Precise Interferometric Phase Determination

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A precise determination of phase shifts from interferometric fringes is necessary to accurately determine density structure. This is accomplished by a careful comparison of the pair of interferograms representing the initial and final phases. A step-by-step procedure is given for determining the interpolated phase shift from fringes crossing a given axial position of a medium with axial symmetry. Non-uniform final fringe spacing is assumed and accounted for in the interpolation. An example is included, as well as a listing of the computer program.
I. INTRODUCTION

This report is primarily concerned with precise phase-shift determinations where the phase changes rapidly (steep-gradient region) or where the phase changes are small (outer, low-density region). The medium is assumed to have cylindrical symmetry. Two things are required: A precise knowledge of the initial phase (from a pre-shot interferogram) and a precise determination of the final phase by interpolating the shifted fringes of the data interferogram. Abel inversion of the phase-shift information may reveal important low-density structures which would be missed without using these techniques. One should note, in the Abel inversion procedure, that the density determination at a particular cylindrical radius does not depend on what happens at smaller radii. Non-uniform fringe spacing may be important in the steep-gradient regions and is included in the interpolation procedure.

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The purpose of this report is to provide a general background and to set forth the method in a step-by-step procedure that can be put to practical use. The book-keeping details turned out to be rather involved and tricky. Thus, it seemed reasonable to include a detailed procedure for obtaining the necessary input from the pair of pre-shot and data interferograms as well as a listing of the computer program. The procedure is applied to a sample interferogram pair (Fig. (1)) obtained from a laser-produced plasma. The procedure includes preparing the interferogram pair for data extraction, tabulation of the data, and input to the computer program. The computed results (radius and phase shift) are given for the sample interferogram pair. I have attempted to make the program readable by the liberal use of comments to explain and de-limit.

The example illustrated in Fig. 1 is an experimentally-obtained interferogram pair from a plasma containing a laser-produced blast, wave (I>9 to 16). The method to be described provides useful phase-shift information for the region of the blast wave and the outer-most, low density region (I>16). However, the central region (I<7) shows such irregular phase variation that the method offers no advantage in that region.
Fig. 1 Sample interferogram pair with 6 initial, or unshifted (dashed) and 4 shifted (continuous curves) fringes bounding the cut, showing intervals (I), spans (K), and crossing regions (L, between lower shifted fringe crossings). Also shown are the lower unshifted (M1) and shifted (N) fringe numbers and the boundaries of intervals (↔ cut), spans (Υ), unshifted fringe crossings (∥) and shifted fringe crossings (∥).
II. BASIC METHOD

We wish to determine the radial density profile at a given axial position \(Z\), which is represented by the line \(Z = \text{constant}\) (called the "cut") in the R-Z plane of the interferogram pair. See Fig. 1. The final (shifted) fringes in the region of the cut are first divided into a sufficiently large number of radial "intervals" that the fringes are linear in each interval. Next, the region within the interval and between the two fringes bounding the cut is divided into 10 regions by introducing decimal "fringelets" which may be spaced non-uniformly to accommodate information in differing adjacent fringe spacings. The fringelets are illustrated in Fig. 2 with dashed lines but, in practice, are only treated numerically with the computer program. The non-uniform interpolation or fringelet spacing is described in the appendix. Each fringelet carries a known final phase. The intersections (radial position) of the fringelets with the cut, thus, have a known final phase. If no fringelet intersects the cut within the interval, the mid-radius of the interval is assigned the arithmetic average of the phases of the two fringelets which "straddle" the cut. Each intersection or straddle, which assigns a known final phase to a given radius within the interval, is called a "hit". The phase shift at a hit is obtained by subtracting the initial phase at the this radius.
Fig. 2 Shifted (final) fringes within the I'th interval, showing non-uniform decimal fringelets (dashed). Some J=4 distances shown.
The initial phase is determined by the phases of the bounding initial fringes and by interpolation using the fractional distance (at the hit radius) of the cut from the lower fringe.

The implementation of the calculations involves a bit of bookkeeping and indexing, some of which is discussed here. Phase information is recorded by sequentially numbering the final and initial fringes. They must, of course, merge to the same values in the outer most, lowest density region of the medium. The initial fringes are usually close to straight lines but are divided in the region of the cut into a small number of radial "spans" in which the fringes are accurately linear. See Fig. 3.

We are primarily interested in the pairs of initial and final fringes which bound the cut at a given radius. However, due to fringes crossing the cut, these pairs change with radius. Each interval \(I_I\) determines the span, with index \(K(I_I)\), and the crossing region (for final fringes), with index \(L(I_I)\) of that interval. In turn, \(K(I_I)\) and \(L(I_I)\) determine, respectively, the bounding initial and final fringe pairs for that interval. The phase of the lower bounding fringe in an interval is determined by the fringe number: \(M_l(K(I_I))\) for initial fringes and \(N(L(I_I))\) for final fringes. Each hit (intersection or straddle of a shifted fringelet with the cut), with index \(I\), is labeled with the interval number \(I_l(I)\) and fringelet number \(J_l(I)\). See Fig. 2. A variable \(E(I)\) indicates whether a hit is an intersection...
(E(I)=\phi) or is a straddle (E(I)=.5). The interpolated shifted fringe number at the hit is thus \(N(L(I)) + (J(I)-E(I))/\phi\). The interpolated initial fringe number at the hit depends on the fraction \(F(I)\) into which the cut divides the fringe spacing at the hit radius. See Fig. 3. Here, \(F(I) = W_1(I)/(W_2(I)-W_1(I))\). Thus, the interpolated initial fringe number is \(M_1(K(I)) + F(I)\). The phase shift (in units of \(\pi\)) is thus given by twice the difference in the shifted and initial fringe number at the hit.

\[
P(I) = 2 * (N(L(I)) + (J(I)-E(I))/\phi - (M_1(K(I)) + F(I)))
\]

The final result is the hit radius \(R(I)\) and phase shift \(P(I)\), sorted for increasing radius.
Fig. 3 Unshifted (initial) fringes within the K'th span, showing one hit (intersection of shifted fringelet and cut).
III. PROCEDURE AND EXAMPLE

A sample interferogram pair, prepared for extracting data, is shown in Fig.1. This is the superposition of two separate interferograms: The initial or pre-shot interferogram (shown dashed) and the final, shifted or data interferogram. The individual interferograms were projected and the fringes carefully aligned to each other for reference positions and merging to the same outer fringes. This happened to be the interferogram pair from which the procedure was developed and was not the optimum pair of interferograms for accurate application of the method. It may be helpful to refer to Figs. 2 and 3, showing separately information on the initial and final interferograms.

We first draw in the cut at the desired Z-position, taking into consideration the requirement of cylindrical symmetry. We next divide the initial fringes into a small number (4, in the example) of radial regions or spans such that: (1) Initial fringe crossings only occur at span boundaries and (2) the fringes are accurately linear within a span. The symmetry axis (R=Ø) and outer radius (of fringe shifting) are taken as span boundaries. Spans are designated (K) by their left, or inner boundary. Span boundaries (vertical lines) are extended into the region above the cut and the following symbols used to aid recognition: \( \Uparrow \) (for span boundary), \( \uparrow \) (for initial fringe crossing the cut).
Each span is labeled with the span index (K) and lower initial fringe number (M1) of fringes bounding the cut. It is also helpful to note the span boundary radii at each span boundary.

Information about the shifted fringes is indicated in the region well below the cut. First, locate all shifted fringe crossings, pass a vertical line through each crossing and indicate with a slanted dash (\(\backslash m\)) that it is a crossing. Label each crossing region (below the cut) with the crossing index L and lower shifted fringe number N e.g., (\(L=2\) \(N=4\)). Next, draw in (short vertical lines) interval boundaries such that: (1) all fringe crossings (initial or shifted) and span boundaries are interval boundaries, and (2) the final (shifted) fringes are linear in each interval. Intervals are designated (I) by the left or inner boundary. The symmetry axis (I=1, where R=0) and outer radius (I=IØ+1, where IØ is the number of intervals) are also interval boundaries. The interval number of the shifted fringe crossings are indicated below the crossing (e.g., I=7).

We are now in a position to organize the information in tabular form, on data sheets, so that it can be input to the program. At the top of the first sheet, note the identifying (e.g., shot) number, the magnification (needed in Abel inversion) and the number of intervals (IØ), spans (KØ) and shifted fringe crossings (NØ). Since lower fringe numbers (used in
calculating phase) depend directly on the span (initial) and the crossing region (shifted) while information is input for each interval, it is useful to relate each interval index to a span and crossing index. This cross-indexing is calculated by inputs from Table I. Next we record (in Table II) the lower fringe numbers.

The next step is to make detailed measurements of radial and axial distances and to organize this data into tabular form. In the shifted fringes, it is necessary to measure and record (in Tables III and IV), for each interval, the interval index I, the radial position $R_l(I)$ of the left boundary, the axial position (negative) $Z_l(I)$ of the lower fringe from the cut, the fringe slope $S\theta(I) = (dZ/dR)/\text{ABS}(dZ/dR)$, and the lower, central, and upper fringe-pair spacings $D_l(I), D_2(I), D_3(I)$. The distances are all measured in centimeters. The fringe slope is $\theta$ for the cut and +1 or -1 according as $Z$ increases or decreases with $R$ for a fringe. **CAUTION:** At a fringe crossing, we can have either a $J=\theta$ intersection (where $Z_l(I)=\theta$, since $S\theta(I)=-1$) or a $J=1\theta$ intersection (where $Z_l(I)=-D_2(I)$, since $S\theta(I)=1$).

The shifted fringe input is first recorded, in Table III for the outermost radius (where $I=I\theta+1$). The shifted fringe input at all left interval boundaries ($I=1$ to $I\theta$) is recorded in Table IV.
The input data for the initial fringes are recorded at each span. This includes the radius $R_2(K)$ of the (left-hand) span boundary, the axial positions (negative) of the left-side $Z_2(K)$ and right-side ($Z_4(K)$ of the lower fringes and the axial positions (positive) of the left-side $Z_3(K)$ and the right-side $Z_5(K)$ of the upper fringes. The values are recorded (Table V) for the left boundaries of the individual spans.

The detailed shifted-fringe information for each interval (Table IV) is entered, before the program is run, into DATA statements near the end of the program. The data for cross-indexing (Table I), lower fringe identification (Table II), outer radius information for shifted fringes (Table III), and the initial fringe information (Table V) are entered during the running of the program, as requested by input statements.
Table I. Cross-Indexing: The intervals (left interval boundaries) I2 which occur at interior fringe crossings and the intervals (left boundaries) I3 which occur at interior span boundaries are:

<table>
<thead>
<tr>
<th>Crossing Index</th>
<th>Interval Index</th>
<th>Span Index</th>
<th>Interval Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-1</td>
<td>I=I2(L-1)</td>
<td>K-1</td>
<td>I=I3(K-1)</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>3</td>
<td>18</td>
</tr>
</tbody>
</table>

Table II. The lower (shifted/initial) fringe numbers vs. (region/span) index (L/K).

<table>
<thead>
<tr>
<th>Index</th>
<th>Fringe #</th>
<th>Index</th>
<th>Fringe #</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>N(L)</td>
<td>K</td>
<td>M1(K)</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Table III. Shifted fringe input for the outermost radius (IΦ+1).

<table>
<thead>
<tr>
<th>R1=15.3</th>
<th>Z1=0</th>
<th>SΦ=-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1=.30</td>
<td>D2=.30</td>
<td>D3=.30</td>
</tr>
</tbody>
</table>
Table IV. At the left (inner) boundary of each interval, the index I, radius Rl(I), axial position of lower fringe Zl(I), fringe slope S0(I), and lower, central and upper fringe-pair spacings D1(I), D2(I), D3(I) are:

<table>
<thead>
<tr>
<th>I</th>
<th>Rl(I)</th>
<th>Zl(I)</th>
<th>S0(I)</th>
<th>D1(I)</th>
<th>D2(I)</th>
<th>D3(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>-.19</td>
<td>-1</td>
<td>.40</td>
<td>.40</td>
<td>.35</td>
</tr>
<tr>
<td>2</td>
<td>0.87</td>
<td>-.22</td>
<td>-1</td>
<td>.38</td>
<td>.38</td>
<td>.38</td>
</tr>
<tr>
<td>3</td>
<td>1.78</td>
<td>-.30</td>
<td>-1</td>
<td>.40</td>
<td>.40</td>
<td>.40</td>
</tr>
<tr>
<td>4</td>
<td>2.52</td>
<td>-.26</td>
<td>-1</td>
<td>.38</td>
<td>.38</td>
<td>.32</td>
</tr>
<tr>
<td>5</td>
<td>3.69</td>
<td>-.23</td>
<td>-1</td>
<td>.36</td>
<td>.38</td>
<td>.34</td>
</tr>
<tr>
<td>6</td>
<td>5.02</td>
<td>-.25</td>
<td>-1</td>
<td>.36</td>
<td>.35</td>
<td>.30</td>
</tr>
<tr>
<td>7</td>
<td>6.50</td>
<td>0</td>
<td>-1</td>
<td>.37</td>
<td>.32</td>
<td>.32</td>
</tr>
<tr>
<td>8</td>
<td>7.10</td>
<td>-.08</td>
<td>-1</td>
<td>.38</td>
<td>.30</td>
<td>.32</td>
</tr>
<tr>
<td>9</td>
<td>8.40</td>
<td>-.14</td>
<td>-1</td>
<td>.38</td>
<td>.30</td>
<td>.28</td>
</tr>
<tr>
<td>10</td>
<td>9.02</td>
<td>0</td>
<td>-1</td>
<td>.28</td>
<td>.30</td>
<td>.30</td>
</tr>
<tr>
<td>11</td>
<td>9.28</td>
<td>-.02</td>
<td>-1</td>
<td>.30</td>
<td>.32</td>
<td>.33</td>
</tr>
<tr>
<td>12</td>
<td>9.45</td>
<td>-.07</td>
<td>-1</td>
<td>.31</td>
<td>.33</td>
<td>.34</td>
</tr>
<tr>
<td>13</td>
<td>9.67</td>
<td>-.13</td>
<td>0</td>
<td>.27</td>
<td>.33</td>
<td>.34</td>
</tr>
<tr>
<td>14</td>
<td>9.90</td>
<td>-.12</td>
<td>1</td>
<td>.24</td>
<td>.30</td>
<td>.34</td>
</tr>
<tr>
<td>15</td>
<td>10.18</td>
<td>-.25</td>
<td>1</td>
<td>.20</td>
<td>.25</td>
<td>.25</td>
</tr>
<tr>
<td>16</td>
<td>10.37</td>
<td>-.14</td>
<td>1</td>
<td>.20</td>
<td>.24</td>
<td>.33</td>
</tr>
<tr>
<td>17</td>
<td>10.69</td>
<td>-.10</td>
<td>1</td>
<td>.29</td>
<td>.22</td>
<td>.32</td>
</tr>
<tr>
<td>18</td>
<td>10.92</td>
<td>-.10</td>
<td>0</td>
<td>.30</td>
<td>.22</td>
<td>.33</td>
</tr>
<tr>
<td>19</td>
<td>11.51</td>
<td>-.13</td>
<td>-1</td>
<td>.32</td>
<td>.27</td>
<td>.29</td>
</tr>
<tr>
<td>20</td>
<td>12.52</td>
<td>-.17</td>
<td>-1</td>
<td>.30</td>
<td>.28</td>
<td>.29</td>
</tr>
<tr>
<td>21</td>
<td>13.58</td>
<td>-.20</td>
<td>-1</td>
<td>.29</td>
<td>.29</td>
<td>.30</td>
</tr>
</tbody>
</table>
Interferometry Data Sheet - 3
(Enter or requested by Program, during run)

Table V. Initial Fringe Information. The Radii and Axial Position at the Span Boundaries are:

<table>
<thead>
<tr>
<th>Span Index K</th>
<th>Radius R2(K)</th>
<th>Lower Fringe Z2(K) Z4(K)</th>
<th>Upper Fringe Z3(K) Z5(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>-.18 -.30</td>
<td>.12 0</td>
</tr>
<tr>
<td>2</td>
<td>1.78</td>
<td>0 -.31</td>
<td>.31 0</td>
</tr>
<tr>
<td>3</td>
<td>6.50</td>
<td>0 -.30</td>
<td>.30 0</td>
</tr>
<tr>
<td>4</td>
<td>10.92</td>
<td>0 -.29</td>
<td>.29 0</td>
</tr>
</tbody>
</table>
IV. Computer program with data input for the interferogram pair shown in Fig. 1.

10 PRINT "NIFOI, A PROGRAM USING NON-UNIFORMLY-SPACED INTERFERENCE FRINGE DECIMAL-INTERPOLATION. DECIMAL (INTERPOLATED) FRINGES ARE CALLED FRINSELETS."
20 PRINT "THE RADIAL VARIATION OF PHASE IS DETERMINED AT A FIXED AXIAL POSITION OR LINE, CALLED THE CUT."
30 INPUT "SHOT OR IDENTIFYING NUMBER AND MAGNIFICATION",MG
40 PRINT "THE SHIFTED FRINGES ARE MEASURED FOR MANY RADIAL INTERVALS WITH INDEX I."
50 PRINT "THE INITIAL FRINGES ARE TAKEN AS LINEAR FOR A FEW RADIAL SPANS WITH INDEX K(I)."
60 PRINT "ALL SHIFTED AND INITIAL FRINGE CROSSINGS ARE TAKEN AT INTERVAL BOUNDARIES. ALL UNSHIFTED FRINGE CROSSINGS ARE AT SPAN BOUNDARIES."
70 INPUT "THE NUMBER IO OF RADIAL INTERVALS IS",IO
80 INPUT "THE NUMBER K0 OF RADIAL SPANS IS",K0
90 INPUT "THE NUMBER NO OF SHIFTED FRINGE CROSSINGS IS",NO
100 DIM A(10),B(10),C(10),D(10),E(10),F(10),G(10),H(10),I(10),J(10)
110 DIM X(10),Y(10),Z(10)
120 DIM X(10),Y(10),Z(10)
130 DIM X(10),Y(10),Z(10)
140 DIM A(10),B(10),C(10),D(10),E(10),F(10),G(10),H(10),I(10),J(10)
150 DIM A(10),B(10),C(10),D(10),E(10),F(10),G(10),H(10),I(10),J(10)
160 PRINT "THE RADIAL VARIATION OF PHASE IS DETERMINED AT A FIXED AXIAL POSITION OR LINE, CALLED THE CUT."
170 INPUT "SHOT OR IDENTIFYING NUMBER AND MAGNIFICATION",MG
180 PRINT "THE SHIFTED FRINGES ARE MEASURED FOR MANY RADIAL INTERVALS WITH INDEX I."
190 PRINT "THE INITIAL FRINGES ARE TAKEN AS LINEAR FOR A FEW RADIAL SPANS WITH INDEX K(I)."
200 PRINT "ALL SHIFTED AND INITIAL FRINGE CROSSINGS ARE TAKEN AT INTERVAL BOUNDARIES. ALL UNSHIFTED FRINGE CROSSINGS ARE AT SPAN BOUNDARIES."
210 INPUT "THE NUMBER IO OF RADIAL INTERVALS IS",IO
220 INPUT "THE NUMBER K0 OF RADIAL SPANS IS",K0
230 INPUT "THE NUMBER NO OF SHIFTED FRINGE CROSSINGS IS",NO
240 PRINT "THE RADIAL VARIATION OF PHASE IS DETERMINED AT A FIXED AXIAL POSITION OR LINE, CALLED THE CUT."
250 INPUT "SHOT OR IDENTIFYING NUMBER AND MAGNIFICATION",MG
260 PRINT "THE SHIFTED FRINGES ARE MEASURED FOR MANY RADIAL INTERVALS WITH INDEX I."
270 PRINT "THE INITIAL FRINGES ARE TAKEN AS LINEAR FOR A FEW RADIAL SPANS WITH INDEX K(I)."
280 PRINT "ALL SHIFTED AND INITIAL FRINGE CROSSINGS ARE TAKEN AT INTERVAL BOUNDARIES. ALL UNSHIFTED FRINGE CROSSINGS ARE AT SPAN BOUNDARIES."
290 INPUT "THE NUMBER IO OF RADIAL INTERVALS IS",IO
300 INPUT "THE NUMBER K0 OF RADIAL SPANS IS",K0
310 INPUT "THE NUMBER NO OF SHIFTED FRINGE CROSSINGS IS",NO
320 PRINT "THE RADIAL VARIATION OF PHASE IS DETERMINED AT A FIXED AXIAL POSITION OR LINE, CALLED THE CUT."
330 INPUT "SHOT OR IDENTIFYING NUMBER AND MAGNIFICATION",MG
340 PRINT "THE SHIFTED FRINGES ARE MEASURED FOR MANY RADIAL INTERVALS WITH INDEX I."
350 PRINT "THE INITIAL FRINGES ARE TAKEN AS LINEAR FOR A FEW RADIAL SPANS WITH INDEX K(I)."
360 PRINT "ALL SHIFTED AND INITIAL FRINGE CROSSINGS ARE TAKEN AT INTERVAL BOUNDARIES. ALL UNSHIFTED FRINGE CROSSINGS ARE AT SPAN BOUNDARIES."
370 INPUT "THE NUMBER IO OF RADIAL INTERVALS IS",IO
380 INPUT "THE NUMBER K0 OF RADIAL SPANS IS",K0
390 INPUT "THE NUMBER NO OF SHIFTED FRINGE CROSSINGS IS",NO
400 PRINT "THE RADIAL VARIATION OF PHASE IS DETERMINED AT A FIXED AXIAL POSITION OR LINE, CALLED THE CUT."
410 INPUT "SHOT OR IDENTIFYING NUMBER AND MAGNIFICATION",MG
420 PRINT "THE SHIFTED FRINGES ARE MEASURED FOR MANY RADIAL INTERVALS WITH INDEX I."
430 PRINT "THE INITIAL FRINGES ARE TAKEN AS LINEAR FOR A FEW RADIAL SPANS WITH INDEX K(I)."
440 PRINT "ALL SHIFTED AND INITIAL FRINGE CROSSINGS ARE TAKEN AT INTERVAL BOUNDARIES. ALL UNSHIFTED FRINGE CROSSINGS ARE AT SPAN BOUNDARIES."
450 INPUT "THE NUMBER IO OF RADIAL INTERVALS IS",IO
460 INPUT "THE NUMBER K0 OF RADIAL SPANS IS",K0
470 INPUT "THE NUMBER NO OF SHIFTED FRINGE CROSSINGS IS",NO
480 PRINT "THE RADIAL VARIATION OF PHASE IS DETERMINED AT A FIXED AXIAL POSITION OR LINE, CALLED THE CUT."
490 INPUT "SHOT OR IDENTIFYING NUMBER AND MAGNIFICATION",MG
500 PRINT "THE SHIFTED FRINGES ARE MEASURED FOR MANY RADIAL INTERVALS WITH INDEX I."
510 PRINT "THE INITIAL FRINGES ARE TAKEN AS LINEAR FOR A FEW RADIAL SPANS WITH INDEX K(I)."
520 PRINT "ALL SHIFTED AND INITIAL FRINGE CROSSINGS ARE TAKEN AT INTERVAL BOUNDARIES. ALL UNSHIFTED FRINGE CROSSINGS ARE AT SPAN BOUNDARIES."
520 A(I) = (D(I) + DZ(I))/20
530 B(I) = (-19*A(I) + 9*H(I))/R
550 NEXT I
550 FOR I = 1 TO 10 + 1
570 X(I,0) = 0
580 Z(I,0) = Z(I)
580 NEXT I
600 FOR I = 1 TO 10 + 1
610 FOR J = 1 TO 9
620 V(I,J) = B(I) + (2*J - 1)*C(I)/3
630 X(I,J) = J*(A(I) + (J-1)*V(I,J)/2)
640 Z(I,J) = Z(I) + X(I,J)
650 NEXT J
660 Z(I,10) = Z(I) + DZ(I)
670 NEXT I
680 -------------------
690 -------------------RIGHT-HAND INTERVAL BOUNDARY VALUES-----------------
720 FOR I = 1 TO 10
730 FOR J = 1 TO 9
740 IF Z(I,J) = 0 OR Z(I,J) = -DZ(I+1) THEN 750 ELSE 720
750 X(I,J) = X(I,J)
760 SOTO 790
770 IF Z(I,J) = 0 THEN 780 ELSE 770
780 X(I,J) = (DZ(I+1)/DZ(I+2))X(I,J)
790 IF Z(I,J) = 0 THEN 800 ELSE 790
800 Z(I,J) = X(I,J) - D(I+1)
810 SOTO 850
820 IF Z(I,J) = -DZ(I+1) THEN 830 ELSE 820
830 Z(I,J) = X(I,J)
840 SOTO 850
850 Z(I,J) = Z(I,J) + X(I,J)
860 NEXT J
870 NEXT I
880 -------------------RIGHT-HAND INTERVAL BOUNDARY VALUES-----------------
890 -------------------RIGHT-HAND INTERVAL BOUNDARY VALUES-----------------
910 FOR I = 1 TO 10
920 FOR J = 1 TO 9
930 IF Z(I,J) = 0 OR Z(I,J) = -DZ(I+1) THEN 940 ELSE 930
940 X(I,J) = X(I,J)
950 SOTO 960
960 IF Z(I,J) = 0 THEN 970 ELSE 960
970 IF 2*Z(I,J) = 0 THEN 980 ELSE 970
980 X(I,J) = X(I,J)
990 SOTO 960
1000 IF Z(I,J) = 0 THEN 1010 ELSE 1000
1010 X(I,J) = -DZ(I) THEN 1020 ELSE 1010
1020 X(I,J) = DZ(I) THEN 1030 ELSE 1020
1030 IF Z(I,J) = 0 THEN 1040 ELSE 1030
1040 X(I,J) = X(I,J)
1050 SOTO 1100
1060 IF Z(I,J) = 0 THEN 1070 ELSE 1060
1070 IF Z(I,J) = 0 THEN 1080 ELSE 1070
1080 FOR J = 1 TO 9
1090 IF 2*Z(I,J) = 0 THEN 1010 ELSE 1090
1100 IF Z(I,J) = 0 THEN 1120 ELSE 1100
1120 IF Z(I,J) = 0 THEN 1140 ELSE 1120
1140 X(I,J) = X(I,J)
1150 SOTO 1120
1160 NEXT J
1170 NEXT I
1180 GOTO 1130
1190 ------------------------------COUNT AND LABEL HITS-----------------------------
1170 ---------------INTERSECTION COUNTER FOLLOWS----------------------
1180 H = H + 1
1190 E(H) = 0
1200 I1(H) = I
1210 II(H) = J
1220 IF J = 3 THEN 1040 ELSE 1230
1230 IF J = 10 THEN 1040 ELSE 1240
1240 IF J = 1 THEN 1070 ELSE 1120
1250 ---------------STRADDLE COUNTER FOLLOWS------------------------
1260 H = H + 1
1270 E(H) = J
1280 II(H) = I
1290 GOTO 1120
1300 ---------------OUTER INTERSECTION--------------------------------
1310 I = 10
1320 IF Z(I;J) = Z(I;J-1) THEN 1340 ELSE 1350
1330 J = 10
1340 GOTO 1320
1350 J = J - 1
1360 E(H) = J
1370 I1(H) = J
1380 IF Z(I;J) = 0 THEN 1420 ELSE 1500
1390 J(J) = J + 1
1400 GOTO 1400
1410 FOR J = 1 TO 9
1420 IF Z(I;J) = 0 THEN 1520 ELSE 1530
1430 J(J) = J + 1
1440 GOTO 1400
1450 NEXT J
1460 E(I) = 0
1470 IF Z(I;J) = 0 THEN 1420 ELSE 1520
1480 J(J) = J + 1
1490 GOTO 1400
1500 FOR J = 2 TO 10
1510 IF Z(I;J) = Z(I;J-1) THEN 1610 ELSE 1620
1520 J(J) = J
1530 GOTO 1400
1540 NEXT J
1550 ----------- FIND RADII OF FRINGE FRACTURES---------------------
1560 FOR I = 2 TO H - 1
1570 IF Z(I;J(J)) = 0 THEN 1620 ELSE 1700
1580 IF E(I) = 0 THEN 1620 ELSE 1710
1590 R(I) = R(I;J(J)) + Z(I;J(J)) + (R(I;J(J)) + 1) - R(I;J(J)) / (Z(I;J(J)) + J)
1600 NEXT I
1610 NEXT J
1620 NEXT J
1630 NEXT J
1640 NEXT J
1650 --------- FIND RADII OF FRINGE FRACTURES---------------------
1660 FOR I = 1 TO H
1670 IF Z(I;J(J)) = 0 THEN 1680 ELSE 1700
1680 NEXT I
1690 NEXT J
1700 NEXT J
1710 NEXT J
1720 NEXT J
1730 IF I = 1 TO H
1740 IF Z(I;J(J)) = 0 THEN 1660 ELSE 1700
1750 NEXT J
1760 NEXT J
1770 NEXT J
1780 NEXT I
1790 STOP
1800
1810 "------------------INITIAL FRINGE CALCULATIONS------------------"
1820 "-------------------SPAN-TO-INTERVAL INDEXING--------------------"
1830 PRINT "THE SPAN BOUNDARIES ARE LOCATED AT I = I0 + I, AND AT";
1840 "--------------------------I = K -1 FOR THE FOLLOWING LOOP";
1850 FOR I = 1 TO K0-1
1860 INPUT "IS(K-1) =", IZ(I)
1870 NEXT I
1880 K = 0
1890 U2 = 1
1900 "-------------------------------------I = INTERVAL FOR FOLLOWING LOOP--------------------------"
1910 FOR I = 1 TO IS(K0 - 1)
1920 IF [I] THEN 1940
1930 U2 = U2 + 1
1940 X(I) = UC
1950 NEXT I
1960 FOR I = [I][K0 - 1] TO I0
1970 [K(I) = K0
1980 U2 = I
1990 "-----------------------------------------I = INTERVAL FOR FOLLOWING LOOP--------------------------"
2000 PRINT "THE LEFT-HANDED SPAN BOUNDARIES ARE AT RAII"; "---RZ(1)=Q---"
2010 FOR I = 1 TO K0
2020 INPUT "RZ(K) =", RZ(I)
2030 NEXT I
2040 RZ(K+1) = RZ(2)
2050 PRINT "THE INITIAL LOWER FRINGE NUMBERS ARE"
2060 FOR I = 1 TO K0
2070 INPUT "MI(K) =", M(I)
2080 NEXT I
2090 "--------------------------FIND L.K.N,M! AT HITS-------------------------------"
2100 PRINT "THE LEFT-SIDE AXIAL POSITIONS (NES.) OF THE LOWER INITIAL FRINGES ARE"
2110 FOR I = 1 TO K0
2120 INPUT "Z2(K) =", Z2(I)
2130 NEXT I
2140 "--------------------------FIND L.K.N,M! AT HITS-------------------------------"
2150 PRINT "THE RIGHT-SIDE AXIAL POSITIONS (NES.) OF THE LOWER INITIAL FRINGES ARE"
2160 FOR I = 1 TO K0
2170 INPUT "Z4(K) =", Z4(I)
2180 NEXT I
2190 "--------------------------FIND L.K.N,M! AT HITS-------------------------------"
2200 PRINT "THE LEFT-SIDE AXIAL POSITIONS (POS.) Z3(K) OF THE UPPER INITIAL FRINGES ARE"
2210 FOR I = 1 TO K0
2220 INPUT "Z3(K) =", Z3(I)
2230 NEXT I
2240 "--------------------------FIND L.K.N,M! AT HITS-------------------------------"
2250 PRINT "THE RIGHT-SIDE AXIAL POSITIONS (POS.) Z5(K) OF THE UPPER INITIAL FRINGES ARE"
2260 FOR I = 1 TO K0
2270 INPUT "Z5(K) =", Z5(I)
2280 NEXT I
2290 "--------------------------FIND INITIAL FRINGE FRACTION AT EACH HIT--------------------------"
2300 PRINT "---W(Z2) AND W(Z5) ARE AXIAL POSITIONS OF LOWER AND UPPER FRINGES AT A HIT, WHILE S1 AND S2 ARE THE FRINGE SLOPES;";
2310 PRINT "--------------------FIND INITIAL FRINGE FRACTION AT EACH HIT--------------------------"
2320 F(I) = -Z2(I)/Z2(I) - Z2(I)
FOR I = 2 TO H-1
2360 S1(I) = (Z2(K(I(I))) - Z3(K(I(I))))/(RZ2(K(I(I))) + 1) - RZ2(K(I(I)))
2370 Z2(I) = Z2(K(I(I))) - Z3(K(I(I)))/(RZ2(K(I(I))) + 1) - RZ2(K(I(I)))
2380 W1(I) = Z4(K(I(I))) - S1(I) + (RZ2(K(I(I))) + 1) - RZ2(K(I(I)))
2390 W2(I) = Z2(K(I(I))) - S2(I) + (RZ2(K(I(I))) + 1) - RZ2(K(I(I)))
2400 F(I) = -W1(I)/W2(I) - W1(I)
2410 NEXT I
2420 FOR I = 1 TO H-1
2425 PRINT 'H,S1,S2,W1,W2';I;S1(I);S2(I);F(I)
2440 NEXT I
2450 IF F(I) < 0.1 GOTO 2720
2460 IF I = 1 TO H
2470 NEXT I
2480 'STOP

FIND THE PHASE SHIFT P(I) AT EACH HIT-------------------
2500 FOR I = 1 TO H
2510 IF R(I) < R(I+1) PRINT 'H,P';I;P(I)
2520 NEXT I
2530 'STOP

SORT AND INDEX FOR INCREASING RADIUS---------------------
2550 FOR I = 1 TO H
2560 IF R(I) < R(I+1) PRINT 'H,N,M,J,R,P';I;S(I);E(I);J(I);S(I));R(S(I));P(I)
2580 NEXT I
2590 'STOP

DATA--------------------------------------------
2610 DATA 1,0,.19,-.1,.4,.4,.35
2620 DATA 2,.87,-.22,-1,.38,.38,.38
2630 DATA 3,.78,-.3,-1,.38,.38,.38
2640 DATA 4,.62,-.26,-1,.38,.38,.38
2650 DATA 5,.49,-.23,-1,.38,.38,.38
2660 DATA 6,.39,-.2,-1,.38,.38,.38
2670 DATA 7,.28,-.18,-1,.38,.38,.38
2680 DATA 8,.18,-.16,-1,.38,.38,.38
2690 DATA 9,.08,-.14,-1,.38,.38,.38
2700 DATA 10,0,.12,-1,.38,.38,.38
2710 DATA 11,.02,-.0,-1,.38,.38,.38
2720 DATA 12,.02,-.02,-1,.38,.38,.38
2730 DATA 13,.02,-.04,-1,.38,.38,.38
2740 DATA 14,.02,-.06,-1,.38,.38,.38
2750 DATA 15,.02,-.08,-1,.38,.38,.38
2760 DATA 16,.02,-.1,-1,.38,.38,.38
2770 DATA 17,.02,-.12,-1,.38,.38,.38
2780 DATA 18,.02,-.14,-1,.38,.38,.38
2790 DATA 19,.02,-.16,-1,.38,.38,.38
2800 DATA 20,.02,-.18,-1,.38,.38,.38

20
3020 DATA 16,10.37,-.14, 1.,20.,24.,33
3030 DATA 17,10.69,-.10, 1.,29.,22.,32
3040 DATA 18,10.92,-.10, 0.,30.,22.,33
3050 DATA 19,11.51,-.13,-1.,32.,27.,29
3060 DATA 20,12.52,-.17,-1.,30.,28.,28
3070 DATA 21,13.58,-20,-1.,29.,29.,30
4000 END
V. Final results, giving hit number (H), straddle index (E), interval index (I), fringelet index (J), and radius (R) and phase (P) at each hit.

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22
Interpolation of the non-uniformly-spaced shifted fringes is accomplished by dividing the axial space between the two fringes which bound the cut, within an interval, into ten non-uniform spaces by introducing decimal "fringelets". The lower bounding fringe is taken as the $J=0$ fringelet and the upper bounding fringe is taken as the $J=10$ fringelet. Refer to Fig. 2. Let $D_1(I)$, $D_2(I)$, and $D_3(I)$ denote, respectively, the axial fringe-pair spacing at the (left) interval boundary of the lower, central (bounding the cut), and upper fringe pairs. It is necessary to determine the distance $D(I,J)$, for $J=1$ to 10, between the $J-1$ and $J$ fringelets. First require that the sum of the fringelet spacings be the central fringe-pair spacing.

\[
\sum_{J=1}^{10} D(I,J) = D_2(I)
\]

Information about the non-uniform adjacent fringe-pair spacings is included by requiring that the lower fringelet spacing $D(I,1)$ be one-tenth of the average fringe-pair spacing for the lower and
central fringe-pairs and that the upper fringelet spacing \( D(I,10) \) be one-tenth of the average fringe-pair spacing for the upper and central fringe pairs.

\[
D(I,1) = \frac{D_1(I) + D_2(I)}{2} \quad A2
\]

\[
D(I,10) = \frac{D_2(I) + D_3(I)}{2} \quad A3
\]

In order to meet these three requirements, \( D(I,J) \) must be at least quadratic in \( J \). It is assumed that

\[
D(I,J) = A(I) + B(I)(J-1) + C(I)(J-1)^2. \quad A4
\]

The coefficients \( A, B, \) and \( C \) are determined by using Eq. (A4) in Eqs. (A1-A3). It is immediately seen that \( A(I) \) is \( D(I,1) \) and is thus given by Eq. (A2). The other coefficients are evaluated, after a little algebra, as

\[
B(I) = \frac{(-19*G(I) + 9*H(I))}{8} \quad A5
\]

\[
C(I) = \frac{(3*G(I) - H(I))}{8} \quad A6
\]
where \( G(I) \) and \( H(I) \) are defined by

\[
G(I) = \frac{(D_3(I) - D_1(I))}{18} \quad \text{(A7)}
\]

\[
H(I) = \frac{(D_2(I) - D_1(I))}{3} \quad \text{(A8)}
\]

In calculating the intersections of the fringelets with the cut, it is necessary to know the distance \( X(I,J) \) between the lower bounding fringe and the \( J \) fringelet. This distance is the sum from \( J' = 1 \) to \( J \) of \( D(I,J') \). Evaluation of the sum shows that

\[
X(I,J) = J \cdot (A(I) + (J - 1) \cdot V(I,J)/2) \quad \text{(A9)}
\]

where

\[
V(I,J) = B(I) + (2J - 1) \cdot C(I)/3 \quad \text{(A10)}
\]
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