in Figure 6. For each model, the ABC ($P_i$, $Q_i$, $R_i$) array retains the input parameter values. Iterative solution of the resonator problems uses the values stored in the IGDL, ABC, or similar arrays to direct the optical train through the same path. Noniterative calculations are also stored in the IGDL and ABC arrays, although the arrays are not used to redirect calculations.

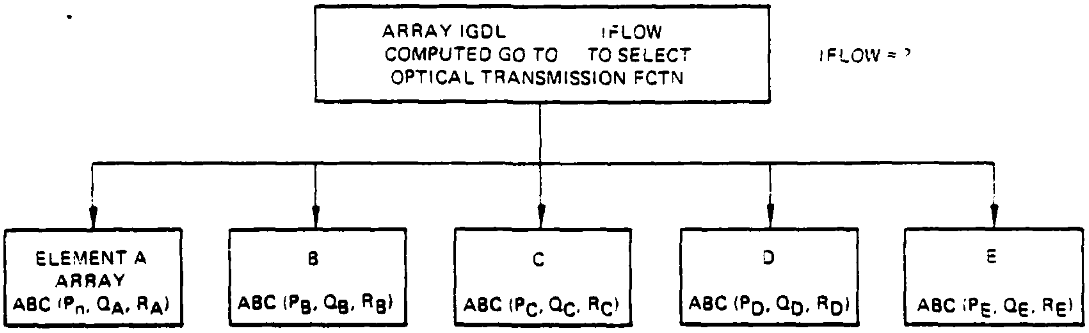


Figure 6. Subroutine GDL.

The notable exception to this philosophy is subroutine CAVITY with its own input and memory system (Fig. 7). The subroutine CAVITY arrays are structured according to the cavity input, and are a function of the number of cavities used.

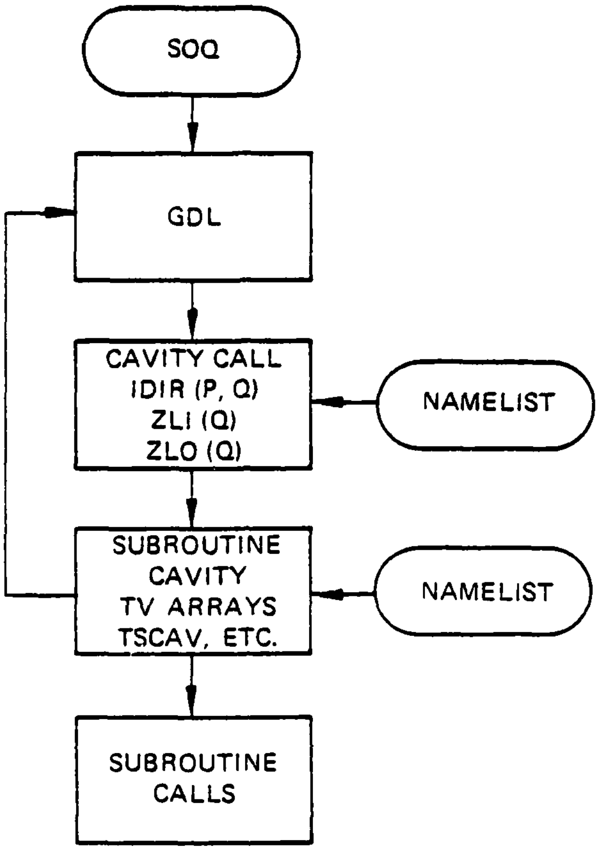


Figure 7. Subroutine CAVITY with its own input and memory system.

The overall SOQ macroscopic flow chart can now be constructed. The overall flow chart, shown in Figure 8, delineates the main program and the subroutine called from each level. Basically, two branches ("QUAL" and "GDL") can be followed. Within each branch the precise calculations and input are read to define the physical problem being simulated.

## 6. OVERVIEW OF SOQ CODE OPERATION

A previously defined optical train with known relevant physical parameters, the analyst may identify the SOQ routines necessary to simulate the optical train or configuration of interest. With the relevant SOQ model(s), the analyst may use the detailed description of the model contained herein to correlate his physical input parameters with those required to run the SOQ code.

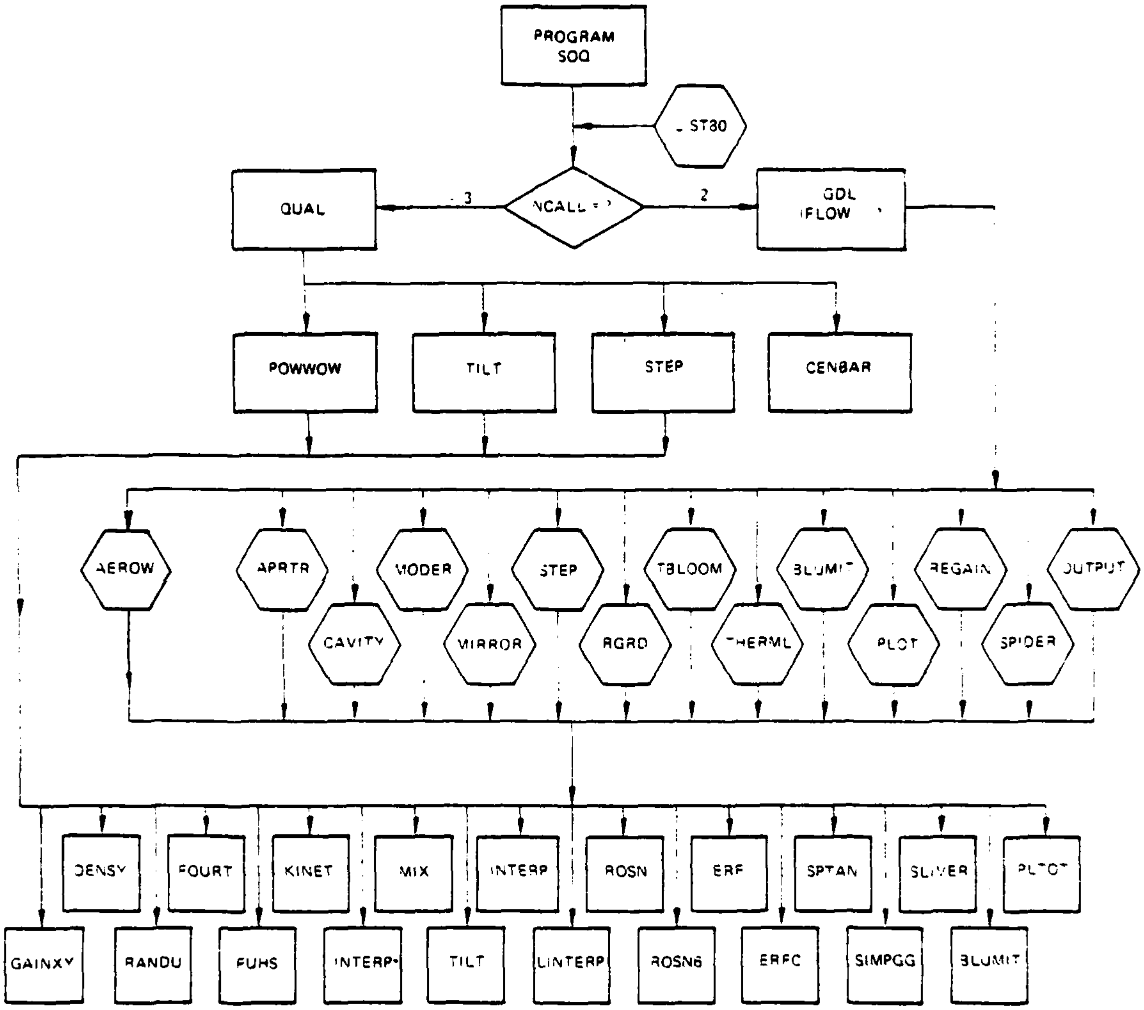


Figure 8. Overall SOQ macroscopic flow chart.

The input is then coded with SOQ namelist input descriptions to direct the calculations to the appropriate subprograms. The following demonstrates the procedure that may be used to execute the SOQ code. Actual test cases specifically illustrating SOQ code setup are included in Section V and are maintained on the AFWL-CDC Cyber 176 computer.

| | | |
|---|---|---|
| I | Initialize SOQ parameters and load input distribution | Namelist START activates code "SOQ" |
| II | Transfer to "GDL" for optical train/resonator calculations or calculate beam quality through "QUAL" | Parameter NCALL = 2 in START namelist activates "GDL" NCALL = 3 activates "QUAL" |
| III | In GDL read namelist parameters to pick model | Namelist CONTROL, IFLOW = IVWX<br>IVWX = Chosen model number |
| IV | When model has been defined, GDL branches to the appropriate namelist for the chosen model | Namelist XYZPQ, where XYZPQ is associated with an appropriate chosen model, such as an aperture or mirror |
| V | Repeat input calls to initialize additional models | Repeat steps II through IV |
| VI | Branch out of GDL and stop, or start a new set of optical model calculations. | Namelist CONTROL, IFLOW = 9, returns to program SOQ from GDL |

The actual job setup necessary to achieve this is described schematically in Figure 9.

A more detailed analysis with examples of the input and permanent (perm) file stream necessary to execute the "SOQ" code follows this illustration.

## 7. USER ACCESS AND PERMANENT FILES REQUIRED

Input:

The SOQ code is configured so that all input parameters are input through standard namelists. To find the specific namelist required, go to Section III where inputs for the chosen subroutines are identified. Section III describes the basic procedure used and namelist called to initiate the optical calculations. This is best illustrated in Figure 10.

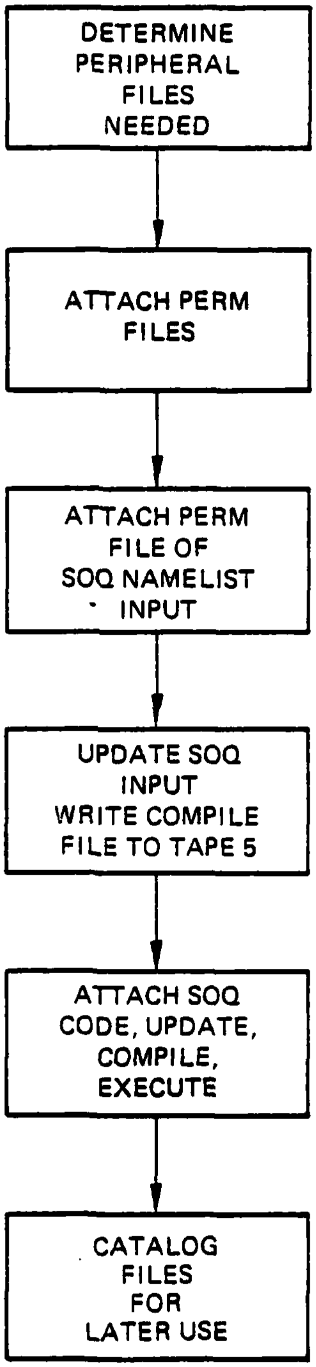


Figure 9. Job setup necessary for providing subprograms of interest.

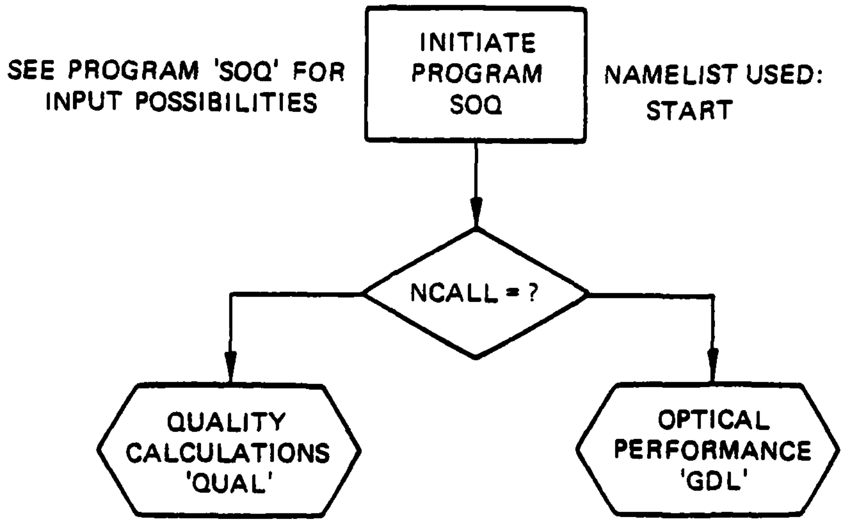


Figure 10. Section III describing the basic procedure used and the requisite namelist called to initiate optical calculations.

If the user desires quality calculations in the branch to QUAL, the code looks for input provided by namelist QLOT. If the user chooses the GDL calculation flowpath, then the code expects its next level of input from namelist CONTRL associated with GDL. After close inspection of subroutine GDL, the user will determine the appropriate namelist to specify his optical train. As each new model is applied in the optical train, the user executes a new $ CONTRL input followed by the appropriate model/transmission function input. The following computer printout is included to demonstrate the calling sequence. Without particular regard for the parameters used, the user is directed to the sequence of input and the comments appended. In this set of input, Item I input is used to initialize the SOQ main program and branch to subprogram GDL. Items II through VII control branches within GDL. Item VIII branches out of GDL back to the main program and Item IX branches in SOQ to terminate the SOQ run. All SOQ input is handled in the same manner, whether it is a simple propagation test case or a model of a complex loaded resonator and optical train system.

```
*****************************************************CARD INPUTS*****************************************
CARD             11111111112222222222333333333344444444445555555555666666666677777777778
COLUMN  12345678901234567890123456789012345678901234567890123456789012345678901234567890    CARD.

          TEST SAMPLING AND WINDOWING CRITERIA FOR AN SOQ FIELD                              1
            (NT,DELZ) = (5,5.E3),(10,2.5E3),(25,1.E3)                                          2
       $START  WWL=0.0010, NCALL=2, DCAL=12.50, NNPTS=128,                                   3
         IB=8, DDRX=0.0, DDRY=0.0, AMPGES=50.0, DGAUSS=0.0,           Activate 'SOQ'         4
  I      RESTRT=.FALSE., PLOTS=1.0, IN=5,                             Pass to 'GDL'          5
         SYMTRC=.FALSE., PHIRAD=0.0, $END                                                    6
        PROPAGATION TEST - STRAIGHT PROPAGATION - OVERLAP = 1.25                             7
       $CONTRL  IFLOW=4,  $END                                        GDL Branch             8
  II      APERTURE THE FIELD  TO A 10. CM. DIAMETER BEAM              Title                  9
       $APTUR  DOUT=10.,  DIN=0., XPOS=0.0, YPOS=0.0,   $END          Aperture              10
       $CONTRL IFLOW=8,  $END                                         GDL Branch            11
             PLOT THE INITIAL FIELD                                   Title                 12
  III  $PLOT   $END                                                   Plot Request          13
           INITIAL FIELD - APERTURED TO A 10. CM DIAMETER             Title                 14
       $CONTRL  IFLOW=3,  $END                                        GDL Branch            15
  IV     PROPAGATE WITH A TUBE FRESNEL NUMBER OF 10.                  Title                 16
       $PROPGT DELZ=2.5E3, WINDOX=.05, WINDOK=0., IIFG=1, IIPS=0,     Propagation Step      17
         IITP=1, ROCURV=0.0,  $END                                                          18
       $CONTRL IFLOW=8,  $END                                         GDL Branch            19
          PLOT THE PROPAGATED FIELD                                   Title                 20
  V    $PLOT   $END                                                   Plot Request          21
           PROPAGATED FIELD                                           Title                 22
       $CONTRL  IFLOW=4,  $END                                        GDL Branch            23
  VI      APERTURE THE PROPAGATED FIELD  TO A 10. CM. DIAMETER BEAM   Title                 24
       $APTUR  DOUT=10.,  DIN=0., XPOS=0.0, YPOS=0.0,   $END          Aperture              25
       $CONTRL IFLOW=8,  $END                                         GDL Branch            26
  VII      PLOT THE PROPAGATED FIELD - APERTURED TO A 10. CM. DIAMETER  Title               27
       $PLOT   $END                                                   Plot Request          28
           PROPAGATED FIELD - APERTURED TO A 10. CM. DIAMETER         Title                 29
  VIII $CONTRL IFLOW=9,  $END                                         GDL Branch            30
            RETURN TO MAIN PROGRAM                                    Title                 31
  IX   $START WWL=-1.,  $END                                          Return to Main.Deactivate 32
                                                                      SOQ Calculations
CARD             11111111112222222222333333333344444444445555555555666666666677777777778
COLUMN  12345678901234567890123456789012345678901234567890123456789012345678901234567890    CARD.
```

## 8. PERMANENT FILE REQUIREMENTS AND JOB EXECUTION

During execution the SOQ computer program may use several random access, on-line, permanent files. These files, called tapes but actually disk files, are used to access the data base or write to the data base. Permanent files or scratch files may be created by storing complex field information representing the propagating wave, the complex gain distribution in cavities, or far fields distribution information. Internally, the code also stores complex field information on files to protect it during some operations. This discussion is included to acquaint the user with the hierarchy of files which are reserved and freed during the SOQ code execution.

Reference is made to the program definition in Program SOQ which defines the tapes used by the program.

Additionally, the user must attach, as a minimum, the SOQ code either as a source file or as a binary file to provide a compliable and/or exectuable module for the computer.

The code currently defines tapes 1 through 31 in the program card. The following delineates the file correspondence for normal SOQ calculations.

| TAPE | |
|---|---|
| 1 | Used automatically by QUA1 |
| 2 | Open |
| 3 | Open |
| 4 | Open |
| 5 | Reserved for input file |
| 6 | Reserved for output file |
| 7 | Reserved for scratch storage |
| 8 | Reserved for cutout of feedback resonator field |
| 9 | Reserved for complex field and associated coordinates |
| 10 | Used automatically by CAVITY |
| 11 | Reserved for cavity calculations |
| 12 | Reserved for cavity calculations |
| 13 | Reserved for cavity calculations |
| 15 | Reserved for cavity calculations |

| TAPE | |
|---|---|
| 16 | Reserved for cavity calculations |
| 17 | Reserved for cavity calculations |
| 18 | Reserved for cavity calculations |
| 19 | Reserved for cavity calculations |
| 20 | Reserved for cavity calculations |
| 21 | Used automatically by CAVITY |
| 22 | Reserved for cavity calculations |
| 23 | Reserved for cavity calculations |
| 24 | Reserved for cavity calculations |
| 25 | Reserved for cavity calculations |
| 26 | Reserved for cavity calculations |
| 27 | Reserved for cavity calculations |
| 28 | Reserved for cavity calculations |
| 29 | Reserved for cavity calculations |
| 30 | Reserved for digital density field |
| 31 | Reserved for digital density field |

The user may increase the allocation of logical files, but must be aware of the usual file correspondence that is currently automatically allocated in the program.

The attached day file for a normal SOQ resonator run establishes the usual file correspondence and delineates the way the user obtains an executable module under the NOS/BE Cyber 176 system. The following computer printout is an example.

## 9. SOQ OUTPUT FORMAT

When properly executed, the SOQ code will calculate relevant system performance either in the near field (Fresnel) or far field (Fraunhofer) sense. Each of the SOQ transmission functions which modifies the complex field is programed to display or echo the relevant input parameters, the calculated relevant system parameters, and the amount of energy in the beam. The routines generally calculate integrated energy loss, if applicable, and the location of maximum or peak flux loads. The description of each subroutine, along with its listing provides insight into the actual output values. The system of test cases provided on the AFWL/CDC computer allows the user to exercise the SOQ routines and to evaluate the output parameters with the individual routines.

```
JRA2A,STMF7,P4000,T177.     NCR1076093167 - NO  TILT 135 WITH 6600 INPUT
ACCOUNT(URALT,********-***,CM,1731)
ATTACH(AAA,FTNCOMPAR2LIB3)
LIBRARY(AAA)
FILE,NCRIN,RT=S.
REQUEST(TAPE2,*PF)
REQUEST(TAPE4,*PF)
REQUEST(TAPE8,*PF)
REQUEST(TAPE9,*PF)
REQUEST(TAPE11,*PF)
REQUEST(TAPE12,*PF)
REQUEST(TAPE13,*PF)
REQUEST(TAPE22,*PF)
REQUEST(TAPE23,*PF)
REQUEST(TAPE24,*PF)
GETPF(NCRIN,NCR10INPUT,ID=********)
UPDATE(F,P=NCRIN,C=TAPE5,*,D,8,L=A1234-7)
RETURN(NCRIN)
GETPF(OLDPL,SOQ77128,ID=********)
UPDATE(F,N,*,L=0)
FTN(I,LCM=I,PL=20000,L=0,A)
RETURN(OLDPL)
GETPF(PF8,NCR1076093190CUSM,ID=********)
GETPF(PF9,NCR1076093167CU,ID=********)
GETPF(PF11,NCR1076093167CG11,ID=********)
GETPF(PF12,NCR1076093167CG12,ID=********)
GETPF(PF13,NCR1076093167CG13,ID=********)
GETPF(PF22,NCR1076093167CG21,ID=********)
GETPF(PF23,NCR1076093167CG22,ID=********)
GETPF(PF24,NCR1076093167CG23,ID=********)
GETPF(PF30,OPR1031111PTASECCONTXY,ID=********)
GETPF(PF31,OPR1131141PTASECCONTXY,ID=********)
LGO(PL=60000)
PURGE(WAPE8,NCR1076093167CUSM,ID=********,LC=1)
PURGE(WAPE9,NCR1076093167CU,ID=********,LC=1)
PURGE(WAPE11,NCR1076093167CG11,ID=********,LC=1)
PURGE(WAPE12,NCR1076093167CG12,ID=********,LC=1)
PURGE(WAPE13,NCR1076093167CG13,ID=********,LC=1)
PURGE(WAPE22,NCR1076093167CG21,ID=********,LC=1)
PURGE(WAPE23,NCR1076093167CG22,ID=********,LC=1)
PURGE(WAPE24,NCR1076093167CG23,ID=********,LC=1)
CATALOG(TAPE8,NCR1076093167CUSM,ID=********,RP=999)
CATALOG(TAPE9,NCR1076093167CU,ID=********,RP=999)
CATALOG(TAPE11,NCR1076093167CG11,ID=********,RP=999)
CATALOG(TAPE12,NCR1076093167CG12,ID=********,RP=999)
CATALOG(TAPE13,NCR1076093167CG13,ID=********,RP=999)
CATALOG(TAPE22,NCR1076093167CG21,ID=********,RP=999)
CATALOG(TAPE23,NCR1076093167CG22,ID=********,RP=999)
CATALOG(TAPE24,NCR1076093167CG23,ID=********,RP=999)
[illegible]
```

Request Perm File Space For Data Generated During Run

Input File

Namelist Input File

Tapes = Input

SOQ Deck

Create SOQ Source File & Compile to Create Binary

Complex Field from Previous Iterations

Load Complex Gain Arrays

Load Density Fields

Execute Binary

Remove Old Files From System

Store Results of Current Iterations For Further Use

By providing performance information at each optical element, the user may determine those specific areas at each element which violate his system constraints. The SOQ code also provides far-field performance calculations, through subprogram QUAL. The output of these calculations allows the user to assess the far-field performance of the complex field distribution. The test cases provided in Section V demonstrate the far-field calculation output.

## 10. SOQ ROUTINES

SOQ routines are presented below to establish correlations between the high energy laser modeling task and the names of the specific SOQ routines within specifically identifiable areas. The routines may be called up to perform, either in whole or in part, the desired modeling function. A more detailed description of each model or element is presented in subsection K, the Director of SOQ Models.

| GENERAL AREAS: | SUBROUTINES |
|---|---|
| Laser Cavity Calculations: | |
| Kinetics of lasing media | CAVITY, KINET, GAINXY,<br>SIMPGG, MIX<br>REGAIN |
| Density Inhomogeneitics | DENSY, AEROW |
| Beam Propagation | STEP, GDL, CAVITY<br>FOURT |
| Far Field Calculation | QUAL, PLTCT, POWWOW<br>Tilt, CENBAR |
| Numerical Interpolation | INTERP, ROSN, ROSN6<br>LINTERP, RGRD |
| Thermally Induced Distortions | BLUMIT, TBLOOM<br>THERML, FUHS |
| Optical Elements | MIRROR, APRTR, SLIVER<br>SPIDER |
| Resonator Iteration & Mode Properties within GDL | MODER |
| General: Write or echo input to obtain printer plots of complex distribution | LIST80, OUTPUT, IPLOT |

## 11. DIRECTORY OF SOQ MODELS

| | |
|---|---|
| SOQ | Executive program used to initialize field distribution, call optical train calculations through subroutine GDL, or compute far field performance through calls to subroutine QUAL. |
| GDL | Executive and computational program used to direct optical train and resonator calculations. Subroutine GDL may perform any of the following tasks:<br>1. Read input<br>2. Apply loaded cavity calculations<br>3. Apply mirror model<br>4. Apply propagation algorithm<br>5. Apply aperture<br>6. Apply thermal blooming<br>7. Determine convergence<br>8. Plot field distributions<br>9. Branch to program SOQ<br>10. Load or read field from disk<br>11. Apply aerodynamic window model<br>12. Orthogonalize resonator modes<br>13. Scale entire complex field by arbitrary magnification<br>14. Flip field about chosen axis<br>15. Apply sinusoidal density variations<br>16. Regrid the field to different sized DCALC<br>17. Write field to punched cards<br>18. Apply mirror thermal boundary layer model<br>19. Apply telescope spider<br>20. Perform Fox-Li iterative resonator calculations. |
| QUAL | Executive and computational routine for the calculation of far field complex distribution. Subroutine QUAL may be used to:<br>1. Identify the tilt and defocus components in optical field<br>2. Computer the field centroid<br>3. Determine the far field irradiance distribution |
| AEROW | Apply the aerodynamic window root-mean-square (RMS) phase |

| | |
|---|---|
| RANDU | Calculate uniformly distributed random numbers on the interval (0,1). |
| APRTR | Apply various types of apertures<br>1. Circular<br>2. Rectangular<br>3. Annular |
| BLUMIT | Apply and calculate intra- or intercavity thermally-induced phase distortion due to interaction of the complex field with the cavity gases. |
| CAVITY | Apply the effect of nonlinear saturable GDL gain and phase disturbance to a complex field and propagate |
| CENBAR | Calculate the beam centroid. |
| DENSY | Calculate and load the density-induced phase distortion for cavity calculations. |
| FOURT | Calculate forward or backward Fourier Transform of a specified two-dimensional input distribution via Fast Fourier Transform techniques. |
| FUHS | Calculate and apply the effects of lower laser level-to-ground-state heat addition perturbations to cavity density in the supersonic flow field. |
| GAINXY | Calculate small signal or loaded gain for cavity. |
| INTERP | Perform linear interpolation of an arbitrary complex field distribution. |
| IPLOT | Create line printer plots of the complex field including plots of the intensity and phase. |
| KINET | Calculate kinetics and small signal gain for use in the routine GAINXY. |
| MIRROR | Apply the effects of mirrors to a propagating field, including nonlinear interaction of the complex field and the induced mirror surface response. |
| MIX | Calculate relaxation and pumping rates for KINET. |

| | |
|---|---|
| MODER | Apply mode orthogonalization capability via Gramm-Schmidt procedure to calculate higher order, bare, or loaded cavity modes. |
| OUTPUT | Generate amplitude (or intensity) and phase printer plots at three slices through the field. |
| PLTOT | Calculate and produce printer plot of far field distribution and calculate, via POWWOW, the far field integrated irradiance within a specified far field radius. |
| POWWOW | Calculate intercepted power (integrated irradiance) in far field coordinates. |
| REGAIN | Calculate and apply the effect of the complex field on the nonlinear gain medium during resonator iterative calculations. |
| RGRD | Regrid the current SOQ complex field to a user-defined size. |
| ROSN | Perform cubic spline interpolation of interferometric density data stored on peripheral device. |
| LINTERP | Perform linear interpolation of density field data parameterized by aerodynamic sidewall projection. |
| ROSN6 | Bivariate interpolation of the spline fit data using cubic splines. Allow inclusion of the cavity density field from direct interferogram data reduction. |
| SIMPGG | Calculate loaded gain by 3-level closed form solution for a $N_2$-$CO_2$ GDL system. |
| **SILVER** | Apply an annular aperture to the complex field. |
| SPIDER | Apply a multi-element beam obscuration as found in a telescope spider. |
| SPTAN | Obtain a tangent function on the interval $(0, 2\pi)$. |
| STEP | Propagate the complex field, via scalar wave theory, using a variable or constant mesh. Fourier Transform is used to solve the scalar wave equation. |

| | |
|---|---|
| TBLOOM | Apply and calculate nonlinear thermally-induced phase distortion on the complex field due to interaction of the complex field with the medium through which it is propagating. |
| THERML | Apply and calculate effects of thermally-induced boundary layers on the complex field. |
| TILT | Calculate the complex field tilt and sphere. |
| ERF, ERFC | Evaluate the error function and complementary error function. |

## 12. FUNDAMENTAL COMPUTATIONAL STRUCTURE OF THE SOQ CODE

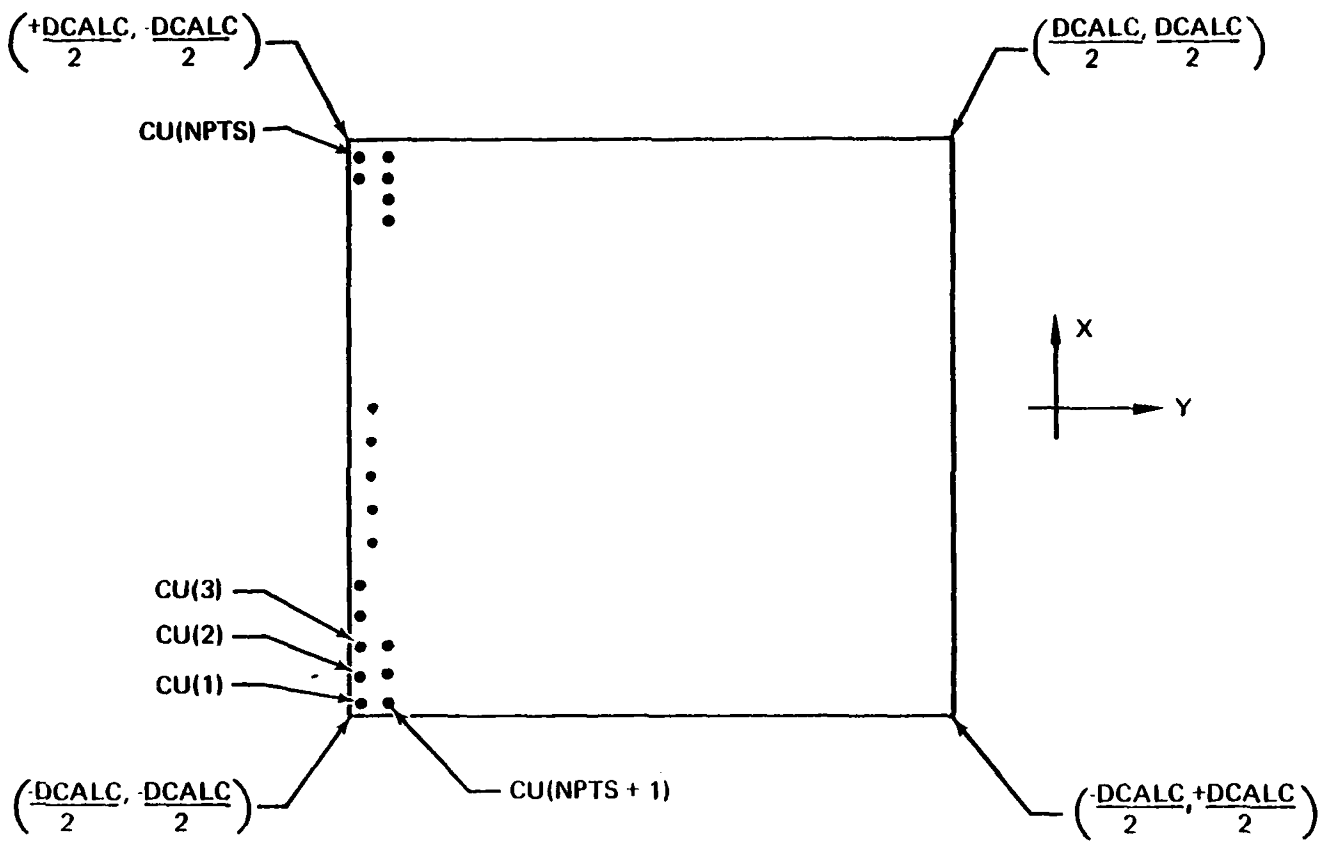
The purpose of this section is to define the correspondence between the complex numerical field, CU, used in the SOQ code and the real Cartesian coordinate system. Throughout the SOQ code, the fundamental approach to calculating the complex field has been to represent the optical field interaction as a complex transmission function. The complex field, then, is generated and modified at each optical element/subelement in the following format:

$$CU'(x,y) = CU(x,y) * T(x,y,z, CU(x,y), \vec{P}) \tag{5}$$

where $x,y$ represent transverse spatial coordinates (cm), $z$ represents coordinates along the optical axis (cm), $CU(x,y)$ represents the complex field in Cartesian $(a(x,y), b(x,y))$ form, and $\vec{P}$ represents a vector of scalar parameters specific to the transmission function model, T, being applied. T represents the complex transmission function.

It is assumed in the SOQ computer code that each operation on the field, CU, can be represented as a complex transmission function or as a product of transmission functions. Each optical operation or "interaction" of the propagating field with the surroundings modifies the transmission function framework.

Within the SOQ code, the primary carrier of this field information is the complex array CU, stored in common /MELT/. The correspondence between physical coordinates and the CU array indices is illustrated in Figure 11.



FD 162894

Figure 11. Correspondence between physical coordinates and CU array indices.

The calculation region is defined to be a DCALC X DCALC square subdivided by NPTS number of points to define the spatial coordinates, where NPTS = $2^K$ i.e.,

$$\Delta X = DCALC/NPTS \tag{6}$$

$$\begin{aligned} X_1 &= -\frac{DCALC}{2} + \frac{\Delta X}{2} \\ X_2 &= X_1 + \Delta X \\ &\vdots \\ X_n &= X_1 + (n-1)\,\Delta X \end{aligned} \tag{7}$$

Since the mesh is square, no additional storage for y is defined because the x and y coordinates may be represented by the same array. Additionally, the CU array is defined as a singly dimensioned string whose length is $(NPTS)^2$ = NOB. The correspondences of CU with the real spatial coordinates are:

| | | |
|---|---|---|
| CU(1) | X(1), Y(1) | (X(I) = Y(I)) |
| CU(2) | X(2), Y(1) | |
| CU(3) | X(3), Y(1) | |
| CU (NPTS) | X(NPTS), Y(1) | |
| CU (NPTS+1) | X(1), Y(2) | |
| CU (NPTS+2) | X(2), Y(2) | |
| etc. | | |

The CU array and the X array are stored in common /MELT/. Other arrays stored in /MELT/ are:

| | |
|---|---|
| CFIL | Dummy work array |
| WL | Radiation wavelength |
| NPTS | Number of points in x direction |
| DRX | Integrated displacement of optical axis from beam centerline in x direction. |
| DRY | Integrated displacement of optical axis from beam centerline in y direction. |

Principally, common /MELT/ is the carrier of the complex field information at any location of station in the optical train. The correspondences between the Cartesian (x,y,z) coordinate system and the indices of the CU and X arrays are maintained throughout the SOQ code as a standard field orientation scheme, within which each optical transmission function is applied.

DAT

FILM