

# Lab Programs

## Optical Properties

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## A. Introduction

This document describes the data analysis programs used in our lab. Much of what is here is on their help screens,\* but there are some additional notes found here.

This manual is for the Windows versions of the programs. (Earlier versions were written for “DOS,” i.e., 16-bit, EGA graphics. Beginning about the time of Windows 98 SP2 and Windows NT, both the Windows operating system and computer hardware became less and less compatible with the older graphics modes. So the programs have been ported over to Windows. They are not true Windows applications, though. They lack all of the message boxes, drop-down menus, radio buttons, tool tips, animated paper clips. etc. that we’ve come to know and love.)

The ones that do graphics are compiled as “QuickWin” applications. They show a white screen and make 16 color plots. Some use the mouse. Others, text only, are “Windows console” programs. They are intended to be run from a command window (cmd.exe, 4nt.exe, etc.) but can be run from windows explorer.

### 1. *Installation and use*

Put the programs in a directory on your path. I use D:\datan\. If the directory you choose is not on the path, add it. (Google “path windows <ver>,” where <ver> is xp or vista or 7 or ... for instructions on how to set the path.)

Run the programs from a command window. Nowadays, the command window is CMD.EXE. I suggest adding a desktop link to this program. A better command processor is available from JP Software (<http://www.jpsoft.com/>). This program started as 4DOS for use in the 16 bit DOS world. The 32 bit version (Win98/NT/XP) used to be called 4NT. The present version is TCC/LE, and is free to all. Versions with even more features are available at a modest price.

You can add links on the desktop to the data analysis programs as well, and most will accept drag/drop from windows explorer.

### 2. *List of “QuickWin” programs*

These programs make plots of the data during their operation.

2c.exe	fft.exe	kkg.exe	q.exe
bits.exe	ftgram.exe	mav.exe	ql.exe
cmp.exe	fts.exe	mend.exe	qp.exe
dfc.exe	gtf.exe	op.exe	ranu.exe
dff.exe	ifft.exe	pfit.exe	rnm.exe
dlcalc.exe	inject.exe	pik.exe	tcalc.exe
ema.exe	interp.exe	pik2.exe	tff.exe

---

\* Type <prog> /h or answer ? to the first prompt.

### 3. List of “Windows console” programs

These programs do text-only input and output.

addtime.exe	interpc.exe	rd rude.exe	w2l.exe
aph2ri.exe	j2w.exe	ri2aph.exe	xro.exe
bins.exe	kk.exe	rph2e.exe	xy2y.exe
cm pc.exe	l2rph.exe	rph2nk.exe	xy2yx.exe
deriv.exe	nk2rph.exe	rph2s.exe	z2w.exe
e2e.exe	opc.exe	s2rph.exe	
e2rph.exe	pinkify.exe	t2a.exe	
gtfc.exe	prm2par.exe	t2approx.exe	

### 4. Obsolete programs

Some programs are no longer maintained, either because they have been supplanted by newer or better programs, or because they just are not used any more. Examples are DLfit.exe (Drude-Lorentz fit), MFLfit.exe, KEfit.exe, and TLfit.exe, which made fits of optical data to the Drude-Lorentz model, the Marginal Fermi Liquid mode, etc. The functionality of all of these (plus some more) is included in dff.exe (Dielectric Function Fit).

Here are the depreciated or obsolete programs, with the replacement in parentheses:

dlcalc.exe (dfc)	kefit.exe (dff)	reseq.exe (e2e)
dlfit.exe (dff)	kkold.exe (kk)	safit.exe (unused)
elphit.exe (dff)	mflfit.exe (dff)	sel-ftran.exe (fft)
flmfit.exe (tff)	prmave.exe (unused)	threefit.exe (unused)
ftran.exe (fft)	relfit.exe (unused)	tlfit.exe (dff)

### 5. Common features

The programs have several things in common. All have switches that control their behavior. You can pass file names and switches on the command line or have the program prompt you for them. Filenames should be separated by spaces. Switches may be introduced with ‘/’ or ‘-’, have optional spaces between them, and may be in upper or lower case. Thus, for example, you can say either `qp f1006.s1 f1100.s1 /xlog /a` or `QP f1006.s1 f1100.s1 -XLOG-A` to plot the files named `f1006.s1` and `f1100.s1` with autoscaling and with the x-axis on a log scale.

The programs can handle long file names. File names with a space in them need to be delimited with ". Thus, `Data.300k.first.refl` is OK, and the programs will take “`refl`” as the extension (possibly to be replaced in the output file by “`RPH`” or “`SMO`”). “`Data 300k first.refl`” is also fine, as long as the quotes are used.

Case in names is preserved. (Earlier versions changed them to uppercase.)

The data can be in multiple columns even if only two ( $x$ ,  $y$  values) are to be used. You will be prompted for the column number for  $x$  and  $y$ . These can be passed on the command line as well, by saying either `/Ci,j` or `/COLi,j` to read columns  $i$  and  $j$ .

The programs have a help screen. It is displayed if you type the `/h` or `/?` switch (e.g., `pik /?`), or by saying `?` to the first prompt.

Another useful switch is `/q` for “quick.” “Quick” bypasses most of the questions, using instead default values. Some of the programs (depending on the whim of the programmer) default to “quick” mode; ordinary mode is regained by using the “verbose” switch, `/v`. A few have three states, “quick” == `/q`, “usual” (no switch), and “verbose” == `/v`. The help screen lists the switches that change how many questions are asked. If you say `/v` when that is not an option you will get a message `?-<program>-W-Ignoring unknown command! /V`.

The programs can be divided into data analysis programs, data fitting programs, spectral analysis programs, and utilities for converting data files. They are briefly described on the following pages.

## B. Data analysis programs

These programs manipulate data from our spectrometers. They merge, average, smooth, KK transform, and carry out calculations on the data.

### 1. *CMP and CMPc*

CMP—CoMPute—is a program to “compute” or “compare” data files: It will calculate sum, difference, product, or ratio; it also will scale either the  $x$  or  $y$ -data. Finally it will calculate the inverse of the  $y$ -data, or subtract it from unity.

CMPc is a “console” version. It is CMP without any graphics.

The data are produced as follows:

$$Y_{data} <action> Y_{ref} \Rightarrow Y_{out}$$

$Y_{data}$  = sample;  $Y_{ref}$  = file to modify  $Y_{data}$ ;  $<action>$  any of +, −, /, and \*.

or

$$<action> Y_{data} \Rightarrow Y_{out}$$

$Y_{data}$  = sample;  $<action>$  = one of 1.0−, 1.0/, or a rescale.

Files entered on the command line in the sequence: **data**, **ref**, **out** or **data**, **out**. CMP will then do its thing with **data** and (if needed) **ref** and produce **out**. If not enough file names are entered, you will be prompted for the ones that are needed.

If only one file name is entered and if one or both of the /XA, B or /YA, B switches have been entered, CMP will assume that you want to scale this file. Similarly if you respond to the “second file” prompt with a <cr>, CMP will assume that you want to scale the first file. You will be prompted for the scaling/shifting factors for the  $y$ -data. (Note that the only way to scale the  $x$ -data is to use the /XA, B or the /X switches.)

Switches: /h, /q, /v, and

/+	— add two files.
/−	— subtract the two files (default if no $<action>$ entered).
/*	— multiply them.
//	— divide.
/&	— combine in 3 columns.
/A	— average 2 or more files.
/S	— sum (integrate) data. Note: Change from versions 3 and earlier, when it meant scale. (Use /y and /x for that.)
/R	— square root: $\sqrt{Y_{data}}$ .
/U	— subtract from unity: $1. - Y_{data}$ .
/I	— Invert: $1/Y_{data}$ .
/L	— Log: $\log_{10}(Y_{data})$ .
/E	— Exponentiate: $10^{(Y_{data})}$ .
/X**n	— Raise to power: $(X_{data})^n$
/Y**n	— Raise to power: $(Y_{data})^n$
/ABS	— Absolute value: $ Y_{data} $ .
/CLA, B	— Clip data to range A to B.
/x or /y	— rescale data, with prompt for scaling factors
/yA or /yA, B	— rescale data as $y \Leftarrow y \times A + B$ .



<code>/xA</code> or <code>/xA,B</code>	— rescale data as $x \leftarrow x \times A + B$ .
<code>/2</code>	— use $x$ -data of 2nd file for output $x$ values.
<code>/Ci,j</code>	— read Cols $i, j$ .
<code>/O</code>	— Omit duplicate $X$ values.
<code>/D</code>	— Include Duplicated $x$ values (default). (Was <code>/E!</code> )
<code>/RPH</code>	— data are in an RPH file.

Examples:

`CMP /- Mydata.mrg Myphon.on Myout.dat`

`Mydata.mrg - Myphon.on  $\Rightarrow$  Myout.dat`

`CMP Mydata.mrg Myref.mrg //`

`Mydata.mrg / Myref.mrg  $\Rightarrow$  Mydata.div`

Note the following default extensions for CMP's output files.

`ADD: /+`

`DIF: /-`

`DIV: //`

`MUL: /*`

`INV: /I i.e., 1/`

`1-Y: /U i.e., 1-`

`SCA: scaled data`

## 2. *FTS*

FTS—Fourier Transform Smooth—is a program for smoothing and fringe elimination by Fourier transforming data and filtering the transform. The basic idea is that the noise components have a white frequency spectrum, whereas the data are more slowly varying. Thus, by Fourier-transforming the file and reducing the amplitude of the high-frequency part of the transform, the noise can be reduced.

Fringes in the spectrum have a sinusoidal pattern, and so are at well-defined locations in the transform. By zeroing the fringe signature, the fringe pattern can be reduced without much affecting the rest of the spectrum.

You will be asked for four breakpoints, which you enter by clicking the mouse. The program multiplies the data by a function which goes to zero as a quadratic between the first two breakpoints and returns to 1 between the next two.

To remove fringes, click twice to left of signature and twice to right of it:



If you click outside the frame, the breakpoints are moved to the end of the transform data. To apply an overall smooth to the data, click once about 10% of the way in, a second time where the amplitude of the transform has gotten to its high-frequency value, and twice to the right of the frame.

After the transform has been filtered, the inverse transform is done and the smoothed file is plotted. You can accept this result, try again from the start, or apply further smoothing. If you answer ‘R’ at the prompt, you can retry with the original data. If you answer ‘M,’ you can continue with additional smoothing.

Switches: /h, /q, and

/O	— Order of polynomial to fit, e.g., /O3 $\Rightarrow$ cubic.
/Cnnn,nnn or /ynnn,nnn	— Clip data outside range supplied.
/COLi,j	— read Cols i, j.

Example:

```
FTS s114.bru s114.ftc /c0,1 /q
```

Here, `s114.bru` is the input file and `s114.ftc` is the output. /c0,1: Data clipped to window 0–1 before FT. /q: First plot is skipped; no rescaling is done.

### Important notes:

1. Smooth individual files rather than merged or combined spectra.
2. Too much smoothing is not a Good Thing; the data look unnatural in that case.

### 3. *GTF and GTFc*

GTF—Glover-Tinkham Film or Glover-Tinkham Frontside—extracts the conductivity of a thin film on a thick substrate from the transmittance and reflectance. The algorithm is the one by Glover and Tinkham. This program assumes that the reflectance was measured on the film side of the film/substrate combination.

GTF is the graphics version; GTFc the windows console version.

You will be asked for the file to output  $\sigma_1$  and  $\sigma_2$  and then for data files for  $\mathcal{T}$ ,  $\mathcal{R}$ , and the substrate. The latter may be a \*.nk, \*.rph, or \*.prm file. \*.nk is assumed if another extension is used. The output is a \*.s12 file. (This may be converted to \*.rph with s2rph.exe.)

You can provide a list of files instead of responding to the prompt. The LOF must have the same name as the s12 file and extension 'LOF'. Then start the program with GTF <lof-file-name>. In the LOF file, you put the names of the  $\mathcal{T}$ ,  $\mathcal{R}$ , and substrate files on the first 3 lines followed by film thickness (Angstroms) and substrate thickness (cm) on the next 2.

Switches: /h, /q, /v, and

/Tnnn — Film thickness in Angstroms is *nnn*.

/Snnn — Substrate thickness in cm is *nnn*.

/Wnnn — Stop at frequency *nnn*.

A list of files would be in MYDATA.LOF, which might look like

f1006.tra

f1006.ref

sub.prm

2500 (film thickness in Angstroms)

0.07 (substrate thickness in cm)

#### 4. *INTERP and INTERPc*

INTERP—INTERPolate—allows data to be interpolated, either on a finer or coarser scale than originally. The interpolation can be done on either a logarithmic or linear scale. INTERP can also scale data. The default is to ask for scale factors for the Y-data, but command line switches modify this.

INTERPc has the graphics removed.

Switches: /h, /q, and

/Xnnn,mmm	— $x$ -axis plot range = $nnn$ – $mmm$ — <i>also</i> the interpolation range.
/Xmmm	— $x$ -axis plot range = 0– $mmm$ — <i>also</i> the interpolation range.
/Ynnn,mmm or /Ymmm	— $y$ -axis plot range
/XL,	— do $x$ axis on Log scale (also interpolation)
/YL,	— do $y$ axis on Log scale
/Dnnn	— Delta $x$ is $nnn$
/G	— do interpolation loGarithmically
/S	— reScale $y$ axis data
/Sx	— reScale $x$ and $y$ axis data
/N	— No rescaling
/Ci,j	— Data in Columns $i, j$ .

Examples:

```
INTERP f1006.s1 f1006c.s1 /x0,5000 /log /y0,3000
```

Interpolate f1006.s1 logarithmically, using the X-values in f1006c.s1.

```
INTERP f1006.s1 -y3000 -q -s
```

Here, the  $x$ -axis is autoscaled;  $y$ -axis is from 0 to 3000. The user is asked for output file and for  $A, B$  for  $x \Leftarrow A * x + B$ .

## 5. *KK*

*KK*—Kramers-Kronig transform—performs a Kramers-Kronig transform for (single-bounce) reflectance  $\mathcal{R}$  and (slab) transmittance  $\mathcal{T}$  data. *KK* uses graphics window to show you some of the intermediate steps.

You will need to specify the extrapolations to be used outside the data. In 2012 these were changed significantly.

At high frequencies, you must use a `<compound name>.xro` file. These are generated by the `xro` program described on page 33. Examples would be `Ag.xro` or `YBa2Cu3O6.93.xro`. The `xro` files extend from  $80,660\text{ cm}^{-1}$  (10 eV) to  $241,980,000\text{ cm}^{-1}$  (30,000 eV). Above this range, the data are extrapolated as  $\mathcal{R} \sim \omega^{-4}$  as appropriate for completely free electrons.

Unless your data extend to  $80,600\text{ cm}^{-1}$  or so (unlikely if you do not have vacuum ultraviolet instrumentation) there will be a gap. Optical data typically stop between  $20,000$  and  $40,000\text{ cm}^{-1}$ , or 2.5 and 5 eV. There are 4 methods of bridging the gap between your measured data and the `.xro` data:

1. A power law in  $1/\omega$ :  $\mathcal{R} = A + B/\omega + C/\omega^2 + D/\omega^3 + \dots$  (Say **L#** at the prompt.)
2. A power law in  $\omega$ :  $\mathcal{R} = A + B\omega + C\omega^2 + D\omega^3 + \dots$  (Say **W#** at the prompt.)
3. A cubic spline can also be used. (Not recommended, but sometimes it works.)
4. No bridge. This is equivalent to a straight line connection.

For the two power laws you are shown a plot of  $\mathcal{R}$  in the bridge region, and asked to select the points used in the fit. You also specify the order (the highest power of  $\omega$  used in the fit).<sup>\*</sup> The order is 3 in the above equations. The earlier extrapolation (in *KKold*) used  $1/\omega^D$  with  $D$  in the range 0 to 4. Thus the power law in  $1/\omega$  is probably the best choice. The default is to use  $1/\omega$ .

Sometimes the x-ray (`xro`) calculation produces a rather high reflectance in the  $80,000$ – $300,000\text{ cm}^{-1}$  region. The reflectance is “high” if it is well above the measured data in the visible/uv. The bridge will have a positive slope, and can contribute to a negative  $\sigma_1(\omega)$  in the *KK* results. To work around this, use the `/W` or `/G` option. Before asking about the fit over the bridge region, *KK* will then show the high-frequency end of the data and the low end of the x-ray-extension reflectance. You will be asked to click twice to select the new start and end of the gap. Generally you will (1) click just right of the first data point (keeping all the data<sup>†</sup>) and (2) in the `xro` data where it has fallen below the measured data. This click pushes the start of the x-ray extension to higher energies and uses a power law over the wider gap.

In verbose mode (`\v`), *KK* will ask if you want to widen the gap. Verbose mode also asks if you want to keep (include) the low- and high-frequency extrapolated data (reflectance and phase). These options are also available with `/KL` and `/KH` switches. If you do keep the extrapolations in the output file, be sure to remove the extrapolation data before making plots for publication!

---

<sup>\*</sup> If the order is too large, the fitting routine produces a singular matrix. In this case, *KK* reduces the order by 1 and tries again. You are limited to order  $\leq 9$ .

<sup>†</sup> You may of course click somewhere inside your data if you want to trim what seem like unreliable uv data.

There are several low frequency extrapolations possible, controlled by a parameter COND. For KK of  $\mathcal{R}$ , one has:

>0	$\Rightarrow$	COND is the known DC conductivity, in $\Omega^{-1}\text{cm}^{-1}$	
=0 or i	$\Rightarrow$	Reflectance is assumed constant to DC	
-1 or m	$\Rightarrow$	Metallic conductivity assumed:	$\mathcal{R} = 1 - A\omega^{1/2}$
-2 or t	$\Rightarrow$	Two-fluid model:	$\mathcal{R} = 1 - A\omega^2$
-3 or l	$\Rightarrow$	Marginal Fermi Liquid:	$\mathcal{R} = 1 - A\omega^1$
-4 or s	$\Rightarrow$	Superconducting:	$\mathcal{R} = 1 - A\omega^4$
-5 or f	$\Rightarrow$	Use a parameter file. (You will be asked for the name of the *.PAR file.)	

The use of a parameter file (-5, f, or /P<file>) is strongly recommended. KK will use the parameters to calculate the low frequency reflectance or transmittance.\*

You also need to specify the file names for input or output. The file order on command line is: Data, X-ray, Parameter, Output. KK will construct the output name from the data file name, with extension .rph or .tph if the name is not specified.

The data can be scaled or shifted and are clipped to 0. $\leftrightarrow$ 1. range.<sup>†</sup>

Switches: /h, /q, and

/F<file>	— Use <file> (.XRO) for high freq extrapolation
/BL<number>	— Bridge with $\mathcal{R} = A + B/\omega + C/\omega^2 + \dots$ up to <number>
/BW<number>	— Bridge with $\mathcal{R} = A + B\omega + C\omega^2 + \dots$ up to <number>
/BS	— Bridge with cubic spline (which sometimes does not work...)
/BN	— No bridge (equivalent to a straight line)
/W or /G	— Widen Gap using mouse to select highest data and lowest .xro points to keep
/Cnn	— low frequency extrapolation using $\sigma_{dc} = nnn$
/I or /C0	— Reflectance is assumed constant to DC (default)
/C or /C-1	— Metallic conductivity assumed: $\mathcal{R} = 1 - A\omega^{1/2}$
/L or /C-2	— London (two-fluid) model: $\mathcal{R} = 1 - A\omega^2$
/M or /C-3	— Marginal-Fermi Liquid: $\mathcal{R} = 1 - A\omega^1$
/S or /C-4	— Superconducting: $\mathcal{R} = 1 - A\omega^4$
/P<file>	— Use <file> (.PAR or .PRM) for low frequency extrapolation (preferred)
/KH	— Keep high frequency extrapolation points
/KL	— Keep low frequency extrapolation points
/T	— transform of Transmittance
/TPH	— transform Transmittance and write *.TPH file
/Xnnn or /xnnn	— film thickness (Angstroms) (for $\mathcal{T}$ )
/Ynnn,mmm	— Scale data as $Y \leftarrow nnn * (Y - mmm)$
/COLi,j	— Data in Columns i, j.

---

\* If the fit is not good at low frequencies, you may want to pick out the data up to say  $500\text{ cm}^{-1}$  and optimize the parameters for a good low-frequency fit.

<sup>†</sup> The actual clipping algorithm allows the data to be 1.0 as long as it is 1.0 at all lower frequencies; otherwise 0.999999 is the largest value allowed.

Examples:

```
KK F1A100.rnm YBa2Cu306.93.xro /t /c-1 -q
```

Transform `f1a100.rnm`, a transmittance file. Use built-in defaults, except extend low-frequency region as metal. Use `YBa2Cu306.93.xro` at high frequencies.

```
KK F1A100.RAW /FYBa2Cu306.93 /PYBa2Cu306.93.PAR /BL4 /KH
```

```
KK F1A100.RAW YBa2Cu306.93 YBa2Cu306.93.PAR /BL4 /KH
```

Transform `f1a100.raw`. The low frequencies are extrapolated using the parameters in `YBa2Cu306.93.PAR`. Use `YBa2Cu306.93.xro` in the x-ray region. Bridge with  $\mathcal{R} = A + B/\omega + C/\omega^2 + D/\omega^3 + E/\omega^4$ . Keep the high-frequency extrapolation data.\* Note: the two command-line strings produce identical results.

KK produces an `RPH` file, where the three data columns are frequency, reflectance, and phase shift on reflectance;  $\omega$ ,  $\mathcal{R}$ ,  $\phi$ . From these, the complex refractive index is

$$N(\omega) = \frac{1 + \sqrt{\mathcal{R}(\omega)}e^{i\phi(\omega)}}{1 - \sqrt{\mathcal{R}(\omega)}e^{i\phi(\omega)}}.$$

The program `OP` can calculate a wide variety of optical constants from the `RPH` file. See pages 15–27 for the list and formulas.

---

\* If you use `/KH` be sure to remove the extrapolation data before making plots for publication! Ditto for `/KL`.

## 6. *KK /T*

KK with the /T switch does the Kramers-Kronig analysis of transmittance.

Most of the comments above apply to transmittance.

KK /T produces an RPH file, where the three data columns are frequency, reflectance, and phase shift on reflectance;  $\omega$ ,  $\mathcal{R}$ ,  $\phi$ . From these, the complex refractive index is

$$N = \frac{1 + \sqrt{\mathcal{R}} e^{i\phi}}{1 - \sqrt{\mathcal{R}} e^{i\phi}}.$$

Note that the values of  $\mathcal{R}$  and  $\phi$  are those of the *same* material measured as single-bounce reflectance.

The bridging and x-ray (**\*.xro**) high frequency extrapolations are as in the case of  $\mathcal{R}$ . KK /T assumes coherent transmission through a slab.\* Above the x-ray range, the data are extrapolated as  $\mathcal{T} \sim 1 - C\omega^{-2}$  as appropriate for completely free electrons.

There are several low frequency extrapolations possible, controlled by a parameter COND. For KK of  $\mathcal{T}$ , one has:

=0 or c $\Rightarrow$	Transmission is assumed constant to DC	
-1 or m $\Rightarrow$	Metallic conductivity assumed:	$\mathcal{T} = B + C\omega^2$
-2 or s $\Rightarrow$	Superconducting:	$\mathcal{T} = A\omega^2$

---

\* Otherwise the phase would not be meaningful.



## 7. MAV

MAV—Merge and AVerage—This program merges and/or averages several blocks of  $x, y$  data to produce one data set. It is intended for spectral data, where the experiment measures in several overlapping ranges. For example, you may obtain `file1` over the range 1–100, `file2` over 90–180, `file3` and `file4` over 150–350, etc.. MAV will combine these data. It compares in the overlap region the quantities  $\int dx \text{file1}$  and  $\int dx \text{file2}$  and multiplies the data in `file2` by a constant so as to make the two integrals equal. Then, the two data sets are combined using a weighted average that starts with 100% `file1` and ends with 100% `file2`.

MAV *will* combine non-overlapping ranges, but it doesn't work so well. It will merely equate the first point of the second-range data with the last point of the first-range data.

In use, you select the region where data are combined by clicking with the mouse. Click at each end of the data. The overlap region is the data between the left and right mouse clicks.

After the merge is calculated, the program will ask “Is this OK.” If you don't like the result, say ‘N’, and enter the scaling factor for the second-range data.

To average files, enter the file names on a single line. Merging and averaging can be intermixed. In other words, you can average a bunch of files taken over identical  $x$  ranges, and then merge the average with data from other  $x$  ranges.

At the end, MAV prints a list of the scaling factors used (and their inverses) and gives you a chance to make a final scaling of the merged data. This gives you a chance to set the scaling factor for your “best” data to 1.

You will be asked for the names of the output file and at least two data files. You can provide a list of files instead of responding to the prompt. The LOF must have the same name as the output file and extension ‘LOF.’ Then start the program with MAV <lof-file-name>.

Switches: /h, /q, and

/C	— Cumulative: Initial scale is previous.
/S	— Find average and std dev of a set of files.
/Ynnn,mmm or /Ymmm	— y-axis plot range.
/COLi,j	— Data in Columns i, j.
/P or /PE	— data are ‘PE’ Columns 1 and 3.

Example:

MAV MYDATA.MRG

A list of files would be in MYDATA.LOF, which might look like

Y04A.bru

Y03A.bru,y03b.bru, y03C.bru

Y02A.bru y02b.bru

Y01A.bru

This will merge four frequency regions, averaging data sets A, B, and C in region 2 and data sets A and B in region 3.

## 8. MEND

MEND is a program to “MEND” a data file.

MEND used to be named PATCH, but Windows 7 invokes the “Do you want this program to make changes?” dialogue any time a program named `patch.exe` is started. No matter what it does! What a bunch of maroons.

MEND replaces sections of data with a power-law fit. Data are selected with the mouse. You select first the range to be replaced; then, the range to be fitted. The second range should include the first.

The program can also scale data. The default is to ask for scale factors for the  $y$ -data, but command line switches modify this.

Switches: `/h`, `/q`, and

<code>/Xnnn,mmm</code>	— $x$ -axis plot range = $nnn$ – $mmm$
<code>/Xmmm</code>	— $x$ -axis plot range = $0$ – $mmm$
<code>/Ynnn,mmm</code> or <code>/Ymmm</code>	— $y$ -axis plot range
<code>/XL</code> , <code>/yl</code> ...	— do axis on Log scale
<code>/XA</code> , <code>/ya</code> , <code>/A</code> ...	— Autoscale axis (A:both)
<code>/S</code> or <code>/Sx</code>	— ask about reScale of $x$ -axis data
<code>/N</code>	— No rescaling
<code>/Dn</code>	— Degree of fit is $n$ (0–4)
<code>/C</code>	— Change $x$ increment in output data
<code>/COLi,j</code>	— Data in Columns $i$ , $j$ .

Examples:

```
Mend f1006.s1 f1006c.s1 /x0,5000 /xlog /y0,3000
```

```
Mend f1006.s1 -xauto-y3000 -q -s -d3
```

In the first, MEND plots file `f1006.s1` semilog, puts patched data in `f1006c.s1`. In the second, the  $x$ -axis is autoscaled  $y$ -axis is from 0 to 3000. A cubic fit is used for the patch. User is asked for output file and for  $A$ ,  $B$  for  $x \Leftarrow A \times x + B$ .

## 9. Patch.bat

Patch.bat is a batch file which calls Mend. If you are used to typing patch, this will avoid file-not-found errors.

## 10. OP and OPc

OP—Optical Properties—computes Optical Properties from KK-determined reflectance and phase. 38 different functions may be calculated. The program can also subtract a model dielectric function from the data.

OPc is the windows console version.

Switches: /h, /q, and

/Vnnn	— unit cell Volume is <i>nnn</i>
/Wpnnn	— Plasma frequency is <i>nnn</i>
/Infnnn	— $\epsilon_\infty$ is <i>nnn</i>
/Wnnn,mmm	— calculate between frequencies <i>nnn</i> and <i>mmm</i>
/Wmmm	— calculate from 0.0 to maximum frequency <i>mmm</i>
/ALL or /all	— do ALL functions (38 files created)
/P<file>	— Partial dielectric function, $\epsilon - \epsilon_{\text{model}}$

The unit cell volume is needed for sum rules. The plasma frequency and  $\epsilon_\infty$  are used for self-energy, effective mass etc. The max frequency (/Wnnnn) can be used to limit file size.

The switch for “Partial dielectric function” subtracts a model contribution to the dielectric function from  $\langle\epsilon(\omega)\rangle$  before calculation of the optical function. It uses parameters in a \*.PAR file produced by DFF.

Response function switches:

/S1 or /S	— $\sigma_1$	/S2	— $\sigma_2$
/E1 or /E	— $\epsilon_1$	/E2	— $\epsilon_2$
/N	— refractive index, $n$	/K	— extinction coefficient, $\kappa$
/A	— Absorption coefficient, $\alpha$	/SK	— SKin depth, $\delta$
/L	— Loss function, $-\text{Im } 1/\epsilon$	/LS	— Surface loss function, $-\text{Im } 1/(\epsilon - 1)$
/RH	— Optical resistivity $\rho$	/RH2	— Imaginary $\rho$
/SU	— SUM rule on $\sigma_1(\omega)$ , $N_{\text{eff}}$	/SF	— Sum rule surFACE loss function
/SL	— Sum rule Loss function	/RE	— REal(self-energy), $\Sigma_1$
/I	— $-\text{Imag}(\text{self-energy})$ , $-\Sigma_2$	/G2	— $\Gamma_2$
/G	— $\Gamma_1$	/M	— effective Mass, $m^*/m$
/T	— $1/\tau(\omega)$		
/Wps	— superfluid plasma frequency, $\omega_{ps}$		
/LL	— London Length, $\lambda_L$	/NFR	— delta-fn weight
/F	— Free carrier: $\epsilon_1$ vs $1/\omega^2$		
/D	— Drude model: $1/\sigma_1$ vs $\omega^2$		
/E	— Abs(Epsilon)	/S	— Abs(Sigma)
/TAN	— Tan(delta)	/TAN	— Abs(Tan(delta))
/R	— Reflectance, $\mathcal{R}$	/RPH	— $\mathcal{R}$ is in file from KK
/TI	— Slab T(incoherent)	/TC	— Slab T(coherent)
/RI	— Slab R(incoherent)	/RC	— Slab R(coherent)

Examples:

OP F1A006 /S1

Calculate conductivity ( $\sigma_1$ ) from file F1A006.RPH

OP F1A006 -sum -v162.1 -q

Calculate Sum rule from file F1A006.RPH; output in F1A006.SUM. Unit cell volume = 162.1 Å<sup>3</sup>. Be quick.

OP uses as input an RPH file, containing in 3 columns the frequency (in cm<sup>-1</sup>), the power reflectance  $\mathcal{R}$ , and the phase shift on reflection  $\phi$ . This file is produced either by KK or, for simulated data, by DFC.

The complex (amplitude) reflectivity is  $\sqrt{\mathcal{R}}e^{i\phi}$ . The complex refractive index is calculated from the reflectivity:

$$N = \frac{1 + \sqrt{\mathcal{R}}e^{i\phi}}{1 - \sqrt{\mathcal{R}}e^{i\phi}}. \quad (1)$$

and the complex dielectric function is

$$\epsilon = \epsilon_1 + i\epsilon_2 = N^2. \quad (2)$$

A number of the optical functions depend on  $\Delta\epsilon$ , the dielectric function with something subtracted. If there is a single low energy band, with all the high frequency behavior lumped into  $\epsilon_\infty$  then

$$\Delta\epsilon = \epsilon - \epsilon_\infty. \quad (3)$$

More generally, one may want to subtract off the contributions of phonons, interband transitions, etc. In this case,  $\Delta\epsilon$  is the Partial dielectric function,  $\epsilon - \epsilon_{model}$  that you invoke with /P<file>. OP will prompt you for  $\epsilon_\infty$  if it is needed and not known.

Here are the functions that OP calculates. The frequencies are in wavenumbers (cm<sup>-1</sup>), with  $\omega[\text{cm}^{-1}] = f[\text{Hz}]/c = \omega[\text{rad/s}]/2\pi c$ . The computed results are in SI, mostly.

## ***Optical “constants”***

### **1. Sigma\_1**

The complex conductivity and dielectric function are related. In cgs the conductivity and frequency are both measured in sec<sup>-1</sup> and the relation is

$$\epsilon = 1 + \frac{4\pi i\sigma}{\omega}, \quad (4)$$

whereas in SI the conductivity is in  $\Omega^{-1}\text{cm}^{-1}$ , and it is

$$\epsilon = 1 + \frac{i\sigma}{\omega\epsilon_0}. \quad (5)$$

with  $\epsilon_0$  the dielectric function of empty space.

In lab units, frequencies are in  $\text{cm}^{-1}$  and conductivities are in  $\Omega^{-1}\text{cm}^{-1}$ , and the relation is

$$\epsilon = 1 + \frac{60i\sigma}{\omega}, \quad (6)$$

The real part of the optical conductivity (in  $\Omega^{-1}\text{cm}^{-1}$ ) is then

$$\sigma_1 = \frac{\omega\epsilon_2}{60}, \quad (7)$$

with  $\omega$  in  $\text{cm}^{-1}$ . This equation\* can be compared to the expression in cgs:

$$\sigma_1 = \frac{\omega\epsilon_2}{4\pi}, \quad (8)$$

with  $\omega$  in  $\text{sec}^{-1}$  and  $\sigma_1$  also in  $\text{sec}^{-1}$ . The cgs conductivity is  $9 \times 10^{11}$  times larger than the SI conductivity.

## 2. Sigma\_2

The imaginary part of the optical conductivity (in  $\Omega^{-1}\text{cm}^{-1}$ ) is

$$\sigma_2 = -\frac{\omega(\epsilon_1 - 1)}{60}. \quad (9)$$

If you are using the /P (partial) option, then OP calculates

$$\sigma_2 = -\frac{\omega(\Delta\epsilon_1)}{60}. \quad (10)$$

## 3. Epsilon\_1

$$\epsilon_1 = \text{Re}(\epsilon) \quad (11)$$

## 4. Epsilon\_2

$$\epsilon_2 = \text{Im}(\epsilon) \quad (12)$$

## 5. Refr Index

$N$  is calculated from reflectance and phase via the inversion of

$$\sqrt{\mathcal{R}} e^{i\phi} = \frac{N - 1}{N + 1} \quad (13)$$

and

$$n = \text{Re}(N) \quad (14)$$

---

\* The same factor of 60 appears if you calculate  $\sigma_{dc}$  from the plasma frequency and relaxation rate,

$$\sigma_{dc} = \frac{\omega_p^2}{60(1/\tau)}$$

with  $\omega_p$  and  $1/\tau$  in  $\text{cm}^{-1}$  and  $\sigma_{dc}$  in  $\Omega^{-1}\text{cm}^{-1}$ . In reality,  $60 = 377 \Omega/2\pi$ .

## 6. Ext Coeff.

The imaginary part of  $N$  is

$$\kappa = \text{Im}(N) \quad (15)$$

## 7. Alpha

The absorption coefficient (in  $\text{cm}^{-1}$ ) is

$$\alpha = 4\pi\omega\kappa, \quad (16)$$

correct for  $\omega$  in  $\text{cm}^{-1}$ . In cgs, this is

$$\alpha = 2\omega\kappa/c. \quad (17)$$

where  $\omega$  is in  $\text{sec}^{-1}$ .

## 8. Skin depth

In the skin effect the electric field goes as  $e^{-x/\delta}$  but of course the wave governed by a refractive index  $N$  has a field which decays as  $e^{-\kappa\omega x/c}$  ( $\omega$  in rad/s). Hence:

$$\delta = \frac{10^8}{2\pi\omega\kappa}, \quad (18)$$

with  $\omega$  in  $\text{cm}^{-1}$ . The factor of  $10^8$  makes the units of  $\delta(\omega)$  in Å.

## 9. Loss Fnctn

The energy loss function governs the transmission of fast electrons through the material. These depend on the longitudinal response of the dielectric. It is typically written as  $-\text{Im}(1/\epsilon)$ ; here we use  $L$ .

$$L = \frac{\epsilon_2}{(\epsilon_1^2 + \epsilon_2^2)} = -\text{Im} \frac{1}{\epsilon}. \quad (19)$$

## 10. Surface Loss Fnctn

The “surface” energy loss function is

$$L_s = \frac{\epsilon_2}{((\epsilon_1 - 1)^2 + \epsilon_2^2)} = -\text{Im} \frac{1}{\epsilon - 1}. \quad (20)$$

## Sum rules

### 11. Sumrule S\_1

This is the most important sum rule function calculated by OP. The f-sum rule for solids can be written

$$\int_0^\infty \sigma_1(\omega') d\omega' = \frac{\omega_{p,tot}^2}{8}, \quad (21)$$

where  $\omega_{p,tot} = \sqrt{4\pi n_{tot} e^2 / m}$  is the plasma frequency for all the electrons in the solid. We may write a partial sum rule (for the conduction band, say) as

$$\int_0^\omega \sigma_1(\omega') d\omega' = \frac{\pi n e^2}{2m^*}, \quad (22)$$

where  $m^*$  is the average effective mass of the band. If the upper limit is above the free-carrier contribution and below the onset of the interband transitions, the right hand side becomes  $\omega_p^2/8$  with  $\omega_p$  the conduction band plasma frequency.

Next, write  $n = N_{eff}/V_c$  and let  $m$  be the free electron mass. The density is in the number of effective electrons per unit cell volume or formula volume. It generally better to consider the latter:  $V$  is the volume of the formula unit, typically  $V_{cell}/Z$  as specified by the structural paper.  $Z$  is the number of formula units in the unit cell. For example, NaCl is fcc with a lattice constant of 5.64 Å. The unit cell volume is 179.4 Å<sup>3</sup> but  $Z = 4$ , so  $V = 44.8$  Å<sup>3</sup>. Note that if you know the density you can always calculate the volume:  $V = M/\rho$  with  $\rho$  the density and  $M$  the mass of the atom in the element or atoms in the compound.

Then, OP calculates

$$N_{eff} \frac{m}{m^*} = \frac{2mV_c}{\pi e^2} \int_0^\omega \sigma_1(\omega') d\omega' \quad (23)$$

with  $m$  the mass of an electron and  $m^*$  the effective mass of the charge carriers.

### 12. Sumrule LossFn

We may write a partial sum rule (for the conduction band, say) of the loss function as

$$\frac{1}{4\pi} \int_0^\omega \omega' L(\omega') d\omega' = \frac{\pi n e^2}{2m^*}, \quad (24)$$

where  $m^*$  is the average effective mass of the band. If the upper limit is above the free-carrier contribution and below the onset of the interband transitions, the right hand side becomes  $\omega_p^2/8$  with  $\omega_p$  the conduction band plasma frequency. (The factor of  $1/4\pi$  is the same as appears in  $\omega_{e2}/4\pi = \sigma_1$ .) Thus,

$$N_{eff} \frac{m}{m^*} = \frac{mV_c}{2\pi^2 e^2} \int_0^\omega \omega' L(\omega') d\omega' \quad (25)$$

### 13. Sumrule SurfaceLossFn

Same as Eqs. 24 and 25, but for  $L_s$ .

### ***Frequency-dependent scattering, self-energy, and effective mass functions***

The dielectric function of perfectly free (noninteracting) carriers with density  $n$ , charge  $\pm e$  and mass  $m$  is given by

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega^2} \quad (26)$$

with  $\omega_p$ , the plasma frequency (in cgs)

$$\omega_p = \sqrt{\frac{4\pi n e^2}{m}}. \quad (27)$$

If now we allow scattering of free carriers from impurities, defects, surfaces, and lattice oscillations,\* with a mean free time  $\tau$  or scattering rate  $1/\tau$ , independent of the frequency, the dielectric function has the Drude form:

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega/\tau} \quad (28)$$

Now, if we turn on interactions, the scattering rate becomes a function of frequency (and probably also of temperature). However, to allow the scattering rate,  $1/\tau$  to vary with frequency and remain real quantity would cause the dielectric function (and conductivity) to violate the Kramers-Kronig relation. One may accommodate this either by considering the scattering rate to be a complex function or by also having the effective mass  $m^*$  to vary with frequency.

Theorists have devised a number of such functions: the complex self-energy function  $\Sigma$ ,<sup>†</sup> the complex scattering (or memory) function  $\Gamma$ , a complex scattering rate  $1/\tau^*$  and effective mass  $m^*$ , and a complex scattering rate  $1/\tau^*$  and mass enhancement factor  $\lambda$ . OP can take the KK-derived dielectric function and compute each and all of these quantities.

#### **14. -Imag self-energy (one-particle)**

In some theories (such as the marginal Fermi liquid) the imaginary part of the self energy  $\Sigma$  plays the role of a scattering rate, with the dielectric function written as

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega[\omega - \Sigma(\omega)]}. \quad (29)$$

with  $\omega_p$  the (unrenormalized)<sup>‡</sup> plasma frequency and  $\epsilon_\infty$  the limiting high frequency value of the dielectric function. The imaginary part of  $\Sigma$  is related to the quasiparticle lifetime through  $1/\tau^*(\omega) = -\text{Im } \Sigma(\omega)/(m_b/m^*(\omega))$  with  $m^*$  the effective mass and  $m_b$  the band mass.

\* In principal, coupling to phonons scatters the charge carriers by either absorption or emission of a phonon. In turn, these processes lead to a frequency and temperature-dependent scattering rate. For this discussion, the frequency dependence is ignored, as are the emission processes. Thus, we consider only the high-temperature limit.

<sup>†</sup> There are actually two of these.

<sup>‡</sup> Unrenormalized means “what it would be if there were no interactions.”



OP computes  $-\text{Im } \Sigma$  via

$$-\text{Im } \Sigma(\omega) = -\frac{\omega_p^2}{\omega} \text{Im } \frac{1}{\Delta\epsilon}. \quad (30)$$

with  $\Delta\epsilon = \epsilon - \epsilon_\infty$ . You must enter the plasma frequency and  $\epsilon_\infty$ . Or, use the **partial** (/P<file>) option to subtract a model dielectric function. Subtraction removes optical phonons and interband transitions which may occur.

#### 15. Real self-energy (one-particle)

The real part of  $\Sigma$  is related to the effective mass  $m^*$  of the interacting carriers by

$$m^*(\omega)/m_b = 1 - \text{Re } \Sigma(\omega)/\omega. \quad (31)$$

Hence, OP computes

$$\text{Re } \Sigma(\omega) = \frac{\omega_p^2}{\omega} \text{Re } \frac{1}{\Delta\epsilon} + \omega. \quad (32)$$

#### 16. -Imag self-energy (two-particle)

A slightly different approach recognizes that optical excitations are created in pairs (electron and hole) and that the self-energy should be a two-particle process. Still, the imaginary part of the self energy  $\Sigma$  plays the role of a scattering rate, with the dielectric function written as

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega[\omega - 2\Sigma(\omega/2)]}. \quad (33)$$

with  $\omega_p$  the (unrenormalized) plasma frequency and  $\epsilon_\infty$  the limiting high frequency value. The factors of 2 occur because the excitations are created in pairs (electron-hole pairs or quasiparticle pairs). (These factors do not appear in all theoretical treatments. Indeed the “one-particle” versions are much more commonly seen.) The imaginary part of  $\Sigma$  is related to the quasiparticle lifetime through  $1/\tau^*(\omega) = -2 \text{Im } \Sigma(\omega/2)(m_b/m^*(\omega))$  with  $m^*$  the effective mass and  $m_b$  the band mass.

OP computes  $-\text{Im } \Sigma$  via

$$-\text{Im } \Sigma = -\frac{\omega_p^2}{2\omega} \text{Im } \frac{1}{\Delta\epsilon}. \quad (34)$$

with  $\Delta\epsilon = \epsilon - \epsilon_\infty$ . You must enter the plasma frequency and  $\epsilon_\infty$ .

After computing the right hand side of the above equation, OP divides the frequencies by 2, so that the dielectric function value at 400  $\text{cm}^{-1}$  (for example) generates the  $-\text{Im } \Sigma$  value at 200  $\text{cm}^{-1}$ .

Note that optical phonons and interband transitions may occur; OP allows you to subtract these from  $\epsilon$  via its /P<file> capability.

### 17. Real self-energy (two-particle)

The real part of  $\Sigma$  is related to the effective mass  $m^*$  of the interacting carriers by

$$m^*(\omega)/m_b = 1 - 2 \operatorname{Re} \Sigma(\omega/2)/\omega. \quad (35)$$

Hence, OP computes

$$\operatorname{Re} \Sigma(\omega/2) = \frac{\omega_p^2}{2\omega} \operatorname{Re} \frac{1}{\Delta\epsilon} + \omega/2. \quad (36)$$

After computing the right hand side of the above equation, OP divides the frequencies by 2, so that the dielectric function value at  $400 \text{ cm}^{-1}$  (for example) generates the  $\operatorname{Re} \Sigma$  value at  $200 \text{ cm}^{-1}$ .

### 18. Gamma\_1

The frequency dependent and complex damping is often written in an extended Drude model by replacing  $1/\tau$  by a “memory function”  $\Gamma$ . We write

$$\epsilon = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\Gamma)} \quad (37)$$

with  $\Gamma = \Gamma_1 + i\Gamma_2$ .

$$\Gamma_1 = -\frac{\omega_p^2}{\omega} \operatorname{Im} \frac{1}{\Delta\epsilon}. \quad (38)$$

Note that  $\Gamma_1 = -\Sigma_2$  (one-particle).

### 19. Gamma\_2

The imaginary part of  $\Gamma$  is

$$\Gamma_2 = \frac{\omega_p^2}{\omega} \operatorname{Re} \frac{1}{\Delta\epsilon} + \omega \quad (39)$$

Note that  $\Gamma_2 = +\Sigma_1$  (one-particle).

### 20. tau^-1\*

$$1/\tau = -\omega \frac{\operatorname{Im}(\Delta\epsilon)}{\operatorname{Re}(\Delta\epsilon)} \quad (40)$$

### 21. m\*/m

$$\frac{m^*}{m} = -\frac{\omega_p^2}{\omega^2} \operatorname{Re} \left( \frac{1}{\Delta\epsilon} \right) \quad (41)$$

## 22. Mass enhancement factor $\lambda(\omega)$

The effective mass may be written in terms of a mass enhancement factor  $\lambda(\omega)$ :

$$\frac{m^*}{m} = 1 + \lambda(\omega). \quad (42)$$

Hence

$$\lambda(\omega) = -\frac{\omega_p^2}{\omega^2} \text{Re}\left(\frac{1}{\Delta\epsilon}\right) - 1 \quad (43)$$

## *Specialized functions, mostly for superfluids*

### 23. Superfluid plasma freq

A superfluid has a dielectric function that is

$$\epsilon = \epsilon_\infty - \frac{\omega_{ps}^2}{\omega^2} \quad (44)$$

with  $\omega_{ps}$  the superfluid plasma frequency. OP calculates

$$\omega_{ps} = \sqrt{\omega^2 |\text{Re}(\Delta\epsilon)|} \quad (45)$$

where the absolute value is used instead of a minus sign to avoid numerical problems. Be sure that  $\epsilon$  is negative when you invoke this function!

If  $\omega_{ps}$  is (nearly) constant in frequency, the behavior is that of a superfluid.

### 24. N\_eff (free-el)

Again, writing

$$\epsilon = \epsilon_\infty - \frac{\omega_{ps}^2}{\omega^2} \quad (46)$$

with  $\omega_{ps}$  the superfluid plasma frequency. OP then writes  $\omega_{ps}^2 = 4\pi n_s(\omega)e^2/m$  so that:

$$n_s(\omega) = \omega^2 V_c C |\text{Re}(\Delta\epsilon)| \quad (47)$$

where  $C$  is a numerical constant.

$n_s(\omega)$  should be nearly constant as a function of frequency for the concept to be valid.

### 25. London penetra. depth

The dielectric function in 23 is that of a London superconductor, so one may also calculate  $\lambda_L$  as

$$\lambda_L = \frac{10^8}{2\pi\omega\sqrt{|\text{Re}(\Delta\epsilon)|}} \quad (48)$$

with  $\omega$  in  $\text{cm}^{-1}$ . The factor of  $10^8$  makes the units of  $\lambda_L(\omega)$  in Å.

$\lambda_L(\omega)$  should be nearly constant as a function of frequency for the concept to be valid.

### *Other specialized functions*

#### 26. Epsilon\_1 vs $1/\omega^2$

If

$$\epsilon = \epsilon_{\infty} - \frac{\omega_{ps}^2}{\omega^2} \quad (49)$$

then a plot of  $\epsilon$  vs  $1/\omega^2$  should be a straight line, with slope  $-\omega_{ps}^2$ . So this is equivalent to function 23.

#### 27. $1/\sigma_1$ vs $\omega^2$

If the dielectric function is Drude like, then

$$\sigma_1(\omega) = \frac{\sigma_{dc}}{1 + \omega^2 \tau^2} \quad (50)$$

so you can make a plot of  $1/\sigma_1$  vs  $\omega^2$ . The plot goes like is

$$\frac{1}{\sigma_1(\omega)} = \frac{1}{\sigma_{dc}} + \frac{\tau^2}{\sigma_{dc}} \omega^2$$

This plot should be a straight line with intercept  $1/\sigma_{dc}$  and slope  $\tau^2/\sigma_{dc}$ . If needed,  $\sigma_{dc}$  can be read off the plot of  $\sigma_1(\omega)$  assuming that the data extend well below  $1/\tau$ . Otherwise one can write the slope as  $4\pi\tau/\omega_p^2$  and get  $\omega_p$  from the plot of  $\epsilon_1$  vs.  $1/\omega^2$ .

#### 28. Resistivity (real)

The optical resistivity is just the inverse of the optical conductivity, so the real part is

$$\rho_1 = \text{Re}\left(\frac{1}{\sigma}\right). \quad (51)$$

Because  $\sigma$  is complex,  $\rho_1 = \sigma_1/(\sigma_1^2 + \sigma_2^2)$ .

#### 29. Resistivity (imag)

The imaginary part of the optical resistivity is

$$\rho_2 = \text{Im}\left(\frac{1}{\sigma}\right). \quad (52)$$

#### 30. Abs(eps)

There are examples where the magnitude of the complex dielectric function  $|\epsilon|$  displays power law behavior. Hence OP calculates

$$|\epsilon| = \sqrt{\epsilon_1^2 + \epsilon_2^2} \quad (53)$$

Note that this should be the entire function, so  $\epsilon_{\infty}$  is not automatically subtracted. If you want to compute  $\Delta\epsilon$ , use the /P option.

### 31. Abs(sigma)

This is

$$|\sigma| = \sqrt{\sigma_1^2 + \sigma_2^2} \quad (54)$$

### 32. Tan(delta)

The loss tangent is commonly used in the analysis of RF and microwave experiments. It is

$$\tan \delta = \frac{\epsilon_2}{\epsilon_1}. \quad (55)$$

This calculation uses the entire function, so  $\epsilon_\infty$  is not automatically subtracted. If you want to compute  $\Delta\epsilon$ , use the /P option.

### 33. Abs(Tan(delta))

If you want this to be always positive, use

$$\tan \delta_{abs} = \left| \frac{\epsilon_2}{\epsilon_1} \right|. \quad (56)$$

## ***Transmission and reflection***

OP uses the complex dielectric function (and the thickness, if needed) to calculate reflectance and transmittance. For a sample of finite thickness, you have a choice to treat it as “thick” (i.e., incoherent) or “thin” (coherent). In the first case, OP adds intensities of multiple internal reflections while in the second OP adds amplitudes. The second case allows for interference, with fringes in the transmittance or reflectance.

### 34. Reflectance

The power reflectance (single-bounce reflectance) is

$$\mathcal{R} = \left| \frac{N-1}{N+1} \right|^2. \quad (57)$$

OP actually computes this rather than just reading the values from the .RPH file.

### 35. T slab (thick)

Add intensities.

OP computes

$$\mathcal{T} = \frac{(1 - \mathcal{R}_{sb})^2 e^{-\alpha d}}{1 - \mathcal{R}_{sb}^2 e^{-2\alpha d}} \quad (58)$$

with  $d$  the thickness,  $\alpha$  the absorption coefficient, and  $\mathcal{R}_{sb}$  the single bounce reflectance.  $\mathcal{R}_{sb} = [(N-1)/(N+1)]^2$ .

### 36. T slab (fringes)

Add amplitudes.

To compute the coherent transmittance, OP first calculates the phase gain on passing the sample (one way),

$$\delta = 2\pi\omega Nd, \quad (59)$$

the amplitude transmitted *into* the slab, from vacuum,

$$t_1 = \frac{2}{N+1}, \quad (60)$$

the amplitude transmitted *out of* the slab,

$$t_2 = \frac{2N}{N+1}, \quad (61)$$

and the amplitude reflection at the interfaces, incident from within

$$r_{in} = \frac{N-1}{N+1}. \quad (62)$$

Then the formula for the transmission coefficient (amplitude) is

$$t = \frac{t_1 t_2 e^{i\delta}}{1 - r_{in}^2 e^{2i\delta}} \quad (63)$$

and to get the transmittance, OP calculates

$$\mathcal{T} = tt^* \quad (64)$$

This is the Airy formula.

### 37. R slab (thick)

Add intensities.

OP computes

$$\mathcal{R} = \mathcal{R}_{sb} + \frac{\mathcal{R}_{sb}(1 - \mathcal{R}_{sb})^2 e^{-2\alpha d}}{1 - \mathcal{R}_{sb}^2 e^{-2\alpha d}} \quad (65)$$

with  $d$  the thickness,  $\alpha$  the absorption coefficient, and  $\mathcal{R}_{sb}$  the single bounce reflectance.  $\mathcal{R}_{sb} = [(N-1)/(N+1)]^2$ .

### 38. R slab (fringes)

Add amplitudes.

To compute the coherent reflectance, OP first calculates the phase gain on passing the sample (one way),

$$\delta = 2\pi\omega Nd, \quad (66)$$

the amplitude transmitted *into* the slab, from vacuum,

$$t_1 = \frac{2}{N+1}, \quad (67)$$

the amplitude transmitted *out of* the slab,

$$t_2 = \frac{2N}{N+1}, \quad (68)$$

the amplitude reflection at the interfaces, incident from within

$$r_{in} = \frac{N-1}{N+1}, \quad (69)$$

and the front-surface reflectance

$$r_{fs} = \frac{1-N}{1+N}. \quad (70)$$

Here, the sign matters; these definitions make  $r_{fs}$  negative and  $r_{in}$  positive if  $N > 1$ .

Then the formula for the reflection coefficient (amplitude) is

$$r = r_{fs} + \frac{t_1 r_{in} t_2 e^{2i\delta}}{1 - r_{in}^2 e^{2i\delta}}. \quad (71)$$

Finally, to get the reflectance, OP calculates

$$\mathcal{R} = rr^* \quad (72)$$

## 11. *PIK and PIK2*

PIK—PIcK—Is a program to pick sections out of a data file.

Data are selected with the mouse. The output contains all data *between* the left and right mouse clicks. The program can also scale data. The default is to ask for scale factors for the *y*-data, but command line switches modify this.

Switches: /h, /q, and

/Pnnn,mmm	— Pick data between <i>nnn</i> and <i>mmm</i>
/S or /Sx	— ask about reScale of <i>x</i> axis data
/N	— No rescaling
/Xnnn,mmm	— <i>x</i> -axis plot range = <i>nnn–mmm</i>
/Xmmm	— <i>x</i> -axis plot range = 0– <i>mmm</i>
/Ynnn,mmm or /Ymmm	— <i>y</i> -axis plot range
/XL, /yl ...	— do plot on Log scale
/XA, /ya...	— Autoscale axis
/Ci,j	— data are in Cols <i>i</i> and <i>j</i>

(Pik2 does not have the /S and /N options.)

The first file name on command line is the input; second is the output.

Examples:

```
PIK f1006.s1 f1006c.s1 /x0,5000 /xlog /y0,3000
```

```
PIK f1006.s1 -xauto-y3000 -q -s
```

In the first, PIK plots file `f1006.s1` semilog on scales given, puts picked data in `f1006c.s1`. In the second, the *x*-axis is autoscaled while the *y*-axis will be plotted from 0 to 3000. User is asked for output file and for *A*, *B* for  $x \Leftarrow A \times x + B$ .

PIK2 is a version which is designed for large data sets. After the plot you can Expand, Compress, Shift or shift Back the plot by typing ‘E,’ ‘C,’ ‘S,’ or ‘B. S shifts the viewpoint to the right (higher *x* values) and B shifts to the left. The program loops to allow multiple selections. It works from left to right, starting each subsequent plot from the end of the previous selection.

Click the x box at the top of the screen to end it.



## 12. QP, Q, and QL

QP—QuickPlot—makes a plot on PC screen. Q is equivalent to QP /q. QL makes the plot with lines, rather than dots at each point.

After files on the command line are plotted, you can tell QP to plot more files, change scales, print the plot, or exit. You change plot scales by answering '/'. All files read so far will be replotted. A 'p' gives a screen dump. Exit by answering a <cr> to the next-file prompt.

Switches: /h, /q, and

/N /Xnnn,mmm	— $x$ -axis plot range = $nnn$ – $mmm$
/Xmmm	— $x$ -axis plot range = 0– $mmm$
/Ynnn,mmm or /Ymmm	— $y$ -axis plot range
/XR(ect) or /Yr	— do axis on Rectilinear scale
/XL(og) or /Yl	— do axis on Log scale
/R	— both $x$ and $y$ on Rectilinear scales
/XA(uto) or /Ya	— Autoscale axis
/A	— Autoscale both $x$ and $y$ axes
/Sx or /Sy	— ask about factor to reScale data
/O	— omit duplicate data points
/E	— read every point, even duplicates (default)
/P or /PE	— data are 'PE,' cols 1 and 3
/Ci,j	— data are in Cols $i$ and $j$

Examples:

```
qp f1006.s1 f1100.s1 /x0,5000 /xlog /y0,3000
```

Plot two files in semilog format on scales given:

```
qp f1006.s1 f1100.s1 -xauto-y3000
```

Autoscale  $x$ -axis, plot  $y$ -axis from 0 to 3000:

```
qp s647.44 s647.45 s647.46 /pe /sy
```

Plot 3 files, which are in PE format (data in columns 1, 3); rescale  $y$ -data:

### 13. RNM

RNM—ReNorMalize—is a program written to correct reflectance data for systematic errors from surface scattering, sample area, and reference reflectance.

RNM corrects the reflectance data by dividing the data by the reflectance of a coated sample and then multiplying by a file representing the reflectance of the coating. It can also be used to correct for the non-unity reflectance of a reference mirror. More generally, RNM will multiply/divide any data files.

The data are scaled as follows:

$$R_{out} = \frac{R_{data}}{R_{coated}} \times R_{ref} \quad (73)$$

Here  $R_{data}$  = sample;  $R_{coated}$  = coated sample;  $R_{ref}$  = coating or reference mirror.

Switches: /h, /q, and

/A1 — ref is in RAL.DAT  
/Ag — ref is in RAG.DAT  
/N — No coated sample data  
/T — Transmission: no Ref file  
/R — Repeat RNM on additional data  
/Ci,j — data are in Cols i and j

Example:

RNM Mydata.mrg Mycoat.mrg Ral.dat Mydata.rnm

(Mydata.mrg / Mycoat.mrg) \* Ral.dat  $\Rightarrow$  Mydata.rnm

RNM /N Mydata.mrg Ral.dat

Mydata.mrg \* Ral.dat  $\Rightarrow$  output; user prompted for file name.

RNM Mydata.mrg Myblank.mrg /T /q

(Mydata.mrg / Mycoat.mrg)  $\Rightarrow$  Mydata.rnm; /q makes output name equal to name of first data file.

## 14. T2A

T2A—Transmittance to Alpha—computes absorption coefficient from transmittance. It is intended to be used for thick samples, not thin films. Here “thick” means  $d \gg \lambda$ . ( $d$  is thickness and  $\lambda$  is the wavelength.) It can take into account the (single-bounce) reflectance either from a file or a value of the refractive index.

The absorption coefficient  $\alpha$  is calculated from the measured transmittance  $\mathcal{T}$  by inverting

$$\mathcal{T} = \frac{(1 - \mathcal{R}_{sb})^2 e^{-\alpha d}}{1 - \mathcal{R}_{sb}^2 e^{-2\alpha d}} \quad (74)$$

with  $d$  the thickness and  $\mathcal{R}_{sb}$  the single-bounce reflectance. This equation is quadratic in  $e^{\alpha d}$  with one positive root. The solution is

$$e^{\alpha d} = \frac{(1 - \mathcal{R}_{sb})^2}{\mathcal{T}} \left[ 1/2 + \sqrt{1/4 + \frac{\mathcal{R}_{sb}^2 \mathcal{T}^2}{(1 - \mathcal{R}_{sb})^4}} \right] \quad (75)$$

T2A can also calculate the extinction coefficient  $\kappa$ , related to  $\alpha$  by  $\alpha = 2\omega\kappa/c$ .

If you do not have data for  $\mathcal{R}_{sb}$ , give a value for the refractive index  $n$ . Then T2A will use  $\mathcal{R}_{sb} \approx [(n - 1)/(n + 1)]^2$ . The approximation is typically OK, because for a transparent sample,  $n \gg \kappa$ .

Switches: /h, /q, and

- /Tnnn or /Dnnn — Thickness is *nnn*
- /R<file> — Reflectance (single-bounce) is in <file>
- /Nnnn — approximate reflectance using refractive index *nnn*
- /K or /E — calculate  $\kappa$  (Extinction coefficient)
- /P or /PE — PE file
- /Ci,j — Data are in columns i and j

Example: T2A MYDATA /T0.12 /Rrefl.dat

## 15. T2Approx

T2Approx—Transmittance to Alpha—computes absorption coefficient from transmittance. It can take into account in an approximate way the reflectance either from a file or a value of the refractive index. It considers  $\mathcal{R}_{sb}$  in Eq. 74 to be small, so  $\mathcal{R}_{sb}^2$  is really small. Then the transmittance  $\mathcal{T}$  is  $\mathcal{T} \approx (1 - \mathcal{R}_{sb})^2 e^{-\alpha d}$  and  $e^{\alpha d} \approx (1 - \mathcal{R}_{sb})^2 / \mathcal{T}$

Switches: /h, /q, and

- /Tnnn or /Dnnn — Thickness is *nnn*
- /R<file> — Reflectance is in <file>
- /Nnnn — approximate reflectance using refractive index *nnn*
- /K or /E — calculate  $\kappa$  (Extinction coef)
- /P or /PE — PE file
- /Ci,j — Data are in columns i and j

Example: T2Approx MYDATA /T0.12 /Rrefl.dat

## 16. *TwoC (2c)*

2C—Two Component—is a program that makes a two-component decomposition of optical conductivity  $\sigma_1(\omega)$  into Drude and midinfrared components. The algorithm was invented by Danilo Romero.

You will be asked first for the file to output the MIR average and then for at least two data files. First is the lowest  $T$  conductivity, which is used as the first estimate of the MIR conductivity. The rest are the ones to be decomposed.

To average files, enter the file names on a single line.

You can provide a list of files instead of responding to the prompt. The LOF must have the same name as the MIR average file and extension ‘LOF.’

Switches: /h, /q, and

/Tnnn — Tolerance for convergence *nnn*.

/Wnnn — carry out Drude fits to frequency *nnn*.

A list of files would be in MYDATA.LOF, which might look like

f1006.s1

f1100A.s1, f1100B.s1 f1100C.s1

f1150A.s1 f1150B.sig

f1200.s1

2C will carry out four analyses, averaging A, B, and C in the second and data sets A and B in the third.

## 17. XRO

XRO—X-ray optics—calculates the reflectance, reflectance phase, thin-film transmittance, conductivity, dielectric function, and complex refractive index at X-ray wavelengths.

The scattering functions  $f_1$  and  $f_2$  for atomic constituents are those of Henke (1993)\*, with new KK transforms for  $f_1$ . The data are embedded in the `xro.exe` file; auxiliary files are not needed.

You will need to specify the formula, e. g., `YBa2Cu3O6.93`. Fractional subscripts are fine. Case matters: cobalt (Co) is not carbon monoxide (CO)! XRO does not do very complicated parsing of formulae, so a material with a formula of  $(\text{La}_{0.5}\text{Pr}_{0.5})_{0.67}\text{Ca}_{0.33}\text{MnO}_3$  would be reported as `La0.335Pr0.335Ca0.33MnO3`.

You will also need to specify either  $V$ , the volume per formula unit in cubic Angstroms, or the density, in grams/cc. Here,  $V$  is the volume of the formula unit, typically  $V_{\text{cell}}/Z$  as specified by the structural paper.  $Z$  is the number of formula units in the unit cell. For example, NaCl is fcc with a lattice constant of 5.64 Å. The unit cell volume is 179.4 Å<sup>3</sup> but  $Z = 4$ , so  $V = 44.8$  Å<sup>3</sup>. Note that density always works. You get the same xro data using the density of 2.165 g/cm<sup>3</sup> for NaCl or Na<sub>4</sub>Cl<sub>4</sub>. The volumes  $V$  would be 44.8 and 179.4, respectively.

Examples:

```
XRO YBa2Cu3O6.93 /v186
```

```
XRO silver /fAg /r10.49 /P
```

In the first, XRO calculates for YBCO, using a cell volume of 186 Å<sup>3</sup>. In the second the reflectance and the phase are computed for Ag, based on a density of 10.49 g/cm<sup>3</sup>. The output file is silver.XRP.

Switches:

<code>/F&lt;formula&gt;</code>	— Chemical formula
<code>/Vnnn</code>	— Volume/formula unit is <i>nnn</i>
<code>/Dnnn /Rnnn</code>	— Density is <i>nnn</i>
<code>/E</code>	— Energy in eV rather than cm <sup>-1</sup>
<code>/P</code>	— Write also the phase; 3 columns data
<code>/S1</code>	— Write conductivity, $\sigma_1(\omega)$
<code>/E1</code>	— Write dielectric const, $\epsilon_1(\omega)$
<code>/I</code>	— Write Index ( $n$ and $\kappa$ ) rather than $\mathcal{R}$ and (with \P) $\phi$
<code>/T</code>	— Write Transmittance, $\mathcal{T}$
<code>/Xnnn</code>	— For $\mathcal{T}$ : the thickness (in Å) is <i>nnn</i>
<code>/F</code>	— Write $f_1$ and $f_2$ (for the <i>first</i> atom in the formula)
<code>/q</code>	— Fewer questions

Switches may be introduced with ‘/’ or ‘-’, have optional spaces between them, and may be in upper or lower case.

---

\* B.L. Henke, E.M. Gullikson, and J.C Davis, “X-ray Interactions: Photoabsorption, Scattering, Transmission, and Reflection at E=50–30,000 eV, Z=1–92,” *Atomic Data and Nuclear Data Tables* **54**, 181–342 (1993).

You may enter the formula on command line, as in `XRO YBa2Cu3O6.93 ...` or using the `/F` switch. The output file is `<formula>.XRO`. If you enter a non-formula on the command line, that will be the name of the output file and you will need to use the `/F` switch or answer the prompt for the formula. (Be careful here! YBCO is shorthand for the 123 superconductor, but it also is yttrium boron carbon oxide. Lower case, e. g., `ybco`, is always safe.)

XRO calculates the dielectric function using the original atomic scattering factor data developed by Henke. Some information about this is at [http://henke.lbl.gov/optical\\_constants/](http://henke.lbl.gov/optical_constants/).\*

The dielectric function<sup>†</sup> is

$$\epsilon = 1 - \sum_j \frac{4\pi n_j e^2}{m\omega^2} (f_1^j - i f_2^j) \quad (76)$$

where the sum runs over atoms  $j$  at number density  $n_j$  and with complex scattering factor  $f^j$ . Note that this has the right limiting high-frequency behavior, because  $f_1^j \rightarrow Z^j$  (with  $Z^j$  here the atomic number)<sup>‡</sup> and  $f_2 \rightarrow 0$ , so that  $\epsilon \rightarrow 1 - \sum_j 4\pi n_j Z^j e^2 / m\omega^2$

The refractive index is  $N = \sqrt{\epsilon}$  and the reflectance is calculated from the usual equation, Eq. 57. The transmittance is calculated from Eqs. 59–64.

---

\* XRO uses the first version of the scattering data because it is sampled at identical photon energies for each atom; the newer version is not.

† Henke—and the website above—write an equation for the refractive index  $N = 1 - (nr_0\lambda^2/2\pi)(f_1 + i f_2)$  with  $r_0 = e^2/mc^2$  the classical radius of the electron and  $\lambda = 2\pi c/\omega$  the wavelength. This is clearly an expansion of  $N = \sqrt{\epsilon}$ .

‡ There is a small relativistic correction.

## C. Fitting routines and computational routines

These routines are for fitting data to models. The two most important are DFF and TFF. DFF fits optical conductivity data, single-bounce reflectance, dielectric function, etc. to a Drude-Lorentz model dielectric function. TFF fits to reflectance or transmittance data of multilayer thin films on a substrate.

See page 70 for the file format of the “parameter” file (\*.PAR) produced and used by these programs. (This is the preferred parameter format. The old \*.PRM format is usable if you only want Drude-Lorentz models. It is described on page 72)

This section also lists computational programs. For example, DLC uses the results of DFF to calculate a variety of optical functions, similar to OP for KK results. RDrude calculates reflectance within a Drude model.

### 1. DFF

DFF—Dielectric Function FIT—makes a nonlinear least-square fit to optical data. The data may be any of a number of functions. The formulas used are the same as used in OP, listed on pages 16–27.

1. Optical conductivity,  $\sigma_1$ , (Eq. 8).
2. Imaginary optical conductivity,  $\sigma_2$ , (Eq. 9).
3. Real dielectric function,  $\epsilon_1$ , (Eq. 11).
4. Imaginary dielectric function,  $\epsilon_2$ , (Eq. 12).
5. Refractive index,  $n$ , (Eq. 14).
6. Extinction coefficient,  $\kappa$ , (Eq. 15).
7. Absorption coefficient,  $\alpha$ , (Eq. 16).
8. Loss function,  $-\text{Im}(1/\epsilon)$ , (Eq. 19).
9. Reflectance,  $\mathcal{R}$ , (Eq. 57).
10.  $\mathcal{T}$  of a slab (thick) (Eq. 58).
11.  $\mathcal{T}$  of a slab (fringes) (Eq. 64).
12.  $\mathcal{R}$  of a slab (thick) (Eq. 65).
13.  $\mathcal{R}$  of a slab (fringes) (Eq. 72).

DFF can also be used to calculate these functions.

Several optical models are available, as discussed below. Most of the models calculate the complex dielectric function,

$$\epsilon(\omega) = \epsilon_1(\omega) + \frac{4\pi i}{\omega} \sigma_1(\omega) \quad (77)$$

where  $\epsilon_1$  is the real part and  $\epsilon_2 = 4\pi\sigma_1/\omega$  is the imaginary part. The functions in the above list all may be computed once  $\epsilon(\omega)$  is known.

#### a. High frequency value

The limiting high frequency value of the dielectric function should be unity, but the measurements rarely achieve this frequency, so DFF allows for an  $\epsilon_\infty$ . This is a purely real number, typically between 1 and 4 if data extend to the uv.

In the following formulas, I’ll include  $\epsilon_\infty$  in every formula, though it only comes in once, of course.

*b. Lorentz model*

The Lorentz model (or Drude-Lorentz) dielectric function is the dielectric function of a classical harmonic oscillator or of a lifetime broadened atomic transition.

$$\epsilon = \epsilon_{\infty} + \frac{\omega_p^2}{\omega_0^2 - \omega^2 - i\omega\gamma} \quad (78)$$

where  $\omega_p$  is the “plasma frequency,”  $\omega_0$  the resonant frequency, and  $\gamma$  the damping constant, equal to the inverse lifetime.

In solids, the Lorentzian is used for optically-active phonons (vibrational modes) and for interband transitions. It is a pretty good model for the former, but not so good for the latter as the widths of these transitions are governed by electronic band structure rather than damping.

There can of course be many\* such transitions, so one can write:

$$\epsilon = \epsilon_{\infty} + \sum_{k=1}^N \frac{\omega_{pk}^2}{\omega_k^2 - \omega^2 - i\omega\gamma_{ek}} + \sum_{j=1}^M \frac{\Omega_{pj}^2}{\omega_j^2 - \omega^2 - i\omega\Gamma_j} \quad (79)$$

Here, the electronic and vibrational oscillators are explicitly separated as a reminder that they represent different physics, although the functional forms are the same.

The optical conductivity of the Lorentz oscillator is

$$\sigma_1 = \frac{\omega_p^2 \omega^2 \gamma}{4\pi[(\omega_0^2 - \omega^2)^2 + \omega^2 \gamma^2]} \quad (80)$$

The parameters are entered in the sequence  $\omega_p$ ,  $\omega_0$ , and  $\gamma$ .

*c. Drude model*

If the resonant frequency in the Lorentz model is put to zero, one has the Drude dielectric function:

$$\epsilon = \epsilon_{\infty} - \frac{\omega_{pD}^2}{\omega^2 + i\omega\gamma} \quad (81)$$

where now  $\omega_{pD} = \sqrt{4\pi ne^2/m}$  is the Drude plasma frequency and  $\gamma = 1/\tau$  with  $\tau$  the mean free time between collisions.<sup>†</sup> With these definitions, the optical conductivity becomes

$$\sigma_1 = \frac{ne^2\tau/m}{1 + \omega^2\tau^2} \quad (82)$$

DFF uses the same formulas for Drude and Lorentz models. In the case of the former, you set the middle parameter ( $\omega_0$ ) to zero. DFF is smart enough to leave that at zero and not to adjust during the least squares optimization.

---

\* Up to  $N + M = 666$ .

<sup>†</sup> With frequencies, including  $\gamma$ , in  $\text{cm}^{-1}$ ,  $\tau$  would be in cm. To convert to sec, you divide by  $2\pi c$ . The factor of  $2\pi$  is *required*. It accounts for the fact that frequencies go from  $\text{cm}^{-1}$  to radians/sec by multiplying by  $2\pi c$ .



*d. Rice EMV model*

This model considers a set of phonons interacting with an electronic continuum. The  $N$  phonons are described by a set of coupling constants  $\lambda_k$ , resonant frequencies  $\omega_k$ , and damping  $\Gamma_k$ . The phonons appear in a “phonon propagator”  $D_0$ :

$$D_0 = \sum_{k=1}^N \frac{\lambda_k \omega_k^2}{\omega_k^2 - \omega^2 - i\omega\Gamma_k} \quad (83)$$

which then enters a Lorentz dielectric function as:

$$\epsilon = \epsilon_\infty + \frac{\omega_p^2}{\omega_0^2(1 - D_0) - \omega^2 - i\omega\gamma} \quad (84)$$

The EMV parameters are entered as  $\lambda_k$ ,  $\omega_k$ , and  $\Gamma_k$ . In addition, there must be at least one Lorentz oscillator, with parameters  $\omega_p$ ,  $\omega_0$ , and  $\gamma$ . DFF will use the *first* Lorentz oscillator in the list as the one coupled to the phonons.

*e. Product dielectric function*

If one factors Eq. 78, puts it on a common denominator, and makes a few notation changes, the dielectric function can be written

$$\epsilon = \epsilon_\infty \frac{\omega_L^2 - \omega^2 - i\omega\gamma_L}{\omega_T^2 - \omega^2 - i\omega\gamma_T}, \quad (85)$$

where  $\omega_T = \omega_0$  is the transverse optical frequency (a pole in the response function),  $\omega_L = \sqrt{\omega_p^2/\epsilon_\infty + \omega_0^2}$  is the longitudinal optical frequency (a zero in the response function), and the two damping values  $\gamma_T$  and  $\gamma_L$  are both equal to  $\gamma$ , but here are written as different quantities, to give 4 parameters to the oscillator.

Of course there could be many\* oscillators, so DFF uses a product form:

$$\epsilon = \epsilon_\infty \prod_{j=1}^N \frac{\omega_{Lj}^2 - \omega^2 - i\omega\gamma_{Lj}}{\omega_{Tj}^2 - \omega^2 - i\omega\gamma_{Tj}}. \quad (86)$$

The parameters are entered in the order  $\omega_{Lj}$ ,  $\gamma_{Lj}$ ,  $\omega_{Tj}$ ,  $\gamma_{Tj}$ .

The imaginary part of Eq. 85 is

$$\epsilon_2 = \omega\epsilon_\infty \left[ \frac{\omega_L^2\gamma_T - \omega_T^2\gamma_L + \omega^2(\gamma_L - \gamma_T)}{(\omega_T^2 - \omega^2)^2 + \omega^2\gamma_T^2} \right]. \quad (87)$$

Now,  $\epsilon_2$  cannot be negative, so we require

$$\gamma_T \leq \gamma_L \leq \gamma_T \frac{\omega_L^2}{\omega_T^2} \quad (88)$$

and

$$\omega_L \geq \omega_T. \quad (89)$$

DFF enforces obedience to Eqs. 88 and 89.

\* Up to  $N = 499$ .

*f. Indirect bandgap ( $\sim$  Tauc Lorentz)*

If you look at Eq. 80 you will see that the conductivity (and hence the absorption) falls as  $\omega^2$  for frequencies well below the resonance (so long as  $\gamma$  is not too big). Actual solids have a much more rapid decrease near their gaps, with the optical penetration length changing from kilometers to micrometers over a few thousand wavenumbers. DFF addresses this by using a modified Tauc-Lorentz dielectric function.\* One knows that the absorption for an indirect bandgap semiconductor (or in some cases amorphous semiconductors) just above the gap follows:

$$\alpha(\omega) \sim (\omega - \omega_g)^2, \quad (90)$$

where  $\omega_g$  is the indirect bandgap.

This behavior must stop eventually to maintain finite oscillator strength; experimentally the absorption has a maximum at a frequency somewhere above the gap and falls above this maximum. The Tauc-Lorentz model was written to account for this behavior. The imaginary part of the dielectric function can be written:

$$\epsilon_2 = \begin{cases} 0 & \omega \leq \omega_g \\ C \left( \frac{\omega - \omega_g}{\omega} \right)^2 \frac{\omega_0^2 \omega \gamma}{(\omega_0^2 - \omega^2)^2 + \omega^2 \gamma^2} & \omega \geq \omega_g. \end{cases} \quad (91)$$

$\epsilon_2$  is zero up to  $\omega_g$  and has a maximum at  $\omega_0$ . In Tauc-Lorentz, there are four parameters,  $\omega_g$ ,  $\omega_0$ ,  $\gamma$ , and  $C$ . DFF removes one of these, making  $\omega_0 \simeq 1.45\omega_g$ . In addition, the coefficient  $C$  is adjusted so that

$$\int_0^\infty d\omega' \sigma_1(\omega') = \frac{\omega_p^2}{8} \quad (92)$$

(The oscillator strength in Eq. 91 is *not* independent of  $\gamma$  the way the Drude or Lorentz functions are.) Hence the adjustable parameters are the gap,  $\omega_g$ , the width,  $\gamma$ , and  $\omega_p$  representing the integrated oscillator strength.

The parameters are entered in the sequence  $\omega_p$ ,  $\omega_g$ , and  $\gamma$ .

*g. Direct bandgap*

DFF follows the same approach for a direct bandgap semiconductor, using a modified Tauc-Lorentz dielectric function. One knows that the absorption for a direct bandgap semiconductor just above the gap follows:

$$\alpha(\omega) \sim (\omega - \omega_g)^{1/2}, \quad (93)$$

where  $\omega_g$  is the direct bandgap.

---

\* See also the next subsection for the function for the case of a direct bandgap.

This behavior must also stop eventually to maintain finite oscillator strength; experimentally the absorption has a maximum at a frequency above gap and falls above this maximum. The imaginary part of the direct bandgap dielectric function is written:

$$\epsilon_2 = \begin{cases} 0 & \omega \leq \omega_g \\ C \left( \frac{\omega - \omega_g}{\omega} \right)^{1/2} \frac{\omega_0^2 \omega \gamma}{(\omega_0^2 - \omega^2)^2 + \omega^2 \gamma^2} & \omega \geq \omega_g. \end{cases} \quad (94)$$

$\epsilon_2$  is zero up to  $\omega_g$  and has a maximum at  $\omega_0$ . DFF sets  $\omega_0 \simeq 1.225\omega_g$ . In addition, the coefficient  $C$  is adjusted so that

$$\int_0^\infty d\omega' \sigma_1(\omega') = \frac{\omega_p^2}{8} \quad (95)$$

(The oscillator strength in Eq. 94 is *not* independent of  $\gamma$  the way the Drude or Lorentz functions are.) Hence the adjustable parameters are the gap,  $\omega_g$ , the width,  $\gamma$ , and  $\omega_p$  representing the integrated oscillator strength.

The parameters are entered in the sequence  $\omega_p$ ,  $\omega_g$ , and  $\gamma$ .

#### *h. Marginal Fermi liquid*

The MFL dielectric function is given in Eq. 29.

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega[\omega - \Sigma(\omega)]}. \quad (96)$$

where  $\omega_p$  is a “bare” plasma frequency and  $\Sigma(\omega)$  is the quasiparticle self-energy. The MFL theory has the imaginary part of the self-energy linear in  $\omega$  up to a cutoff frequency; above this frequency it is taken as constant. Hence, below the cutoff,

$$\Sigma = 2\lambda\omega \ln \left( \frac{2\pi T - i\omega}{\omega_c} \right) - 2\pi^2 i\lambda T \quad (97)$$

Above the cutoff, this becomes

$$\Sigma = 2\lambda\omega_c \ln \left( \frac{2\pi T - i\omega_c}{\omega_c} \right) - 2\pi^2 i\lambda T \quad (98)$$

The three parameters are entered as  $\omega_p$ ,  $\lambda$ , and  $\gamma$ . DFF also will need the temperature, in Kelvin.

#### *i. Fermi liquid*

The Fermi liquid dielectric function is

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega[\omega + i\gamma(\omega)]}. \quad (99)$$

where  $\omega_p$  is a “bare” plasma frequency and  $\gamma(\omega)$  is a frequency-dependent damping. The Fermi liquid theory has the imaginary part of the self-energy quadratic in  $\omega$ . This would

continue up to a cutoff frequency of order the Fermi energy. Here, this is assumed to be above the highest measured frequency.

$$\gamma = \gamma_0 + \left( \frac{\omega}{\omega_{FL}} \right)^2. \quad (100)$$

The three parameters are entered as  $\omega_p$ ,  $\gamma_0$ , and  $\omega_{FL}$ .

Note that the model is incomplete in two ways. First, the cutoff ought to be in the parameter set. Second, and more serious, Kramers-Kronig requires the frequency-dependent damping to be a complex function. Alternatively, the mass component of  $\omega_p$  should also be frequency dependent.

*j. Kivelson-Emery model*

This model is based on phase separation (stripes), driven by the lower energy of a spin singlet but frustrated by long-range coulomb interaction. The theory gives the following expression for the optical conductivity:

$$\sigma_1 = e^2 A \frac{\chi_2(\omega, T)}{\omega} + (e^*)^2 \omega \chi_2(\omega, T) \quad (101)$$

where  $e^*$  is the charges of dipolar fluctuations ( $e$  is the charge of the mobile carriers),  $A$  is related to exchange, and  $\chi_2$  is

$$\chi_2 = c \tanh \left( \frac{\hbar \omega}{2kT} \right) \frac{\Gamma}{\Gamma^2 + \omega^2}, \quad (102)$$

where  $c$  is the concentration of dipolar fluctuations,  $T$  is the temperature, and  $\Gamma$  is the Kondo scale of the problem,  $\sim 0.1$  eV (1000 K).

You can only fit this model to the optical conductivity  $\sigma_1$ . The parameters are  $A$ ,  $e^*$ , and  $\Gamma$ . DFF also need to know the temperature.

*k. DFF usage*

DFF will prompt you for the parameters needed, in groups of three or four. For the Lorentz (and Drude) models these are  $\omega_p$ ,  $\omega_0$ , and  $\gamma$ . Unless you are doing optical conductivity, you will also be asked to specify  $\epsilon_\infty$ .

You first provide the parameters (or a file containing them) and are given a chance to change them. This “eyeball fitting” phase of the program can be looped as many times as you wish, producing a plot of the adjusted response function each time. You may also write the parameter file and the calculated function to disk.

During the eyeball fit part, the program replots the fitted calculation after *each* set of 3 parameters is entered, i. e., for one oscillator, makes a plot of the result, and then asks about this oscillator immediately again. This allows you to modify the strength, center frequency, and linewidth for each oscillator until you are happy with it. A <cr> moves you to the next oscillator in turn, and so on, and finally to  $\epsilon_\infty$ .

Answering L to the prompt about what to do (E, L, or Q) causes the program to carry out least square adjustment of parameters you specify. You are asked about the mode of the fit, the maximum number of times to loop through the  $\chi^2$  minimization process, and the criterion for stopping the fit. Then you are given a chance to “fix” or “free” the parameters. The parameters for each oscillator are presented, and you enter “0” to fix them; “1” to free them up. (In the list where they are presented, parameters that are fixed are shown in parentheses. If you want no change, you can enter a “/” or “<cr>”.)

Switches: /h, /q, and

/S	— data are $\sigma_1(\omega)$	/S2	— data are $\sigma_2$
/E	— data are $\epsilon_1(\omega)$	/E2	— data are $\epsilon_2$
/R	— data are Reflectance	/RPH	— in KK file
/L	— data are Loss function		
/A	— data are Absorption coefficient		
/N	— data are refractive index	/K	— extinction coeff.
/TI	— Slab $\mathcal{T}$ (incoherent)	/TC	— Slab $\mathcal{T}$ (coherent)
/RI	— Slab $\mathcal{R}$ (incoherent)	/RC	— Slab $\mathcal{R}$ (coherent)
/TEnnn	— Temperature is <i>nnn</i> , in Kelvin		
/Dnnn	— Thickness is <i>nnn</i> in Angstrom units		
/Pnnn, <i>nnn</i>	— partial fit, to data between the two frequencies given		
/ST	— Read Std dev file		
/PRM	— Use old “.PRM” parameter file		
/Z	— Do not ask about fix/free parameters		
/Mn	— Mode: 1 = std dev; 0 = none; -1 = 1/data		
/Fn	— Fraction of parameter used for initial step		
/Innn	— maximum number of Iterations in least square fit		
/Tnnn	— <i>nnn</i> is Tolerance ( $\chi^2$ has to decrease by at least <tol> to continue least square fits)		
/Ci,j	— Data in Columns i, j.		

“Mode” specifies the way in which  $\chi^2$  is calculated. ( $\chi^2$  is what the program minimizes.) If <mode> = 1, the actual standard deviation of the data is used; you will be prompted for a file containing the standard deviations. If <mode> = 0 each data point is assumed to have the same standard deviation. If <mode> = -1, the standard deviation is set to 1/data.

DFF uses the GRIDLS routine from the book by Bevington.

Example:

```
DFF F1A006.S1 /S F1A006.PRM /T.001 /I25 /P120,990
```

Fit file F1A006.S1, which is  $\sigma_1(\omega)$ , using F1A006.PRM over 120–990  $\text{cm}^{-1}$ . <tol> = .001; <max iterations> = 25

## 2. TFF

TFF—Thin Film Fit—fits reflectance,  $\mathcal{R}$ , or transmittance,  $\mathcal{T}$ , for thin film multilayers to the Drude-Lorentz model. It can also be used to calculate these functions.

The program uses the same models as described in DFF, on pages 35–40. TFF will prompt you for the parameters needed. For Drude-Lorentz models, it needs groups of three:  $\omega_p$ ,  $\omega_0$ , and  $\gamma$ . You will also need to specify  $\epsilon_\infty$  and the thickness.

You first provide the parameters (or a file containing them) for each layer, and are given a chance to change them. This “eyeball fitting” phase of the program can be looped as many times as you wish: the program replots the fitted calculation after *each* set of parameters is entered, starting with  $\epsilon_\infty$  and thickness, and then oscillators. TFF makes a plot of the result, and then asks about this oscillator immediately again. This allows you to modify the strength, center frequency, and linewidth for each oscillator until you are happy with it. A `<cr>` moves you to the next oscillator in turn, and so on. You may also write the parameter file and the calculated function to disk.

Answering L to the prompt about what to do (E, L, or Q) causes the program to carry out least square adjustment of parameters you specify. You are asked about the mode of the fit, the maximum number of times to loop through the  $\chi^2$  minimization process, and the criterion for stopping the fit. Then you are given a chance to “fix” or “free” the parameters. The parameters for each oscillator are presented layer by layer, and you enter “0” to fix them; “1” to free them up. (In the list where they are presented, parameters that are fixed are shown in parentheses. If you want no change, you can enter a “/” or “<cr>”.)

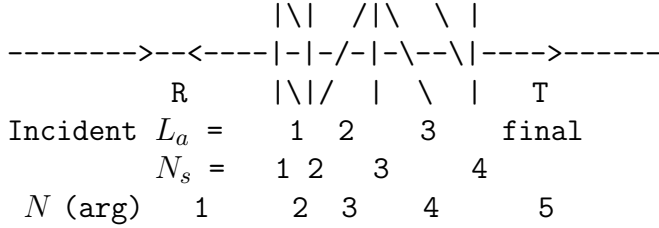
Switches: /h, /q, and

/R	— data are Reflectance	/RPH	— in KK file
/K	— backSide Reflectance		
/T	— data are Transmittance		
/Ln	— $n$ Layers in sample		
/S [/Sn]	— Substrate is thick [not thick]’ /B [/Bn]	---	Back of substrate [not] s
/D	— there is an .RPH file for the substrate		
/Mn	— Mode: 1 = std dev; 0 = none; -1 = 1/data		
/Fn	— Fraction of parameter used for initial step		
/Innn	— maximum number of Iterations in least square fit		
/Onnn	— $nnn$ is tOlerance ( $\chi^2$ has to decrease by at least <tol> to continue least square fits)		
/Xnnn,mmm	— $x$ -axis plot range = $nnn$ – $mmm$		
/Xmmm	— $x$ -axis plot range = 0– $mmm$		
/Ynnn,mmm	— $y$ -axis plot range		
/XL, /y1 ...	— do axis on Log scale		
/Ci,j	— Data in Columns $i, j$		

“Mode” specifies the way in which  $\chi^2$  is calculated. ( $\chi^2$  is what the program minimizes.) If `<mode> = 1`, the actual standard deviation of the data is used; you will be prompted for a file containing the standard deviations. If `<mode> = 0` each data point is assumed to have the same standard deviation. If `<mode> = -1`, the standard deviation is set to 1/data.

Note: The film thicknesses is passed in Angstrom units (even for the thick substrates) to avoid format problems in the I/O routines of TFF. Note further that all parameters except  $eps_\infty$  and the thickness are in units of  $\text{cm}^{-1}$ .

Note 2: The program asks about each layer in sequence, beginning from the top and ending with the substrate (or bottom layer. If there are  $L_a$  layers, then  $N_s = 1 + L_a$  is the number of interfaces. Moreover, there are  $2 + L_a$  distinct media, because the first and last extend to  $\infty$ . Here is a picture:



Note 3: REFTR2, the subroutine for the thin film transmission, does NOT account for any differences between incident and final medium. If these have different refractive indices, then  $\mathcal{T}$  must be multiplied by  $\text{Real}(n(La^{\text{max}})/n(1))$ .

TFF uses a modification of the GRIDLS routine from the book by Bevington.

Examples:

TFF F1A006.DAT F1A006.PRM

Fit file F1A006.DAT, using F1A006.PRM as the parameter file.

TFF F1A006.DAT /T.001 /I25

Fit file F1A006.DAT,  $\langle \text{tol} \rangle = .001$ ;  $\langle \text{max iterations} \rangle = 25$

### 3. DFC

DFC—Dielectric Function Calculate—calculates a variety of optical functions, such as optical conductivity ( $\sigma_1$ ), dielectric constant ( $\epsilon_1$ ), and many more quantities. It also can calculate the function for each component of the model, where that is appropriate. It calculates (from models) all of the optical functions that OP calculates from KK results. See pages 16–27 for the equations governing these functions.

The program uses a number of models (Drude-Lorentz, interband, marginal Fermi liquid, etc.) for the complex dielectric function. The models are described on pages 35–40.

DFC gets its parameters from a \*.PAR file produced by DFF or TFF (or the oldstyle \*.PRM file produced by DLFIT/FLMFIT). It will either ask you for the frequencies at which to do the calculation or use the frequencies in a data file you specify.

Switches: /h, /q, and

/IN	— Do the INdividual components	
/Vnnn	— unit cell Volume is nnn	
/Wpnnn	— plasma frequency is nnn	
/RPHin	— Frequencies come from KK file	
/Xnnn,mmm	— $x$ -axis plot range = nnn–mmm	
/Xmmm	— $x$ -axis plot range = 0–mmm	
/Ynnn,mmm	— $y$ -axis plot range	
/XL, /yl ...	— do axis on Log scale	/XR — linear scale
/Ci,j	— Data in Columns i, j	

The unit cell volume is used for sum rules; the plasma frequency for self-energy and effective mass. *Note:* In calculating the ‘components’,  $\epsilon_\infty = 1.0$  except for  $\epsilon_1(\omega)$  itself where  $\epsilon_\infty = 0$ .

Response function switches:

/S1 or /S	— $\sigma_1$	/S2	— $\sigma_2$
/E1 or /E	— $\epsilon_1$	/E2	— $\epsilon_2$
/N	— refractive index, $n$	/K	— extinction coefficient, $\kappa$
/A	— Absorption coefficient, $\alpha$		
/R	— Reflectance, $\mathcal{R}$		
/L	— Loss function, $-\text{Im } 1/\epsilon$		
/M	— effective Mass, $m^*/m$		
/T	— $1/\tau(\omega)$		
/I	— $-\text{Imag}(\text{self-energy}), -\Sigma_2$	/RE	— $\text{REal}(\text{self-energy}), \Sigma_1$
/SU	— SUM rule on $\sigma_1(\omega), N_{\text{eff}}$	/SL	— Sum r. Loss function
/Wps	— superfluid plasma frequency, $\omega_{ps}$		
/LL	— London Length, $\lambda_L$		
/SK	— SKin depth, $\delta$		
/F	— Free carrier: $\epsilon_1$ vs $1/\omega^2$		
/D	— Drude model: $1/\sigma_1$ vs $\omega^2$		
/RPHout, /3	— Refl and phase; write *.RPH file		

Example:



DFC F1A006.S1 /S F1A006.PRM

Calculate  $\sigma_1(\omega)$ , using F1A006.PRM at the frequencies in F1A006.S1.

Produce F1A006.DLC, F1A006.DRU, F1A006.L1, etc.

#### 4. EMA

This program uses the Bruggeman Effective Medium Approximation to calculate the dielectric function, conductivity, reflectance, refractive index, absorption coefficient, loss function, and other quantities for a 2-component mixture. The program uses a Drude-Lorentz model for the complex dielectric function for each component.

Examples:

EMA met.prm ins.prm

Calculate ema using met.prm ins.prm

EMA F1A006.S1

Calculate fit to F1A006.S1; parameter file names will be requested by the program.

Switches: /h, /q, and

/Xnnn,mmm (/Y)	— x(y) range = nnn-mmm
/NPnnn	— NP points
/XR(/Yr) [/XL..]	— Do axis on rectilinear [log] scale
/Ci,j	— Data are in columns i and j
/RPHin (/RPHout/3)	— Read (write) 3 col *.rph file
/Fnnn	— Fill fraction is <i>nnn</i>
/Dnnn	— Depolarization factor is <i>nnn</i>
/Vnnn	— Unit cell volume is <i>nnn</i>
/Wpnnn	— Plasma frequency is <i>nnn</i>

Response function:

/S1 or /S	— $\sigma_1$	/S2	— $\sigma_2$
/E1 or /E	— $\epsilon_1$	/E2	— $\epsilon_2$
/R	— Reflectance		
/RPH or /3	— Reflectance and phase		
/N	— Refr Index	/K	— Extinction coeff.
/A	— Absorption coeff.	/L	— Loss function
/I	— Imag(self-energy)	/RE	— Real(self-energy)
/G or /G1	— $\Gamma_1(\omega)$	/G2	— $\Gamma_2$
/M	— Effective mass $m^*/m$	/T	— $1/\tau(\omega)$
/SU	— Sum rule: $\sigma_1(\omega)$	/SL	— Loss function
/Wps	— Superfl. plasma freq.	/LL	— London length
/SK	— Skin depth		
/ E	— Abs( $\epsilon$ )	/ S	— Abs( $\sigma$ )
/TAN	— Tan( $\delta$ )	/ TAN	— Abs(Tan $\delta$ )

## 5. *PFIT*

PFit—Power series fit—fits data to a power series.

The data are fitted to a polynomial in  $x$ . Pfit outputs 4000 points (an arbitrarily chosen number) from the fitted curve over the data range.

Switches (must be passed on the command line): `/h`, `/q`, and

<code>/O</code>	— Order of polynomial to fit, eg, <code>/O3==cubic</code> .
<code>/Z</code>	— (Almost) suppress zero offset of x data.
<code>/L</code>	— Fit $\log(x)$ vs. $\log(y)$ , for power law fit. (Order is 1.)
<code>/OM</code>	— Omit duplicate data points in input file.
<code>/Xnnn,mmm</code> or <code>/xmmm</code>	— Compute over x range $nnn-mmm$ or $0-mmm$ .
<code>/Ci,j</code>	— data are in Cols i and j

Default polynomial order: 2 (quadratic, with intercept:  $y = a_0 + b_0x + c_0x^2$  ).

Maximum polynomial order: 8 (octal, with intercept).

To omit the intercept, put *two* 0,0 entries at start of file.

The zero suppress option moves the data array until the first data point is almost at  $x = 0$ . (It is at  $x = x(2) - x(1)$ .) This option does not work if you use the two 0,0 entries to omit the intercept. It is also switched off if  $x(1) = 0$ .)

Example:

```
PFit osc.str osc.fit /col3,1 /o3
```

Here, `osc.str` is the input file and `osc.fit` is the output.

## 6. *RDrude*

Calculate the reflectance for Drude model.

Switches: /h and

/Fnnn,nnn	— Frequency range <i>nnn</i> to <i>mmm</i>
/Dnnn	— Frequency interval is <i>nnn</i>
/Cnnn	— DC Conductivity is <i>nnn</i>
/Pnnn	— Plasma Frequency is <i>nnn</i>
/Ennn	— Epsilon_infinity is <i>nnn</i>

## 7. TCalc

TCalc calculates optical data. It can compute the dielectric function, conductivity, bulk reflectance, and several other quantities. It does this at 2 or more temperatures, making assumptions about  $\gamma(T)$ .

The program uses a Drude-Lorentz model for the complex dielectric function.

Switches: /h, /q, and

/Xnnn,mmm	— $x$ -axis plot range = nnn–mmm	
/Xmmm	— $x$ -axis plot range = 0–mmm	
/Ynnn,mmm	— $y$ -axis plot range	
/XL, /yl ...	— do axis on Log scale	/XR — linear scale
/Vnnn	— unit cell Volume is nnn	
/Wpnnn	— plasma frequency is nnn	
/RPHin	— Frequencies come from KK file	

The unit cell volume is used for sum rules; the plasma frequency for self-energy and effective mass. *Note:* In calculating the ‘components’,  $\epsilon_\infty = 1.0$  except for  $\epsilon_1(\omega)$  itself where  $\epsilon_\infty = 0$ . This is an issue for quantities that are nonlinear functions of  $\epsilon(\omega)$ .

Response function switches:

/S1 or /S	— $\sigma_1$	/S2 — $\sigma_2$
/E1 or /E	— $\epsilon_1$	/E2 — $\epsilon_2$
/N	— refractive index, $n$	/K — extinction coefficient, $\kappa$
/A	— Absorption coefficient, $\alpha$	
/R	— Reflectance, $\mathcal{R}$	
/RPHout, /3	— Refl and phase; write *.RPH file	
/L	— Loss function, $-\text{Im } 1/\epsilon$	
/M	— effective Mass, $m^*/m$	
/T	— $1/\tau(\omega)$	
/I	— $-\text{Imag}(\text{self-energy}), -\Sigma_2$	/RE — $\text{REal}(\text{self-energy}), \Sigma_1$
/SU	— SUM rule on $\sigma_1(\omega), N_{\text{eff}}$	/SL — Sum r. Loss function
/Wps	— superfluid plasma frequency, $\omega_{ps}$	
/LL	— London Length, $\lambda_L$	
/SK	— SKin depth, $\delta$	
/F	— Free carrier: $\epsilon_1$ vs $1/\omega^2$	
/D	— Drude model: $1/\sigma_1$ vs $\omega^2$	

## D. Spectral analysis

These spectral analysis programs do Fourier transforms. There are some test programs included.

### 1. *FFT*

FFT calculates Fourier transforms of a time series.

FFT calculates the transform of the input data, extended to a power of two. It has only two apodization/truncation functions: rectangle (boxcar) and Hamming. It will do up to 4,194,304 points (at 0 zerofill).

Switches: /h, /q, and

/A<char>	— Window (apodization) function.
/AB or /AR	→ Boxcar == Rectangle.
/AH	→ Hamming window (default!).
/Z#	— Zerofill factor (default 1 → none).
/Dnnn	— Sampling interval is <i>nnn</i> sec (for 1 col data).
/Fnnn	— Sampling rate is <i>nnn</i> Hz (for 1 col data).
/P	— Compute Power spectrum.
/aph or /ph	— write amplitude and phase.
/Ci,j	— Data in Columns i, j.

Examples:

FFT s114.bru s114.ftr /c1,2

s114.bru is the input file and s114.ftr is the output.

/c1,2 → data are in columns 1 and 2.

## 2. *FTgram*

**FTGram** calculates Fourier transforms of subsets of a time series. It will do up to 4,194,304 points (at 0 zerofill). It produces many subspectra at (of course) lower resolution than if the entire time series is used. It also produces a list of maxima in the subspectra as ‘Time,’ ‘Peak frequency,’ and ‘N sigma height.’

Switches: /h, /q, and

/U#	— number of sUbspectra. [Should be odd!]
/V#	— degree of oVerlap in time series (default 1).
/S#	— peaks are # Sigma (default 8).
/A<char>	— Window (apodization) function.
/AB or /AR	→ Boxcar == Rectangle.
/AH	→ Hamming window (default!).
/Z#	— Zerofill factor (default 2).
/Dnnn	— Sampling interval is <i>nnn</i> sec (for 1 col data).
/Fnnn	— Sampling rate is <i>nnn</i> Hz (for 1 col data).
/P	— Compute Power spectrum.
/N, /NS, /NOS	— Don’t write spectra.
/NP, /NOP	— Don’t write frequencies of peaks.
/Ci,j	— Data in Columns i, j.

### **3. IFFT**

IFFT program calculates the inverse Fourier transform of a data set. It will do up to 4,194,304 points (at 0 zerofill).

Switches: /h, /q, and

/A<char> — Window (apodization) function.  
/AB or /AR → Boxcar == Rectangle.  
/AH → Hamming window (default!).  
/Z# — Zerofill factor (default 2).

Example:

IFFT s114.ftr s114.tr /c1,2

s114.ftr is the input file and s114.ttr is the output.

/c1,2 → data are in columns 1 and 2.



#### 4. *Bits*

Bits simulates  $N$  bits data resolution. It scales floating-point data to a range of (say)  $-8$ – $+7$ , converts the floating point data to an integer, and then converts back, rescaling the data into (approximately) the same range of values it had before being quantized. Note that one bit is reserved for the sign, so the range  $-8$ – $+7$  (16 distinct values) represents 4-bit data.

The program underfills the window to avoid clipping, with the result that the area under the rms value of the bit-reduced data is smaller than in the original data.

Switches: `/h`, `/q`, `/v`, and

<code>/Nnn</code>	— $N$ -bit data
<code>/Xnnn,mmm</code>	— $x$ -axis plot range = $nnn$ – $mmm$
<code>/Xmmm</code>	— $x$ -axis plot range = $0$ – $mmm$
<code>/S</code>	— reScale $y$ data
<code>/Sx</code>	— reScale $x$ data

Example:

```
Bits Data.rnu /N8 /a2
```

Here, Bits reduces data.rnu to 8 bit ( $\pm 4$  range) data.

## 5. *Inject*

This program injects a sine wave into data. The program can also scale data. The default is to ask for scale factors for the Y-data, but command line switches modify this.

The first file name on command line is input; second is output.

Switches: /h, /q, /v and

/Fnn	— Frequency is <i>nn</i> Hz.
/Dnn	— Doppler chirps the frequency by <i>nn</i> /sec.
/Pnn	— Phase is <i>nn</i> .
/s<file>	— Stored phase in  file .
/Ann	— Amplitude is <i>nn</i> .
/Xnnn,mmm	— x-axis plot range = <i>nnn</i> – <i>mmm</i>
/Xmmm	— x-axis plot range = 0– <i>mmm</i>
/N	— No rescaling
/Sy	— reScale y data
/Sx	— reScale x data

Example:'

Inject Data.rnu /F12340 /a2

Here, Inject injects into data.rnu, at  $f = 12,340$  Hz.

The amplitude is 2.0.

## 6. *Pinkify*

Gaussian noise has desirable properties: well defined spectrum, bounded, stationary... Many noise sources are none of the above, such as for example  $1/f$  noise. Pink noise is white at high frequencies and  $1/f$  at low frequencies. Pinkify (used in conjunction with FFT and IFFT) will convert a time series made up of Gaussian noise to noise with a pink spectrum. To do this you have to generate the Gaussian time series, Fourier transform to get a frequency spectrum, convert to pink noise with Pinkify, inject any signals you want to inject, and then compute the inverse Fourier transform. The result is a time series with pink noise. Note that the phase is unchanged by Pinkify.

In sum: Ranu  $\rightarrow$  FFT to amplitude  $\rightarrow$  Pinkify, as

$$Y(f) = Y(f) * [1 + (\frac{f_0}{f})^a],$$

(phase unchanged)  $\rightarrow$  IFFT to time series.

Switches: /h, /q, /v and

/fnnn —  $1/f$  below frequency nnnn

/aα —  $\alpha$  in  $1/f^\alpha$

## 7. *Ranu*

This program generates a N-point series of random numbers. The maximum number of output points is 4,200,000. The numbers are Gaussian. The default average = 0 and default standard deviation 1.

Ranu simulates a noisy time series, and you can specify the (equally spaced) sampling rate for the time with the /f option. The default is 100 kHz (10  $\mu$ sec).

Switches: /h, /q, /v, \ci,j and

/Nnnn	— Number of points is <i>nnn</i>
/Fnnn	— Sample Frequency is <i>nnn</i>
/Annn	— Make average <i>nnn</i>
/Snnn	— Make standard deviation <i>nnn</i>
/Rnnn	— Random seed is <i>nnn</i>
/Xnnn,mmm	— x-axis plot range = <i>nnn-mmm</i>
/Xmmm	— x-axis plot range = 0- <i>mmm</i>

Example:

```
RaNu Data.rnu /n10240 /f50000 /r123 /v /sx
```

Here, RaNu calculates 10240 points, at time intervals of 20 microseconds (1/50000) using 123 as the seed of the generator. User is asked for output file and for *A*, *B* for  $x \leftarrow A * x + B$ .

## E. Utilities

There are a number of small programs for converting among presentations of complex optical data, converting from wavenumber to wavelength, converting JCAMP/DX files, etc.. These are described in the following.

1. **RPH2E**
2. **RPH2NK**
3. **RPH2S**
4. **E2RPH**
5. **NK2RPH**
6. **S2RPH**
7. **L2RPH**

These programs all convert among presentations of complex optical data. For example, RPH2E gives  $\epsilon_1$  and  $\epsilon_2$  from Kramers-Kronig-determined reflectance and phase. Some programs can also subtract a model dielectric function from the data.

Here are the programs and what they do:

Program	Input file	Output file	Conversion
RPH2E	*.RPH	*.E12	$\omega, \mathcal{R}, \phi \rightarrow \omega, \epsilon_1, \epsilon_2$
RPH2NK	*.RPH	*.NK	$\omega, \mathcal{R}, \phi \rightarrow \omega, n, \kappa$
RPH2S	*.RPH	*.S12	$\omega, \mathcal{R}, \phi \rightarrow \omega, \sigma_1, \sigma_2$
E2RPH	*.E12	*.RPH	$\omega, \epsilon_1, \epsilon_2 \rightarrow \omega, \mathcal{R}, \phi$
NK2RPH	*.NK	*.RPH	$\omega, n, \kappa \rightarrow \omega, \mathcal{R}, \phi$
S2RPH	*.S12	*.RPH	$\omega, \sigma_1, \sigma_2 \rightarrow \omega, \mathcal{R}, \phi$
L2RPH	*.L12	*.RPH	$\omega, \text{Re}(1/\epsilon), \text{Im}(1/\epsilon) \rightarrow \omega, \mathcal{R}, \phi$

Switches: /h, /v, and

- /Wmnnn — calculate up to max frequency *nnn*
- /Ennn —  $\epsilon_\infty = nnn$  (default = 1.0)
- /P<file> — Partial dielectric function,  $\epsilon - \epsilon_{DL}$

Max frequency (/Wmnnn) can be used to limit file size.

The  $\epsilon_\infty$  switch (only in S2RPH) allows  $\sigma_2$  to be corrected for a high-frequency slope (equivalent to  $\epsilon_1(\omega) \rightarrow \epsilon_1(\omega) - 1.0 + \epsilon_\infty$ ) before converting to reflectance and phase.

The “Partial dielectric function” option allows you to subtract a Drude-Lorentz model from  $\langle \epsilon(\omega) \rangle$  before the calculation of optical function. It either uses parameters in a \*.PRM file from DFF or prompts for user responses. This “Partial” switch only exists in RPH2E and RPH2S. And, it only works with oldstyle \*.PRM parameter files. Use OP for more general subtraction.

Example:

RPH2E F1A006

Calculate  $\epsilon_1$  and  $\epsilon_2$  from file F1A006.RPH

## 8. *Deriv*

This program calculates the derivative of data in a file. It is a Windows “console” program.

Switches: /h, /q, /v and

/Ci,j — data are in Columns i and j.

/P or /PE — data are ‘PE’ Columns 1 and 3.

## 9. *E2E*

E2E (end to end) converts optical constants files from ascending to descending order. (or vice versa.) This also works for 3 column data.

Switches: /h, /q, and

/T or /3 — there are 3 Columns of

/Ci,j — data are in Columns i and j

Example:

E2E PY2.K PY2-R.K

Convert PY2.K to descending order.

## 10. *J2W*

J2W—Jcamp to Wavenumber—converts JCAMP-DX files produced by commercial IR machines to a table of wavenumber, data values. It works for Bruker, Nicolet, and a set of test files from the web.

Switches: /h, /q, and

/D — Write fixDate batch file. (Sets /Q also.)

Example:

J2W 27T.DX1 27T.JX1

Convert 27T.DX1 to wavenumber, data. Result in 27T.JX1

Note: The FixDate batch file, if run, sets the date of the converted file to that of the original JCAMP-DX file. It requires 4NT, and uses the internal “touch” function.

## 11. *PRM2PAR*

PRM2PAR converts oldstyle parameter files (.PRM) to newstyle (.PAR) format.

PRM2PAR can also generate a new \*.par file, for the Drude-Lorentz model. Use the /K switch, and PRM2PAR will prompt you for the parameters in groups of three:  $\omega_p$ ,  $\omega_0$  and  $\gamma$ . You will also need to specify  $\epsilon_\infty$ .

Examples:

rm2Par F1A006.PRM F1A006.PAR

Convert parameter file F1A006.PRM to F1A006.PAR’

Prm2PAR/q F1A006

Convert parameter file F1A006.PRM to F1A006.PAR’

## 12. **W2L**

W2L—Wavenumber to Lambda—is a program which converts an optical properties file between wavenumber and wavelength ( $\text{cm}^{-1} \leftrightarrow \text{nm}/\mu\text{m}$ ).

Switches: /h, /q, and

- /M or /U — Wavelength in microns.
- /V — Go from wavelength to wavenumber.
- /R — Input is in descending order (i.e., high to low).
- /SyA or /SyA,B — rescale data as  $y \leftarrow y \times A + B$ .
- /SxA or /SxA,B — rescale data as  $x \leftarrow x \times A + B$ .
- /3 or /T — Three-column data (like \*.RPH).
- /Ci,j — data are in Columns i and j.

Example:

W2L PY2.K PY2-L.K

Convert PY2.K to wavelength.

## 13. **XY2YX**

XY2YX is a program which exchanges columns in a 2 column data file.

Switches: /h, /q, /Ci,j, /PE.

Example:

XY2YX Latt.T temper.lat

Exchange data columns in Latt.T; output in temper.lat.

## 14. **Z2W**

Z2W—Zeiss to Wavenumber—is a program that converts an optical properties file from wavelength to wavenumber ( $\text{nm} \rightarrow \text{cm}^{-1}$ ) and—by default—percents to fractions. The program is designed for Zeiss MPM data. It also tidies up the header, removing unneeded lines and adding the standard “/\*” at the end.

Switches: /h, /q, and

- /N — Do not convert percents to fractions.

Example:

Z2W PY2.K PY2-L.K

Convert PY2.K to wavenumber.

## F. Obsolete and depreciated programs

The notes below describe programs that are no longer maintained. Most have been replaced with better ones, different enough to require a new name. See the list on page 2 for the replacements.

### 1. *DLFIT*

DLFIT—Drude-Lorentz FIT—makes a nonlinear least-square fit of optical conductivity ( $\sigma_1$ ), dielectric constant ( $\epsilon_1$ ), Reflectance ( $\mathcal{R}$ ), refractive index ( $n$ ), absorption coefficient ( $\alpha$ ) to the Drude-Lorentz model. It can also be used to calculate these functions.

The program uses a Drude-Lorentz model for the complex dielectric function. It will prompt you for the parameters needed, in groups of three:  $\omega_p$ ,  $\omega_0$ , and  $\gamma$ . Unless you are doing optical conductivity, you will also be asked to specify  $\epsilon_\infty$ .

You first provide the parameters (or a file containing them) and are given a chance to change them. This “eyeball fitting” phase of the program can be looped as many times as you wish, producing a plot of the adjusted response function each time. You may also write the parameter file and the calculated function to disk.

During the eyeball fit part, the program replots the fitted calculation after *each* set of 3 parameters is entered, i. e., for one oscillator, makes a plot of the result, and then asks about this oscillator immediately again. This allows you to modify the strength, center frequency, and linewidth for each oscillator until you are happy with it. A <cr> moves you to the next oscillator in turn, and so on, and finally to  $\epsilon_\infty$ .

Answering L to the prompt about what to do (E, L, or Q) causes the program to carry out least square adjustment of parameters you specify. You are asked about the mode of the fit, the maximum number of times to loop through the  $\chi^2$  minimization process, and the criterion for stopping the fit. Then you are given a chance to “fix” or “free” the parameters. The parameters for each oscillator are presented, and you enter “0” to fix them; “1” to free them up. (In the list where they are presented, parameters that are fixed are shown in parentheses. If you want no change, you can enter a “/” or “<cr>”.)

Switches: /h, /q, and

/S	— data are $\sigma_1(\omega)$	
/E	— data are $\epsilon_1(\omega)$	
/R	— data are Reflectance	/RPH — in KK file
/L	— data are Loss function	
/N	— data are refractive index	
/A	— data are Absorption coefficient	
/Pnnn,nnn	— fit to data between the two frequencies given	
/Mn	— Mode: 1 = std dev; 0 = none; -1 = 1/data	
/Fn	— Fraction of parameter used for initial step	
/Innn	— maximum number of Iterations in least square fit	
/Tnnn	— nnn is Tolerance ( $\chi^2$ has to decrease by at least <tol> to continue least square fits)	



“Mode” specifies the way in which  $\chi^2$  is calculated. ( $\chi^2$  is what the program minimizes.) If  $\langle \text{mode} \rangle = 1$ , the actual standard deviation of the data is used; you will be prompted for a file containing the standard deviations. If  $\langle \text{mode} \rangle = 0$  each data point is assumed to have the same standard deviation. If  $\langle \text{mode} \rangle = -1$ , the standard deviation is set to 1/data.

DLFIT uses the GRIDLS routine from the book by Bevington.

Example:

DLFIT F1A006.S1 /S F1A006.PRM /T.001 /I25 /P120,990

Fit file F1A006.S1, which is  $\sigma_1(\omega)$ , using F1A006.PRM over 120–990  $\text{cm}^{-1}$ .  $\langle \text{tol} \rangle = .001$ ;  $\langle \text{max iterations} \rangle = 25$

## 2. *ELPHIT*

ELPHIT—ELection-PHOnon fIT—makes a nonlinear least-square fit of optical conductivity ( $\sigma_1$ ), dielectric constant ( $\epsilon_1$ ), Reflectance ( $\mathcal{R}$ ), refractive index ( $n$ ), absorption coefficient ( $\alpha$ ) to the Drude-Lorentz model. It can also be used to calculate these functions.

The program uses the Rice model of coupling a set of phonons to electrons. It will prompt you for the parameters needed, in groups of three:  $\lambda_\alpha$ ,  $\omega_\alpha$  and  $\gamma_\alpha$ ;  $\omega_p$ ,  $\omega_0$  and  $\gamma$ ; also  $\epsilon_\infty$ .

You first provide the parameters (or a file containing them) and are given a chance to change them. This “eyeball fitting” phase of the program can be looped as many times as you wish; the program replots the fitted calculation after *each* set of 3 parameters is entered, i. e., for one oscillator, it makes a plot of the result, and then asks about this oscillator immediately again. This allows you to modify the strength, center frequency, and linewidth for each oscillator until you are happy with it. A  $\langle \text{cr} \rangle$  moves you to the next oscillator in turn, and so on, and finally to  $\epsilon_\infty$ .

Answering L to the prompt about what to do (E, L, or Q) causes the program to carry out least square adjustment of parameters you specify. You are asked about the mode of the fit, the maximum number of times to loop through the  $\chi^2$  minimization process, and the criterion for stopping the fit. Then you are given a chance to “fix” or “free” the parameters. The parameters for each oscillator are presented, and you enter “0” to fix them; “1” to free them up. (In the list where they are presented, parameters that are fixed are shown in parentheses. If you want no change, you can enter a “/” or “ $\langle \text{cr} \rangle$ ”.)

Switches: /h, /q, and

/S	— data are $\sigma_1(\omega)$		
/E	— data are $\epsilon_1(\omega)$	/E2	— data are $\epsilon_2(\omega)$
/R	— data are Reflectance	/RPH	— in KK file
/L	— data are Loss function		
/N	— data are refractive index		
/A	— data are Absorption coefficient		
/Pnnn,nnn	— fit to data between the two frequencies given		
/Mn	— Mode: 1 = std dev; 0 = none; -1 = 1/data		
/Fn	— Fraction of parameter used for initial step		
/Innn	— maximum number of Iterations in least square fit		

/Tnnn — nnn is Tolerance ( $\chi^2$  has to decrease by at least <tol> to continue least square fits)

“Mode” specifies the way in which  $\chi^2$  is calculated. ( $\chi^2$  is what the program minimizes.) If <mode> = 1, the actual standard deviation of the data is used; you will be prompted for a file containing the standard deviations. If <mode> = 0 each data point is assumed to have the same standard deviation. If <mode> = -1, the standard deviation is set to 1/data.

Example:

ELPHIT F1A006.S1 /S F1A006.PRM /T.001 /I25 /P120,990

Fit file F1A006.S1, which is  $\sigma_1(\omega)$ , using F1A006.PRM over 120–990  $\text{cm}^{-1}$ . <tol> = .001; <max iterations> = 25

### 3. **MFLFIT**

### 4. **TLFIT**

### 5. **KEFIT**

Similar programs are MFLFIT, TLFIT, and KEFIT, which respectively fit the marginal Fermi liquid formula, the product (coupled oscillator) model, and the Kivelson-Emery model.

### 6. **FLMFIT**

FLMFIT—FiLM FIT—fits reflectance,  $\mathcal{R}$ , or transmittance,  $\mathcal{T}$ , for thin film multilayers to the Drude-Lorentz model. It can also be used to calculate these functions.

The program uses a Drude-Lorentz model for the complex dielectric function of each layer in the film. It will prompt you for the parameters needed, in groups of three:  $\omega_p$ ,  $\omega_0$ , and  $\gamma$ . You will also need to specify  $\epsilon_\infty$  and the thickness.

You first provide the parameters (or a file containing them) for each layer, and are given a chance to change them. This “eyeball fitting” phase of the program can be looped as many times as you wish: the program replots the fitted calculation after *each* set of 3 parameters is entered, i. e., for one oscillator, makes a plot of the result, and then asks about this oscillator immediately again. This allows you to modify the strength, center frequency, and linewidth for each oscillator until you are happy with it. A <cr> moves you to the next oscillator in turn, and so on, and finally to  $\epsilon_\infty$ . You may also write the parameter file and the calculated function to disk.

Answering L to the prompt about what to do (E, L, or Q) causes the program to carry out least square adjustment of parameters you specify. You are asked about the mode of the fit, the maximum number of times to loop through the  $\chi^2$  minimization process, and the criterion for stopping the fit. Then you are given a chance to “fix” or “free” the parameters. The parameters for each oscillator are presented layer by layer, and you enter “0” to fix them; “1” to free them up. (In the list where they are presented, parameters that are fixed are shown in parentheses. If you want no change, you can enter a “/” or “<cr>”.)

Switches: /h, /q, and

/R	— data are Reflectance	/RPH	— in KK file
/T	— data are Transmittance		

/B	— Back of substrate seen in reflectance
/D	— there is an .RPH file for the substrate
/Mn	— Mode: 1 = std dev; 0 = none; -1 = 1/data
/Fn	— Fraction of parameter used for initial step
/Innn	— maximum number of Iterations in least square fit
/Onnn	— nnn is tOlerance ( $\chi^2$ has to decrease by at least <tol> to continue least square fits)
/Xnnn,mmm	— x-axis plot range = nnn–mmm
/Xmmm	— x-axis plot range = 0–mmm
/Ynnn,mmm	— y-axis plot range
/XL, /y1 ...	— do axis on Log scale

“Mode” specifies the way in which  $\chi^2$  is calculated. ( $\chi^2$  is what the program minimizes.) If <mode> = 1, the actual standard deviation of the data is used; you will be prompted for a file containing the standard deviations. If <mode> = 0 each data point is assumed to have the same standard deviation. If <mode> = -1, the standard deviation is set to 1/data.

Note: The film thicknesses is passed in Angstrom units (even for the thick substrates) to avoid format problems in the I/O routines of FLMMFit. Note further that all parameters except  $\epsilon_{ps\infty}$  and the thickness are in units of  $\text{cm}^{-1}$ .

Note 2: The program asks about each layer in sequence, beginning from the top and ending with the substrate (or bottom layer. If there are  $L_a$  layers, then  $N_s = 1 + L_a$  is the number of interfaces. Moreover, there are  $2 + L_a$  distinct media, because the first and last extend to  $\infty$ . Here is a picture:

```

          | \ |   / | \   \ |
----->--<----| - | - / - | - \ -- \ |----->-----
          R      | \ | /   |   \   |   T
Incident  $L_a$  =    1  2     3     final
           $N_s$  =    1 2     3     4
N (arg)    1     2 3     4     5

```

Note 3: REFTR2, the subroutine for the thin film transmission, does NOT account for any differences between incident and final medium. If these have different refractive indices, then  $\mathcal{T}$  must be multiplied by  $\text{Real}(n(L_{amax})/n(1))$ .

FLMMFit uses a modification of the GRIDLS routine from the book by Bevington.

Examples:

FLMMFIT F1A006.DAT F1A006.PRM

Fit file F1A006.DAT, using F1A006.PRM as the parameter file.

FLMMFIT F1A006.DAT /T.001 /I25

Fit file F1A006.DAT, <tol> = .001; <max iterations> = 25

## 7. RelFit

RelFit—Relative FIT—fits the relative reflectance,  $\mathcal{R}(x)/\mathcal{R}_0$ , or transmittance,  $\mathcal{T}(x)/\mathcal{T}_0$ , for thin film multilayers using the Drude-Lorentz model. Here  $x$  is some parameter (gate voltage, electrochemical potential, light illumination, perhaps temperature) which changes the reflectance or transmittance from the reference value  $\mathcal{R}_0$ . RelFit can also be used to calculate these functions.

The program takes one of the layers as the “active” layer, and adjusts the parameters for that layer to optimize the results for the relative response.

The program uses a Drude-Lorentz model for the complex dielectric function of each layer in the film. It needs you to supply the parameters, in groups of three:  $\omega_p$ ,  $\omega_0$ , and  $\gamma$ . You will also need to specify  $\epsilon_\infty$  and the thickness for each layer.

For the inactive layers and also for the active layer response that is used as the background, the parameters are input in a \*.prm file. The active layer parameters for the data, e.g.,  $\mathcal{R}(x)$ , can be input as a file or in response to prompts. This “eyeball fitting” phase of the program can be looped as many times as you wish: the program replots the fitted calculation after *each* set of 3 parameters is entered, i.e., for one oscillator, makes a plot of the result, and then asks about this oscillator immediately again. This allows you to modify the strength, center frequency, and linewidth for each oscillator until you are happy with it. A <cr> moves you to the next oscillator in turn, and so on, and finally to  $\epsilon_\infty$ . You may also write the parameter file and the calculated function to disk.

Answering L to the prompt about what to do (E, L, or Q) causes the program to carry out least square adjustment of parameters you specify. You are asked about the mode of the fit, the maximum number of times to loop through the  $\chi^2$  minimization process, and the criterion for stopping the fit. Then you are given a chance to “fix” or “free” the parameters. The parameters for each oscillator are presented layer by layer, and you enter “0” to fix them; “1” to free them up. (In the list where they are presented, parameters that are fixed are shown in parentheses. If you want no change, you can enter a “/” or “<cr>”.)

*Only the parameters for the “active” layer are adjusted!* Use `flmfit.exe` to optimize the parameters for the inactive layers and for the background conditions of the active layer.

Many experiments give  $\Delta\mathcal{T}/\mathcal{T}$  rather than  $\mathcal{T}(x)/\mathcal{T}_0$ . But  $\Delta\mathcal{T}/\mathcal{T} = (\mathcal{T}(x) - \mathcal{T}_0)/\mathcal{T}_0$  and this is the same as  $\Delta\mathcal{T}/\mathcal{T} = (\mathcal{T}(x)/\mathcal{T}_0) - 1$ . So compute (using `CMP.exe`)  $(\Delta\mathcal{T}/\mathcal{T}) + 1 = \mathcal{T}(x)/\mathcal{T}_0$ , and proceed.

Switches: /h, /q, and

/R	— data are Reflectance	/RPH	— in KK file
/T	— data are Transmittance		
/Annn	— Layer <i>nnn</i> is the active layer		
/B	— Back of substrate seen in reflectance		
/D	— there is an .RPH file for the substrate		
/Mn	— Mode: 1 = std dev; 0 = none; -1 = 1/data		
/Fn	— Fraction of parameter used for initial step		
/Innn	— maximum number of Iterations in least square fit		
/Onnn	— <i>nnn</i> is tOlerance ( $\chi^2$ has to decrease by at		

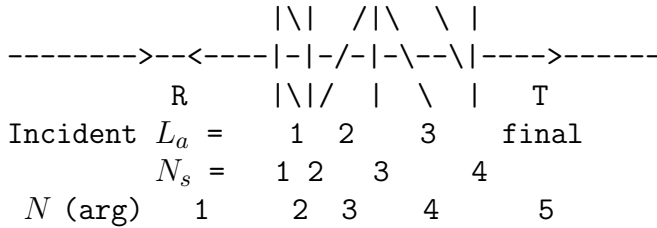
least <tol> to continue least square fits)

/Xnnn,mmm —  $x$ -axis plot range =  $nnn$ – $mmm$   
/Xmmm —  $x$ -axis plot range = 0– $mmm$   
/Ynnn,mmm —  $y$ -axis plot range  
/XL, /y1 ... — do axis on Log scale

“Mode” specifies the way in which  $\chi^2$  is calculated. ( $\chi^2$  is what the program minimizes.) If <mode> = 1, the actual standard deviation of the data is used; you will be prompted for a file containing the standard deviations. If <mode> = 0 each data point is assumed to have the same standard deviation. If <mode> = -1, the standard deviation is set to 1/data.

Note: The film thicknesses is passed in Angstrom units (even for the thick substrates) to avoid format problems in the I/O routines of RelFit. Note further that all parameters except  $\epsilon_{\infty}$  and the thickness are in units of  $\text{cm}^{-1}$ .

Note 2: The program asks about each layer in sequence, beginning from the top and ending with the substrate (or bottom layer. If there are  $L_a$  layers, then  $N_s = 1 + L_a$  is the number of interfaces. Moreover, there are  $2 + L_a$  distinct media, because the first and last extend to  $\infty$ . Here is a picture:



Note 3: REFTR2, the subroutine for the thin film transmission, does NOT account for any differences between incident and final medium. If these have different refractive indices, then  $\mathcal{T}$  must be multiplied by  $\text{Real}(n(L_{\text{amax}})/n(1))$ .

RELFIT uses a modification of the GRIDLS routine from the book by Bevington.

Examples:

RELFIT F1A006.DAT F1A006.PRM

Fit file F1A006.DAT, using F1A006.PRM as the parameter file.

RELFIT F1A006.DAT /T.001 /I25

Fit file F1A006.DAT, <tol> = .001; <max iterations> = 25

## 8. **THREEFIT**

## 9. **SAFIT**

Related programs are THREEFIT and SAFIT. ThreeFit displays transmission, reflection, and backside reflectance in three plots. The fits to all are shown, but the least-squares routine fits to the transmittance.

SAfit is a modification for fitting to a thin film on sapphire, taking into account the anisotropy of the substrate.

## 10. DL CALC

DL CALC—Drude-Lorentz CALC—calculates optical conductivity ( $\sigma$ ), dielectric constant ( $\epsilon$ ), Reflectance ( $\mathcal{R}$ ), refractive index ( $n$ ), absorption coefficient ( $\alpha$ ) and several other quantities. It also can calculate the function for each component of the model.

The program uses a Drude-Lorentz model for the complex dielectric function. It gets its parameters from a \*.PRM file produced by DLFIT or RelFit. It will either ask you for the frequencies at which to do the calculation or use the frequencies in a data file you specify.

Switches: /h, /q, and

/Xnnn,mmm	— $x$ -axis plot range = nnn–mmm	
/Xmmm	— $x$ -axis plot range = 0–mmm	
/Ynnn,mmm	— $y$ -axis plot range	
/XL, /yl ...	— do axis on Log scale	/XR — linear scale
/Vnnn	— unit cell Volume is nnn	
/Wpnnn	— plasma frequency is nnn	
/RPHin	— Frequencies come from KK file	

The unit cell volume is used for sum rules; the plasma frequency for self-energy and effective mass. *Note:* In calculating the ‘components’,  $\epsilon_\infty = 1.0$  except for  $\epsilon_1(\omega)$  itself where  $\epsilon_\infty = 0$ . This is an issue for quantities that are nonlinear functions of  $eps(\omega)$ .

Response function switches:

/S1 or /S	— $\sigma_1$	/S2 — $\sigma_2$
/E1 or /E	— $\epsilon_1$	/E2 — $\epsilon_2$
/N	— refractive index, $n$	/K — extinction coefficient, $\kappa$
/A	— Absorption coefficient, $\alpha$	
/R	— Reflectance, $\mathcal{R}$	
/RPHout, /3	— Refl and phase; write *.RPH file	
/L	— Loss function, $-\text{Im } 1/\epsilon$	
/M	— effective Mass, $m^*/m$	
/T	— $1/\tau(\omega)$	
/I	— $-\text{Imag}(\text{self-energy}), -\Sigma_2$	/RE — $\text{REal}(\text{self-energy}), \Sigma_1$
/SU	— SUM rule on $\sigma_1(\omega)$ , $N_{\text{eff}}$	/SL — Sum r. Loss function
/Wps	— superfluid plasma frequency, $\omega_{ps}$	
/LL	— London Length, $\lambda_L$	
/SK	— SKin depth, $\delta$	
/F	— Free carrier: $\epsilon_1$ vs $1/\omega^2$	
/D	— Drude model: $1/\sigma_1$ vs $\omega^2$	

Example:

```
DL CALC F1A006.S1 /S F1A006.PRM
```

Calculate  $\sigma_1(\omega)$ , using F1A006.PRM at the frequencies in F1A006.S1.

Produce F1A006.DLC, F1A006.DRU, F1A006.L1, etc.

## 11. PrmAve

This program averages parameter files from least-squares fitting of optical data.

## 12. *Reseq*

This program converts optical constants files from ascending to descending order. (or vice versa.) Use E2E.

Example:

RESEQ PY2.K PY2-R.K → Convert PY2.K to descending order.

## 13. *KKold*

KKold—Kramers Kronig Transform old version—performs a Kramers-Kronig transform program for reflectance  $\mathcal{R}$  and transmittance  $\mathcal{T}$  data. KKc, the console (no graphics) version, is no longer distributed.

Use KK or KKg to take advantage of the x-ray optics high frequency extrapolations.

You will need to specify the extrapolations to be used outside the data. Two parameters control the high frequency behavior: the exponent DE and the crossover frequency WA. Above the maximum frequency in the data file, the reflectance is extrapolated  $\omega^{-\text{DE}}$  up to  $\omega = \text{WA}$  and as  $\omega^{-4}$  above  $\omega = \text{WA}$ ; transmittance is  $1 - \mathcal{R}$ . Typical values of DE are 0–2. The book by Wooten recommends a value near 2 but it seems that something between 0.5 and 1.0 works better.

There are several low frequency extrapolations possible, controlled by a parameter COND. For transform of  $\mathcal{R}$ , one has:

>0	⇒ COND is the known DC conductivity, in $\Omega^{-1}\text{cm}^{-1}$	
=0 or c	⇒ Reflectance is assumed constant to DC	
-1 or m	⇒ Metallic conductivity assumed:	$\mathcal{R} = 1 - A\omega^{1/2}$
-2 or t	⇒ Two-fluid model:	$R = 1 - A\omega^2$
-3 or l	⇒ Marginal Fermi Liquid:	$R = 1 - A\omega^1$
-4 or s	⇒ Superconducting:	$R = 1 - A\omega^4$
-5 or f	⇒ Use a parameter file. (You will be asked for the name of a *.PRM file.)	

For transform of  $\mathcal{T}$ , one has:

=0 or c	⇒ Transmission is assumed constant to DC	
-1 or m	⇒ Metallic conductivity assumed:	$\mathcal{T} = B + C\omega^2$
-2 or s	⇒ Superconducting:	$T = A\omega^2$

You also need to specify the file names for input or output. The data can be scaled or shifted and are clipped to 0.↔1. range. (The actual clipping algorithm allows the data to be 1.0 as long as it is 1.0 at all lower frequencies; otherwise 0.999999 is the largest value allowed.)

After the transform, KKold can plot the optical conductivity and give you a chance to change WA and DE and observe the effect the changes have on the conductivity, if you use the /A switch.

Switches: /h, /q, and

/T	— transform of Transmittance
/TPH	— Transmittance. Write *.TPH file
/F	— ask about Factor, zero to multiply, shift data
/Ynnn,mmm	— Scale data as $Y \leftarrow nnn * (Y - mmm)$

<code>/Wnnn</code> or <code>/WAnnn</code>	— free-electron behavior starts at <code>WA</code>
<code>/Dnnn</code> or <code>/DEnnn</code>	— exponent in interband region is <code>DE</code>
<code>/Cnn</code> or <code>/CONDnn</code>	— low frequency extrapolation according to <code>COND</code>
<code>/P&lt; file &gt;</code>	— Use <code>&lt; file &gt;</code> for low frequency extrapolation
<code>/Xnnn</code> or <code>/xnnn</code>	— film thickness (Angstroms) (for $\mathcal{T}$ )
<code>/A</code>	— Adjust high frequency extrapolation manually
<code>/Ynnn,mmm</code>	— Scale data as $Y \leftarrow nnn * (Y - mmm)$
<code>/COLi,j</code>	— Data in Columns <code>i, j</code> .

Examples:

`KKold F1A006.RAW /WA1E6 /D2.2 /C-1 /A`

Transform `f1a006.raw`. Free electron region is  $1,000,000 \text{ cm}^{-1}$ ;  $\mathcal{R} = \omega^{-2.2}$  in intermediate region; extend low region as metal. Plot  $\sigma_1(\omega)$ ; allow user to change `DE` and `WA`. (It is more effective to change `DE`.)

`KKold F1A100.rnm -q-c-1`

Transform `f1a100.rnm`. Use built-in defaults, except extend low-frequency region as metal.

Defaults:

`WA` =  $1,000,000 \text{ cm}^{-1}$

`DE` = 1.0

`COND` = 0

`KKold` produces an `RPH` file, where the three data columns are frequency, reflectance, and phase shift on reflectance;  $\omega$ ,  $\mathcal{R}$ ,  $\phi$ . From these, the complex refractive index is  $N = 1 + \sqrt{\mathcal{R}}e^{i\phi}/1 - \sqrt{\mathcal{R}}e^{i\phi}$ . The program `OP` can calculate a wide variety of optical constants from the `RPH` file.

#### 14. ***KKold /T***

`KKold` with the `/T` switch does the Kramers-Kronig analysis of transmittance.

`KKold /T` produces an `RPH` file, where the three data columns are frequency, reflectance, and phase shift on reflectance;  $\omega$ ,  $\mathcal{R}$ ,  $\phi$ . From these, the complex refractive index is  $N = 1 + \sqrt{\mathcal{R}}e^{i\phi}/1 - \sqrt{\mathcal{R}}e^{i\phi}$ .

Note that the values of  $\mathcal{R}$  and  $\phi$  are those of the *same* material measured as single-bounce reflectance.



## G. File formats

### 1. Data files

Data files are in ascii. They begin with a header. The last line of the header is a “/\*.” Then come the data, in free-format.

Most programs will write information to the header. They typically also transfer all non-redundant, nonblank lines from the header of the input file to the header of the output file. The exceptions are the line that tells how many data points are in the file (which is updated in case the number of points is modified) and the column headers, which are changed by programs such as OP and T2A.

The data columns are separated with one or more spaces, or with a comma. If there are only two columns, they are taken as  $x, y$  pairs. Otherwise, the user is generally prompted for which columns to read. (If the /RPH switch is used, the first and second columns are taken as  $x, y$ ; if /PE the first and third.

In a single column file, the  $x$  values are the point number, starting with  $x = 1$  and continuing to  $x = \text{NP}$ . You can also answer 0 to the **Column no. for X-data?** prompt to have the  $x$  axis be the point number. (This won't work for two column files. You can use an editor to put a third dummy column in the *first* row of data to trick the column-counting mechanism.)

The file is terminated with the DOS end of file [EOF] marker.

Here is an example:

```
YBACUO FILM 100K
0.100000E+07    0.00    -1.00    1.00    0.00
Freq    Sigma_1
646 data points
/*
91.13    6086.82
92.04    6095.79
92.96    6046.8
93.89    6011.65
94.83    5981.28
95.78    5949.78
96.74    5906.65
97.71    5849.56
...
```

The file was written by OP; OP also wrote the last two header lines, and the \\*. The second line was written by KKold and the first either by the user or by MAV.

## 2. Parameter files

DFF, TFF, and DFC write and read parameter (\*.PAR) files. Here is an example.

```
YBACUO FILM 100K
  636 pts. Chisq =      3.921D+03  N*Chisq =      2.447D+06
    26 parameters
Ifix, Parm,  Delta,  Sigma
/*
[Temperature]
  100.

[Marginal Fermi Liquid]
  1 10000.    0.1      0.
  2 1.        0.1      0.
  3 1500.     0.1      0.

[Drude-Lorentz]
  1 2909.084   290.9084  0.3
  3 279.6382  27.9638   0.02
  5 189.5232  18.9523   0.05

  0 7199.863   719.9863  0.4
  0 657.5309   65.7531   0.06
  7 1013.892   101.3892  0.2

  0 14323.75   1432.375   0.9
  0 2126.9     212.69     0.3
  0 5562.322   556.2322   0.9
...
  2 54329.97    79.307    20.
  4 78662.61    29.7171   10.
  6 56049.03    589.6533  70.

[Einfinity]
  8 1.2345     0.1       0.01
```

The \*.PAR file starts with a header, some of which comes from the data file being fitted. DFF or TFF also write some information in the header, such as the  $\chi^2$ . The header ends with a /\*.

The data are organized in blocks, in ([...]), telling the program which of the models the parameters in the block are intended for. Here are the blocks understood by the programs:

1. [Temperature]. “TEM” or “TMP” are OK.\*
2. [Thickness (AA)]. (in Å units). “THI” or “THK” are OK.
3. [Substrate Thickness (cm)] (in cm). “SUB” or “DCM” are OK.
4. [Einfinity]. “EIN,” “EPS,” or “INF” are OK
5. [Drude-Lorentz]. “DRU<sup>†</sup>” or “LOR” are OK.
6. [Product DLF]. “PRO” or “LST” are OK.
7. [Direct band gap]. “DIR” or “DBG” are OK.
8. [Indirect band gap]. “IND” or “IBG” are OK.
9. [Marginal Fermi Liquid]. “MAR” or “MFL” are OK.
10. [Rice EMV]. “RIC” or “EMV” are OK.
11. [Kivelson-Emery] (for DFF and DFC, not TFF). “KIV” or “K-E” are OK .

Moreover, case does not matter: [LOR] and [lor] are equivalent.

As the last header line (Ifix, Parm, Delta, Sigma) indicates, there are four columns for each parameter. The first column is an integer which controls the order in which the fitting routine varies the parameter. A zero entry means not to adjust this parameter. The second column is the parameter; the third the step by which the parameter initially is varied; and the last is supposedly an estimate of the uncertainty of the parameter.

See pages 35–40 for the order of the parameters.

It is OK (and helpful) to leave a blank line between the three or four parameters that represent a single term in  $\epsilon(\omega)$ . The blank lines are not required.

If you are typing up a parameter file for the first time you can simplify to a single column format for the parameters. Here is an example.

```
Silver
/*
[Drude]
70000
0
300

[Eps infty]
4.5
```

---

\* Strictly speaking, the temperature is not a parameter; it is not adjusted to optimize the fit. It is required by some models, however.

<sup>†</sup> Note that although it says “Drude” you must enter three parameters, with the second one—which would be the resonant frequency in the Lorentz model—equal to zero.

### 3. Oldstyle Parameter files

DLFit, FLMMFit, and cousins write and read parameter (\*.PRM or \*.MFL) files. Here is an example.

```

      19      6
1      10242.1600      8720.3090      .1E+02
0          .0000          .0000      .0
3          1.3191          1.0843      .9E-03

4          2671.4760          43.1593      .3
5          264.8839          1.6720      .2E-01
6          146.6709          3.8451      .4E-01
...
18          6353.1720          250.0000      .2E+02

0          1.0000          .1000      .0
YBACUO FILM 6K
DLFIT parameters
for least-sq fit to data in f1006.s1
      637 pts. Chisq =      8.269D+03  N*Chisq =      5.127D+06

```

The first line has the number of parameters and the number of oscillators in the dielectric function model. Then come the individual parameters, one per line in the order  $\omega_p$ ,  $\omega_0$ , and  $\gamma$ . (In MFLFIT, the *first*\* set of 3 are the plasma frequency, coupling constant  $\lambda$ , and the cutoff frequency for the conduction carriers.) There is an (optional) blank line between the three parameters that describe each oscillator. At the end of the parameter list file are lines for  $\epsilon_\infty$  and (if for FLMMFit) film thickness.

In each line, the first column is an integer which controls the order in which the fitting routine varies the parameter. A zero entry means not to adjust this parameter. The second column is the parameter, the third the step by which the parameter initially is varied, and the last is supposedly an estimate of the uncertainty of the parameter.

After the last parameter is a “trailer” containing information from the header of the file that was fitted and the statistics of the fit. This is written by the program but does not need to be entered if you are typing the file.

DLFIT can also use two relaxed versions of the parameter file. In one, the third and fourth columns can be omitted; in the other, the first, third and fourth columns can be omitted.

### 4. The LOF file

Several programs can use a “List of Files” in order to simplify the entry of file names. It contains the names of files in the order in which they will be read. If there are two file names on one line, these will be averaged after they are read in.

---

\* This is a change. Prior to version 3.1 the last set were the MFL parameters.

A LOF might look like:

```
f1006.s1
f1100A.s1, f1100B.s1 f1100C.s1
f1150A.s1 f1150B.sig
f1200.s1
```

## 5. File extensions

ADD	CMP	sum file, $A + B$
ABS	CMP	Absolute value $ y $
AE	OP, DFC	$ \epsilon $
ALP	OP, DFC, T2A	Absorption coefficient, $\alpha(\omega)$
AS	OP, DFC	$ \sigma $
ATN	OP, DFC	$ \tan(\delta) $
AVE	CMP	Average
CLP	CMP	Clip $y$ to band
CMB	CMP	two two-column files $\rightarrow$ one 3 column
D	DERIV	Derivative
DIF	CMP	Comparison file, $A - B$
DIV	CMP	Comparison file, $A/B$
DLC	DLCALC	Results from Drude-Lorentz calculation
DRU	2C, DLCALC	Drude conductivity
DRU	RDRUDE	Drude reflectance
DSL	OP, DFC	$1/\sigma_1$ vs $\omega^2$
E1	OP, DFC	Real diel. function, $\epsilon_1(\omega)$
E2	OP, DFC	Imag. diel. function, $\epsilon_2(\omega)$
E12	RPH2E	Table of frequency, $\epsilon_1(\omega)$ , $\epsilon_2(\omega)$
EMA	EMA	EMA calculation
EYE	DFF, TFF	Results of “eyeball” fit
F	J2W	Output file translated from JCAMP.
FDX	J2W	Output file translated from JCAMP.
FIT	DLFIT, FLMFIT	Results of “least-square” fit
FLP	XY2YX	File with columns interchanged
FRE	OP, DFC	$\epsilon_1$ vs $1/\omega^2$
FTP	FTS, FTgram	Fourier transform of time series
G1	OP, DFC	Real memory function, $\gamma_1(\omega)$
G2	OP, DFC	Imag. memory function, $\gamma_2(\omega)$
INV	CMP	$1./y_{data}$
IP	INTERP	Interpolated file
K	OP, DFC	Extinction coefficient
LAM	OP, DFC	London length, $\lambda_L$
LOF	Several programs	List of files
LOS	OP, DFC	Loss function, $-\text{Im}(1/\epsilon)$
Ln	DLCALC	Lorentzian $n$ response fn
MFL	MFLFIT	Parameter file

MIA	2C	Midinfrared average
MIR	2C	Midinfrared conductivity
MRG	MAV	Merge and average file
MST	OP, DFC	Effective mass ratio, $m^*/m$
MUL	CMP	Product file, $A * B$
N	OP, DFC	Refractive index
NFR	OP	$N_{eff}$ (free electrons)
NK	RPH2NK	Frequency, refractive index, extinction coefficient
PAR	DFF, TFF	Parameter file
PAT	MEND	Data file with “patch”
PIK	PIK	Piece of data
PKS	FTgram	List of peaks from Fourier analysis
PKY	Pinkify	File with added pink noise
PRM	FLMFIT, DLFIT	Parameter file
R	OP, DFC	Reflectance
RFP	OP, DFC	Coherent (Fabry-Perot) reflectance
RHO	OP, DFC	Optical resistivity $\rho_1$
RH2	OP, DFC	Imaginary optical resistivity $\rho_2$
RNM	RNM	Renormalized data
RNU	Ranu	Random-number time series
RPH	KK	Kramers-Kronig output(reflectance, phase)
RSB	OP, DFC	Incoherent slab reflectance
S1	OP, DFC	Optical conductivity, $\sigma_1(\omega)$
S2	OP, DFC	Imag. conductivity, $\sigma_2(\omega)$
S12	RPH2S	Frequency, $\sigma_1(\omega)$ , $\sigma_2(\omega)$
SCA	CMP	Scaled and/or shifted file. (<file> $\times a + b$ )
SE1	OP, DFC	Real self-energy, $\Sigma_1(\omega)$
SE2	OP, DFC	–Imag. self-energy, $-\Sigma_2(\omega)$
SKN	OP, DFC	Skin depth, $\delta$
SLO	OP, DFC	Surface loss function
SMO	FTS	Fourier-transform smooth
SOL	OP	Sum rule on loss function
SQR	CMP	$\sqrt{(y)}$
SSL	OP, DFC	Sum rule, surface loss function
SUM	OP, DFC	Sum rule on $\sigma_1(\omega)$ , $N_{eff}(\omega)$
SUM	CMP	Sum of data, $A + B$
TAN	OP, DFC	$\tan(\delta)$
TAU	OP, DFC	Scattering rate, $1/\tau(\omega)$
TPH	KK	Kramers-Kronig output (transmittance, phase) (obsolete)
TRA	OP, DFC	Incoherent slab transmittance
TFP	OP, DFC	Coherent (Fabry-Perot) transmittance
WPS	OP, DFC	Superfl. plasma freq., $\omega_{ps}$
XPO	CMP	$x \rightarrow x^p$
XRO	XRO	X-ray reflectance

XRP	XRO	X-ray reflectance and phase
XTR	XRO	X-ray transmittance
YPO	CMP	$y \rightarrow y^p$
ZCR	Tcalc	Zero crossing list
1-Y	CMP	$1.0 - y_{data}$

## H. Programming notes

The programs are written in Intel visual FORTRAN and use the quick-win graphics. Most of the routines were written by Charles Porter, the rest by David Tanner.