SolarSoft
TRACE Analysis Guide

Transition Region and Coronal Explorer

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1 Introduction

This is the **TRACE Analysis Guide (TAG)**. The Guide is in two main parts, the TRACE Users Guide (Section 2) and the TRACE Instrument Guide (Section 3). The User Guide describes how to analyse TRACE data and the Instrument Guide discusses aspect of the TRACE instrument. Additional information is provided in the Appendices.

1.1 The TRACE Mission

TRACE is a NASA Small Explorer (SMEX) mission designed to investigate the connections between fine-scale magnetic fields and the associated plasma structures on the Sun. The instrument collects images of solar plasmas from 10^4 to 10^7 K, with one arc second resolution and excellent temporal resolution and continuity.

The TRACE spacecraft was launched on April 2, 1998 (UT) into a Sun-synchronous (98°) orbit of 600×650 km. The baseline mission duration was 1 year. Its orbit allowed continuous observations of the Sun to be made for 7 months before entering an eclipse season of 3 months. Each subsequent year of operation will have a 9 month (mid February to mid November) non-eclipse season. TRACE is operated in coordination with SoHO from an Experimental Operational Facility (EOF) at GSFC, close to the SoHO EOF.

The 30 cm aperture TRACE telescope uses four normal-incidence (NI) coatings in quadrants on its primary and secondary mirrors. Observations are made at several UV and EUV wavelengths, selected using a sector wheel and two filter wheels. A Lumogen-coated 1024×1024 CCD collects images over a 8.5×8.5 arcminute field of view. The images are coaligned and internally stabilized against spacecraft jitter. See the Instrument Guide (Section 3) for more information about the instrument.

1.2 TRACE Instrument Data

The TRACE instrument produces a lot of data – it has been averaging just over 3 GBytes per week. The TRACE instrument data are blocked into hour-long FITS files which have names of the form "**triyyyymmdd.hh00**", where "*tri*" is the prefix for the reformatted files, and "*yyyymmdd.hh*" is the start time of the file. The files contain in-line JPEG compressed images, as downlinked from the spacecraft. They need to be decompressed before the data can be used – this is done automatically by the analysis routine **read_trace** using the shared object binary **trace_decode_idl.so**.

The data files are normally stored under directories that hold a weeks worth of files and have names that correspond to the date of the starting day of the week, i.e. "**weekyyyymmdd**" where "*yyyymmdd*" is the week start date. The directories are addressed in the analysis software through the environment variable **$TRACE_I1_DIR**.

If data are requested from the **TRACE DATA CENTER**, the Multiple eXtension FITS (*.mxf*) files that are returned cover a specific time interval, and contain images that are already decompressed. The name of this file has the form "**trbyyyymmmdd_hhmm.mxf**", where "*trb*" is the prefix of the file, and "*yyyymmdd_hhmm*" is its start date and time. As with the hourly *tri* files, the *.mxf* files can be read using **read_trace**.

Detailed TRACE analysis need certain **ancillary data files**, including the dark current files (*tdc* files). What observations have been made by TRACE can be determined from the catalog files (*tcl*, *tcs* and *tce*). The location of the spacecraft, etc. can be found from the ephemeris files (*fdss_**). These files are all held under directories addressed through the environment variable

$tdb and are normally distributed within the SolarSoft database tree (**$SSWDB** or **/sdb**) – see Appendix C for more information.

1.3 Searching for TRACE Data

The **TRACE DATA CENTER** allows the user to request data based on entries in the TRACE Data Catalog. There are other ways of searching for particular **TRACE** data - these are detailed in Appendix B.3, and include:

- A **Search Engine based on the TRACE Observing PLANS**
- A **TRACE Event List**, sorted by **event type**

1.4 References

TRACE Investigation and Technical Plan (Phase III & IV), August 1994, LMSC P017270P-1.
"The Transition Region and Coronal Explorer (TRACE)", 1994, Tarbell et al., Estes Park proceedings.
"The Transition Region and Coronal Explorer", 1999, Handy et al., Sol. Phys., 187, 229.
"Data Analysis with the SolarSoft System", 1998, Freeland and Handy, Sol. Phys., 182, 497.

1.5 Contacts

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1.6 Acknowledgements

The **TRACE Analysis Guide (TAG)** was prepared by **Bob Bentley** (rdb@mssl.ucl.ac.uk) of the Mullard Space Science Laboratory, with significant help and input from Sam Freeland, Brian Handy, Charles Kankelborg, Jake Wolfson, Ted Tarbell and many other members of the TRACE Team.

2 TRACE User's Guide

This chapter describes the software used to analyze TRACE data. Except for section 2.9, all the descriptions relate to IDL software.

All TRACE software is distributed as part of the **SolarSoft** (**SSW**) software tree which is mastered at NASA-GSFC. To analyse TRACE data, the *gen/*, *trace/* and *packages/binaries/* branches of the tree need to be installed; to use the ANA Browser, the *packages/ana/* branch must also be installed. To use the TRACE catalog, and to apply some of the corrections in **trace_prep**, the TRACE branch of the **SolarSoft DataBase** (**SSWDB**) must also be installed. More details about installing SolarSoft are given in Appendix C.

Within SolarSoft, at the Unix shell level configure your software environment for TRACE, or TRACE and other instruments by entering:

```
> setssw trace
  or
> setssw trace sxt mdi
```

IDL is then started with the command

```
> sswidl
```

The User's Guide gives an outline of how to use the software to analyse TRACE data. For help on how to get additional information on the TRACE software, see Section 2.10. One-line description of useful routines are given in Appendix A.

2.1 The TRACE Catalog and Ephemeris

2.1.1 Using the TRACE Catalog

The TRACE catalogs hold details of the times, wavelengths, pointing, etc. of all observations made by the TRACE instrument. Since the TRACE instrument data files are large and it is therefore difficult for many sites to hold a large number of them on-line, the catalog makes an excellent entry point into the TRACE data. There are several catalogs, all are held under **$tdb**: *tcl* files form the normal catalog; the *tcs* files are a short-form of the catalog; and *tce* are an engineering log. The catalog may be read and listed using the routines **trace_cat** and **trace_list_index**, thus:

```
IDL> trace_cat, start_time, end_time, catalog [,/short]
IDL> more, trace_list_index(catalog)
```

The catalog structure can be used to read in the index and data arrays (see the examples in Section 2.2.2) and plot lightcurves of the average intensity (see Section 2.3.4).

There is an archive of full-disk images taken by TRACE which is formed from mosaics of many spacecraft pointings (available if **$tdb** is installed). This can also provide an insight into what TRACE was observing. The image for a selected date (or the nearest image to that date) may be viewed with **view_trace_mosaic**:

```
IDL> view_trace_mosaic,date
```

The names of any reformatted TRACE files that are on-line at the installation you are using (between a start and end time) may be determined with the function **trace_files**:

```
IDL> more, trace_files(start_time, end_time)
```

2.1.2 TRACE Ephemeris Information

Information relating the TRACE ephemeris can be read with **rd_fdss**, and listed using **pr_fdss**. The *fdss* files used by these routines are held under **$tdb**:

```
IDL> fdss_struct = rd_fdss(start_time, end_time, type)
IDL> pr_fdss, fdss_tsruct
  or
IDL> pr_fdss, start_time, end_time, type
```

where the text string **type** can have the values: '*durevt*' (day, radiation belts (SAA and HLZ's), etc.), '*grndtrk*' (spacecraft ground track), '*orbevt*' (orbit nodes), '*viewpd*' (station-pass view of the spacecraft), and '*station*' (station-pass id).

During each orbit, passages through the radiation belts produce EUV images with a large number of spikes in the data due to energetic particles. Also, each year TRACE is in its eclipse season for a few weeks around the winter solstice between November and February. The status of the spacecraft in relation to these items can be confirmed using the routine **pr_fdss**:

```
IDL> pr_fdss, start_time, end_time, 'durevt'
```

2.2 Reading TRACE data

2.2.1 Using READ_TRACE

Any TRACE file (including *.mxf* files) may be read with the routine **read_trace**. If the file contains JPEG compressed data, the *packages/binaries/* branch must be included in your SolarSoft installation (this contains the shared object binary **trace_decode_idl.so**).

Calling **read_trace** with only one output parameter will just do a fast read of the headers and map them into an IDL structure vector with the same TAGs/field names. The equivalence of the "FITS FIELDS" and IDL structure tags permits vectorized searching on instrument parameters without any string parsing normally associated with FITS files. The same logic applies to SXT, EIT, MDI, etc. when accessed via SolarSoft.

The following commands read the index records (and optionally the data) in the specified files – the ss parameter specifies which images are required; -1 means all images. Again, the **trace_list_index** can be used to list the index structure:

```
IDL> read_trace,files,-1,index
  or
IDL> read_trace,files,ss,index,data
IDL> more, trace_list_index(index)
```

The routine **trace_prep** can also read images with a similar calling sequence.

2.2.2 Using TRACE_CAT2DATA

If you have already extracted a catalog structure using **trace_cat**, this may be used to read in the index and data arrays using **trace_cat2data** with the following calls.

```
IDL> trace_cat2data,catalog,index [,data]
 or
IDL> trace_cat2data,catalog,files,ss,/filedset
IDL> read_trace,files,ss,index,data
```

2.2.3 Selecting a subset of images – (TRACE_SSWHERE)

The **TRACE images are large and there are a lot of them**, so it is better to select a subset before attempting to read them in. The function **trace_sswhere** provides a filter to do this, allowing the user to select images through a widget interface. Thus:

```
IDL> read_trace,files,-1,index          ; get all the index structures
IDL> ss = trace_sswhere(index)          ; select wavalength, etc. of choice
IDL> read_trace,files,ss,index,data     ; read in the desired data
```

For a given index or catalogue structure, the function **trace_sswhere** allows the following to be selected by the user:

- Start and stop time
- Image cadence
- Wavelength
- Minimum and maximum exposure time
- Image dimensions
- Spacecraft pointing

trace_sswhere can be used to select a subset of images from a catalog structure before the data is read in:

```
IDL> trace_cat, start_time, end_time, catalog
IDL> ss = trace_sswhere(catalog)
IDL> trace_cat2data,catalog(ss),index,data
```

It may also be desirable to only read part of the the image since individual images can be quite large, and an array can take a lot of memory. The routine **read_trace_fov** allows the user to select a sub-frame within the *first* selected image before reading the data:

```
IDL> trace_cat, start_time, end_time, catalog
IDL> ss = trace_sswhere(catalog)
IDL> read_trace_fov,catalog,ss,index,data
```

read_trace_fov can also be called with just the files and ss arrays:

```
IDL> read_trace_fov,files,ss,index,data
```

2.2.4 Other filters used to select TRACE data

Filtering can also be done at the IDL command level. For example, this three line segment reads NN file headers (subset of -1 implies all images), applies a filter for full resolution 171 Å images and then reads that data cube.

```
IDL> read_trace,files,-1,index                     ; read all HEADERS->structs
IDL> ss=where(index.wave_len eq '171' and index.naxis1 eq 1024) ;some FILTER
IDL> read_trace,files,ss,index,data                ; read subset DATA (3D)
```

The routine **struct_where** is a more generalized filter that works on index or catalog structures. The selection is made according to filters supplied in a configuration file or string array. This method is particularly useful when the same set of filters are always employed to process data, e.g. when making a movie.

```
IDL> ss = struct_where(index, count, conf_file=conf_file)
  or
IDL> ss = struct_where(index, count, test_array=test_array)
```

Where the contents of conf_file or test_array are of the form:

```
<TAG> <OPERARTOR> <VALUE>
```

For example, a configuration file might contain:

```
;   you can include free-form comments using ';' delimiter
NAXIS1 = 512,1024                ; Lists (comma delimited)
IMG_MIN > 1.                     ; Single value (boolean)
WAVE_LEN = 171,195,284           ;
XCEN=600.~800.                   ; Range (tilde separated)
IMG_AVG > 100 && IMG_MAX < 4096  ; Compound Boolean
```

Or, the following test_array filter would select all TRACE images in 171 Å of 1024×1024 pixels:

```
IDL> filter = ['wave_len = 171','naxis1 = 1024']
IDL> ss = struct_where(index,count,test_array=filter)
```

If you need to select a series of images at a pre-defined cadence from an index or catalog structure, then use **grid_data**. To select images at a particular time, use **tim2dset**. For example:

```
IDL> ss = grid_data(index, min=5)
  and
IDL> trace_cat,'31-may-98 12:00','31-may-98 14:00',cat
IDL> ss = tim2dset(cat,'31-may-98 13:08')
```

2.2.5 Reading using ANA Browser Products

If you have a list of favourite images generated by the **ANA Browser** (section 2.9), this can be read into IDL using **read_analist**. The index and data arrays can then be read with **read_trace**.

```
IDL> read_analist,analist_filename,files,ss
IDL> read_trace,files,ss,index,data
```

The routine **trace2x** will also read a list produced by the ANA Browser (section 2.9) and return a scaled (windowed) array – see the file header for more information.

Image files created by ANA can be read into IDL using **anafrd**:

```
IDL> img = anafrd(ana_image_filename,head)
```

2.3 Displaying TRACE data

For qualitative work, there are a number of routines to try. Here we assume that the index and data arrays have already been read in, e.g. using **read_trace**. Since the TRACE index structure contains the SolarSoft standards for time and pointing references, you can use a lot of standard software including **utplot**, the mapping software, etc..

2.3.1 Displaying Images

For single (2D) images, try the following:

```
IDL> sdata=trace_scale(index,data,/despike,/byte)  ; "standard" scaling
IDL> wdef,im=sdata                                 ; make a window the right size
IDL> trace_colors,index                            ; Load standard wave color table
IDL> tv,sdata
```

Here the function **trace_scale** is used to scale the TRACE image to the desired range, and **trace_colors** loads the standard TRACE color table. If the image is large, it may also be viewed with **slide_image** (the optional keyword inputs change the image display size):

```
IDL> slide_image,sdata  [,xvis=400,yvis=400]
```

When whole (1024×1024 pixel) TRACE images are viewed, the effects of **vignetting** are evident – the cause of this is decribed in Section 3.2.3.

2.3.2 Displaying Movies

TRACE image cubes may be viewed with the generic viewer **xstepper**. This needs a data array, and optionally an information array. The generic IDL (structure to text array) translator **get_infox** is one way of producing the required info array. Sample calls may thus be:

```
IDL> xstepper, sdata, info
IDL> xstepper, sdata, get_infox(index,'naxis1,wave_len,',/fmt_tim)
```

The **xstepper** procedure can also be used to blink between two images. Just load the image pair when starting **xstepper** and adjust the frame rate as desired.

TRACE movies can also be made by other routines, including **trace_uniq_movies** and **image2movie**. To see examples of the Web of movies created with the software mentioned here, look at <http://vestige.lmsal.com/TRACE/last_movies/>.

2.3.3 Plotting Image Lightcurves

Lightcurves of a selected area of an image cube may be made using **lcur_image**:

```
IDL> lcur_image,index,data [,lcur]
```

To mark an arc on an image (e.g. to pick out a loop) and plot the intensity along the strip use **plot_arc**. The lightcurve of the arc may optionally be returned:

```
IDL> plot_arc, index, image, width  [, xlcur=xlcur, lcur=lcur]
```

2.3.4 Plotting Time Series – (UTPLOT)

Time series of parameters may be plotted with **utplot**.

```
IDL> utplot,index,index.XXX          ; time series of some SSW parameter
IDL> outplot,index,index.YYY         ; overplot
IDL> evt_grid,index,ticklen=.1       ; overlay 'events' on existing utplot
```

The normalized lightcurve of the average counts in an image may be plotted using **plot_trace**:

```
IDL> plot_trace,index,wave='1600',nx=256
```

In this example, the average counts of the 1600 Å band from TRACE index (or catalog) structure is plotted (selecting the 256×256 pixel images). Counts in the .img_avg tag are used because the .img_max values are affected by particle-induced spikes in the data. The countrates are normalized for exposure time, after the CCD readout pedestal (section 3.2.2) has been subtracted. **Note:** *The times listed in the index (and catalog) structures are the* **time the shutter closes** (section 3.2.5). The times plotted by **plot_trace** are the **mean time**, i.e. the end time minus half the exposure time. By default, bad data is filtered from the plot.

2.4 Calibrating TRACE data – (TRACE_PREP)

The routine **trace_prep** is intended to guide the processing of TRACE data from raw to level 0 according to the order and algorithms defined by the TRACE PI Team. For those familiar with SolarSoft, it is similar in philosophy and interface to **sxt_prep** and **eit_prep**. A number of TRACE database files need to be installed under **$tdb** to run **trace_prep** – these include the dark current frame files (*tdc*) – see Appendix C for more information.

The **trace_prep** routine will work with both 2D and 3D data arrays. Assuming that the index and data records have already been read in, the call to **trace_prep** is:

```
IDL> trace_prep,index,data,outindex,outdata
          [,/wave2point][,/unspike][,/destreak][,/deripple]
```

Examine the procedure header for the current status of **trace_prep**, or e-mail Richard Nightingale at Lockheed (ngale@lmsal.com). As of November 1999, **trace_prep** performs the following steps:

- Read in image(s) from a datacube and index structure
- Fill pixels of value = 0 with mean pixel value of entire image
- Replace near saturated pixels with value >4095
- Subtract the dark pedestal (ADC offset) and current from each image
- Output the corrected image(s) in an updated structure and data cube

Optionally, the following corrections are applied if the appropriate keywords are used:

- Remove radiation belt spikes and streaks from each image (*/unspike, /destreak*)
- Remove background diffraction pattern (and readout herringbone) (*/deripple*)
- Normalize each image for exposure (*/normalize*)

- Correct pointing **in the index structure** for each channel (*/wave2point*)
- Extract a subimage from each image (keywords *sllex, slley, subimgx, subimgy*)

In the future, it is hoped that **trace_prep** will also:

- Perform CCD gain calibration using flatfielding on each image
- Normalize to physical units using instrument response by wavelength

The TRACE images are large and numerous and it may be necessary to work with only part of each image. Since *some of the corrections are best performed on complete TRACE images*, the extraction should be done after the corrections have been applied. There are four keyword parameters within **trace_prep** that allow the user to extract part of an image after it has been processed. These are: *sllex* and *slley* (which specify the coordinates of the subimage lower left corner), and *subimgx* and *subimgy* (which specify the number of pixels in the x and y axes). If the data are extracted in this way, the pointing and image tags in the index record are updated; the use of the */new_avg* keyword is also recommended. An example of a call including these paramaters, and the keywords to correct the images would be:

```
IDL> trace_prep,index,data,outindex,outdata, $
        /wave2point,/unspike,/destreak,/deripple, $
       sllex=x0,slley=y0,subimgx=nx,subimgy=ny,/new_avg
```

The **trace_prep** routine can also be used to read directly from the raw FITS file and write calibrated data to a new file. Examine the procedure header for more information. Such files can be read in using **read_trace**.

2.4.1 Routines used by TRACE_PREP

Below are examples of calls for routines that are used in correcting and calibrating TRACE data. ***Most can be called as options in* trace_prep *and as such do not need to be called separately***. **Note:** the advantage of calling the routines within **trace_prep** is that *history records* are included in the index structure to flag that the correction has been applied - this reduces the chance of applying the same correction more than once.

Spikes caused by high energy particles in the images (see 3.2.2 and 3.2.7) can be removed by **tracedespike** or **trace_unspike**. The routines **trace_unspike** and **trace_destreak** (together with **trace_cleanjpg**) can be used to remove spikes and streaks, and repair some of the damage caused when the spikes are compressed by the JPEG algorithm. If you have a series of images, the routine **trace_unspike_time** will removing spike-like features that only occur in one frame.

The herring-bone patterning on the CCD pedestal (see 3.2.2) can be removed with **trace_knoise**.

```
IDL> imout = tracedespike(tracedespike(image))    ;twice for faint fields
IDL> imout = tracedespike(image,statistics=6)     ;correct > 6sigma outliers
IDL> imout = tracedespike(image,minimum=100,ri=3) ;low-quartile correrctions

IDL> imout = trace_unspike(image, /cleanjpg [, sens=sens])
IDL> imout = trace_destreak(image [, sens=sens, thresh=thresh])

IDL> clean_data = trace_unspike_time(index,data [,threshold=threshold])

IDL> imout = trace_knoise(image)
```

The routine **trace_wave2point** is used to correct the index structure for differences in the alignment of the TRACE images in different channels (see 3.2.3).

```
IDL> newindex = trace_wave2point(index [,/noapply] [,version=xx] )
```

2.5 Writing TRACE data

Processed TRACE data may be stored in files in a number of formats. Remember that *the data will no longer be compressed and the files will be much bigger than the raw files if all the frames are included.* Use **write_trace** to write such files. The default is a FITS file, but GIF, TIFF and JPEG are also possible:

```
IDL> write_trace,index,data,outfile=filename
```

2.6 Making TRACE Full-disk or Partial-disk Mosaics

TRACE is often rastered about the disk to generate a mosaic image of all or part of the sun: full-disk mosaics are a standard synoptic campaign when EIT is not running, and TRACE began making Lyman Alpha observations of the solar limb in collaboration with UVCS in early 1999. An alternative to using the mosaic database is to generate the mosaics by hand with **trace_build_mosaic**. It is not necessary to have all the images from the mosaic on hand to generate a partial solar mosaic.

```
IDL> file = trace_files('05:00:00 16-JUN-1999', '05:30:00 16-JUN-1999')
IDL> read_trace, file, -1, i, /nodata
IDL> subs = where(i.obs_prog eq 'STD.smallmosaic', count)
IDL> read_trace, file, subs, i, d
IDL> for j=0, count-1 do begin & d[*,*,j]=trace_unspike(d[*,*,j],/cleanjpg)
IDL> trace_prep, i, d, iout, dout
IDL> trace_build_mosaic, iout, dout, mosaic
```

2.7 Comparing TRACE images with other data

2.7.1 Overlaying Images

It is possible to overlay TRACE images with images from other sources using **IDL Map Objects** (<http://orpheus.nascom.nasa.gov/~zarro/idl/maps.html>) – this is a family of routines that was developed by Dominic Zarro (SAC/NASA-GSFC; zarro@smmdac.nascom.nasa.gov). From the index and data arrays the routines create Map Objects which can be spatially scaled, differentially rotated, overlayed, plotted with the limb or a latitude and longitude grid. Note the sequence read_trace > index2map > plot_map used in the example below to create and plot map objects – a similar sequence can be used for many other instruments supported by SolarSoft. For the best source of information on what options are currently available, see the header of the routine **plot_map**.

Assuming that the index and data arrays have been read in, a Map Object of TRACE data may be created and plotted using **index2map** and **plot_map**:

```
IDL> index2map, index, data, tracemap        ; make a map from scaled data
IDL> plot_map, tracemap, fov=10, grid=5      ; plot it, centered in 10 arcmin
                                             ; FOV , overlay 5" solar grid
```

Note that image center defined in the index (or catalog) structure represents the center of the TRACE White Light channel – this is the same in the FITS file header. Since the centers of EUV and UV channels are offset with respect to the white light image (see the Instrument Guide, Section 3.2.6), a correction must be applied before the images can be co-aligned. The correction can be made using **trace_wave2point** – this can be optionally applied when using **trace_prep**.

2.7.2 Tracking an image sub-field

A useful routine to use with Map Objects is **ssw_track_fov**. This extracts a sub-field from the SSW-compliant (2D) image data given the time and image coordinates from a reference Map Object; alternatively, a desired reference time and set of heliocentric coordinates can be supplied as keywords. The interactive selection of coordinates is also possible:

```
IDL> ssw_track_fov, index, data, outindex, outdata, ref_map=ref_map
  or
IDL> ssw_track_fov, index, data, outindex, outdata, helio=[LAT, LON], $
            date_helio=ssw_std_time
  or
IDL> ssw_track_fov, index, data, outindex, outdata, /interactive
```

2.7.3 Co-alignment of images

The co-alignment of images from various sources can be improved by using cross-correlation. There are a number of routine in the SSW tree to do this, but one way is shown below using **align_cube_correl**:

```
IDL> mreadfits, files, index, data [, outsize=xxx]          ; xxx= 256 or 512
IDL> [normalize data cube if possible - might try 'normalize_cube']
IDL> align_cube_correl, data,  outdata [,reference=NN]      ;  CC alignment
```

2.8 Diagnostics with TRACE

Routines that use the TRACE data to determine plasma diagnostics are detailed below. See the Instrument Guide (Section 3.4) for more information on the techniques involved and the limitations of the data.

When TRACE is in or near its eclipse season, care should be taken when using data for diagnostic purposes because of the effects of **atmospheric absorption** – see Appendix B.4.

2.8.1 The TRACE EUV Temperature Response

The response of the TRACE EUV channels with respect to temperature is given by **trace_t_resp**. To plot the response of a channel against temperature use:

```
IDL> temp=1.0e5+1.0e4*findgen(200)           ; generate temperature vector
IDL> response=trace_t_resp('171ao',temp)     ; calculate and plot response
IDL> plot,temp,response
```

2.8.2 Calculating Temperature and Emission Measure

The routine **trace_dem** characterizes the differential emission measure (DEM) along the line of sight by fitting a 3-parameter model. It uses linear techniques to solve what is normally considered an ill-posed inversion problem. The keyword paramater "basis" contains the name of the function that will supply the basic elements necssary of constructing the DEM curves – the default is **trace_sbasis** (see **trace_dem_setup**); **trace_tbasis** is another routine that can be used. The call for **trace_dem** is given below:

```
IDL> trace_dem, index, data, emc, Tavg [,basis=basis]
```

The routine **trace_tmap** produces maps of temperature and emission measure, given two or more TRACE EUV channels as input – it uses chi-squared minimization. The routine is computationally intensive and takes a lot of memory. Like **trace_tmap**, the routine **trace_isothermal** uses chi-squared minimization, but is less memory intensive. Neither method is particularly fast – **trace_isothermal** *is extremely slow and its use is only recommended for small fields-of-view.*

```
IDL> trace_tmap, index, data, tmap=tmap, em=em
  or
IDL> trace_isothermal, index, data, tmap=tmap, em=em
```

The results of **trace_tmap** and **trace_isothermal** can be displayed using **trace_disp_tem**. This produces maps that visualize temperature and emission measure simultaneously by means of hue angle and lightness. The maps look best when viewed on a *24-bit display*, although the output may also be written to the PostScript device. When using an *8-bit display*, the */quantize* keyword is required.

```
IDL> trace_disp_tem, tmap, em [,/legend] [,/quantize]
```

It is also possible to calculate the temperature and emission measure maps from a pair of of TRACE EUV images using the routine **trace_teem**. This is a filter-ratio method that is based on the assumption that a structure seen in the two wavelengths is i) isothermal, and ii) of a temperature that lies between the peak temperatures of the response functions of the two wavelength filters, $T1<T<T2$; suitable pairs are 171 and 195 Å, and 195 and 284 Å. The **trace_teem** is faster than **trace_isothermal** because of its vectorization and because it only requires two wavelength images.

```
IDL> trace_teem,index1,data1,index2,data2,em,te
```

where index1 and data1 relate to the lower wavelength image, and index2 and data2 relate to the higher wavelength image. All data should be prepared using **trace_prep**.

2.8.3 Making C IV Maps

The routine **civ_subtract** can be used to generate a clean C IV image, given an input set of TRACE UV images at 1550 Å, 1600 Å and 1700 Å. Any pair of these channels will produce a result, but the quality is degraded if only two channels are used. The call for **civ_subtract** is:

```
IDL> civ_subtract, index, data, iout, dout
```

2.9 Browsing TRACE data with ANA

It is possible to browse TRACE data using **ANA**. The **ANA** utility was developed during the SMM era by Dick Shine and others. The **Browser** was written to assist the analysis of data from the SOUP instrument on Spacelab 2. A detailed description of the **ANA Browser** is given in the write-up by Dick Shine (shine@lmsal.com; Appendix D), but a few pointers are given here. At most stages, help can be obtained by hitting the *"Help"* button in a particular **Browser** window.

The **ANA Browser** is started at the Unix shell level by entering:

```
> browser
```

2.9.1 Selection of a Dataset

Use the *"File"* pull-down in the *"SOUP data browser"* window to select *"TRACE hourly"*; within this box, hit *"list weeklies"*; select the desired week of files in *"TRACE paths"* and then the desired hourly file in *"TRACE raw hourly files"*. At some sites (e.g. at GSFC and Lockheed), the TRACE data may be held on several disk – the *"primary source"* and *"secondary source"* buttons and *"starting path name:"* window allow the source directory to be changed.

2.9.2 Displaying an Image

You should now have a list of images in a file in a window labelled *"TRACE Image List"*. To view one, just select it – the image will appear in another window. Within the image window, you can manipulate the data using the options on the menu bar. Options include despiking the data, rotating the images, zooming, etc. Other images can be displayed by selecting them in the *"TRACE Image List"* window. Different image windows may be selected using buttons within the *"SOUP data browser"* window.

2.9.3 Extracting a Subset of Images

TRACE data has images at different wavelengths and of different sizes, exposures and pointing all interspersed. A subset may be selected by hitting the *"selection tool"* button in the *"TRACE raw hourly files"* window. In the *"TRACE Image Selection"* window, make the desired selections and hit the green *"apply selection"* button – a list of selected images should appear in a window called in the *"Selected TRACE Image List"*. This list may be saved by naming it – this is necessary if you want to pass the list to IDL, or to make a movie.

2.9.4 Making a Movie

It is possible to make a movie of the selected images. To do this, select *"create movie cube"* from the *"movie tools"* menu in the *"Tools Menus"* on the *"SOUP data browser"* window. When the *"Extract Movie Cube"* window appears, select a saved image list. Then make the *required* selections, including if desired selecting a rectangular area within the image, etc., and hit the red *"do it"* button – the progress of the extraction of the images is shown in the *"Processing a Series of Files"* window. The movie may be played by selecting *"play movie"* within the *"movie tools"* menu on the *"SOUP data browser"*. Use the controls on the *"Play Movie Cube"* window as needed.

2.9.5 Saving the Browser Image List

Having made a selection of images, it is possible to pass this selection to IDL by saving it to a file. To do this, select desired list in the *"List of Image Lists"* window, enter the filename that you wish to save to, and hit the *"save to file (below)"* button. This list can be read and used in IDL as described in Section 2.2.5.

2.9.6 Saving Individual Browser Images

Images may be saved by using the *"save"* option under *"File"* menu on the *"SOUP data browser"* window. The *"save"* window allows you to save the image data in the display window under a user-entered filename. The user may also choose to save scaled and/or cropped images. Various formats are available for the save file (e.g. FITS, JPEG, GIF, TIFF, FZ, etc.) to facilitate reading the images into other applications.

2.9.7 Saving ANA Images Cubes

Within the *"Play Movie Cube"* window (brought up by selecting the *"play movie"* window from the *"movie tools"* menu on the *'SOUP data browser"* window), a set of movie images can be saved for later use by hitting the *"Save"* button. The user has the option of saving movie files as either a full three-dimensional array or a series of two-dimensional image files – again, a range of file types is available. The option is selected by by hitting either the *"Write all to disk"* or *"Write to disk"* button.

When writing a 3-D array, three separate arrays may be written to disk. The three files have default extensions of *".cube"*, *".times"*, and *".notes"* – the filename is supplied by the user (the default is "movie"). Timing information available from the TRACE hourly files (i.e. the time of each exposure) can be saved in the *".times"* array; the *".notes"* array is for optional extra comments. 3-D arrays may be written as either FITS or FZ files.

Arrays of 2-D images may be written in the same formats as single images. The filenames are created from a numbered list based on the file name template (using the *"#"* character) and range. For example, *"movie####.file"* with a range of 1–10 will write ten images with file names *"movie0001.file"* through *"movie0010.file"*.

Note: There is a WYSIWYG file write option, but this works only for users running from Silicon Graphics machines.

2.9.8 Importing ANA cubes into IDL

An image cube created by ANA can be imported into IDL using the routines **open_anacube**, **window_anacube**, and **close_anacube**. After opening the cube with **open_anacube**, the desired sub-window of a reference image can be read using **window_anacube**; frames can be selected using an *ss* vector. Some selection before reading is recommended since the cubes are often quite large. More recently written cubes may have *".times"* and *".notes"* files associated with the *".cube"* file – these contain timing and other information.

```
IDL> open_anacube,filename
IDL> cube = window_anacube(ref_no,/read [,ss=ss])
IDL> close_anacube
```

2.10 Software help

Within IDL, the routines **doc_library**, **doc_library2**, **xdoc**, **sswloc** and **chkarg** can provide imformation on the software – **sswloc** also works at the Unix shell level. Thanks to Dominic Zarro, there is now a searchable WWW front end to routines in the the SolarSoft tree through a Hypertext version of the **xdoc** routine (<http://orpheus.nascom.nasa.gov/~zarro/xdoc/>) – try searching on **read_trace** to check this out.

Within the ANA Browser, at most stages help can be obtained by hitting the "Help" button.

Appendix C gives information on installing SolarSoft.

3 TRACE Instrument Guide

The Instrument Guide is intended to give the user an outline of the TRACE instrument and spacecaft, and to convey some of the salient points relating to the instrument that may be of assistance when analysing the data. It is by no means the only source of this information. The TRACE instrument (Section 3.1) is described in considerably more detail in Handy et al. (1999). Aspects of the instrument properties and calibration (Sections 3.2 and 3.3) are described in a number of calibration notes (see the list in Section 3.5). The C IV diagnostic capabilites of TRACE (Section 3.4) are described in Handy et al. (1998).

3.1 The TRACE Observatory

3.1.1 Instrument Description

The TRACE instrument consists of a 30 cm diameter Cassegrain telescope and a filter system feeding a CCD detector (see Figure 3.1). Each quadrant of the primary mirror is coated for sensitivity to a different wavelength range. Since the four coatings share a common substrate, images in all ranges are co-aligned well. The corresponding quadrants of the secondary mirror are coated in a similar manner. All four mirror quadrants have multilayer coatings, which serve to define the passbands at each wavelength. Entrance filters exclude all visible Light and most of the energy in the UV – this help reduces scattered light and the heat load inside the instrument. A pair of filter wheels contains filters to select particular UV spectral regions. The 1024×1024 pixel CCD camera was developed for the SoHO/MDI program. An image stabilization system drives an active secondary mirror to compensate for spacecraft pointing jitter to a level of $0.1''$. A data handling computer performs basic image manipulation and compression in order to reduce telemetry requirements.

Light entering the instrument passes first through the entrance filter assembly which transmits only far and extreme UV. Visible and near UV radiation (and hence most of the solar energy) are reflected back into space. Radiation transmitted through the entrance filters passes to a quadrant selector wheel that blocks three quadrants of the aperture so that only one quadrant of the telescope is illuminated at a time. Photons passing the wheel's open quadrant proceed to the primary mirror, encountering a multilayer coating for a narrow-band EUV quadrant or a broad-band coating for the UV quadrant.

The reflected beam from the primary mirror proceeds to the secondary mirror which reflects it towards the focal plane. The secondary mirror is active to correct for pointing jitter and has coatings matching those on the four quadrants of the primary mirror – it is also stepped to adjusted the focus of the different TRACE channels. The converging beam from the secondary mirror passes through the central hole in the primary mirror where it encounters two filter wheels in series.

Each four-position wheel has three filters and one open position (see Tables 3.1 and 3.2). The two wheels contain thin film aluminum filters for use with the EUV channels, and four UV filters. A thin aluminum (EUV) filter is located in each wheel for use in series if pinholes in both of them become a problem. This has not been necessary and the baseline/front filter has always been used thus far. The Lyman-α filter (1216 Å) is deposited on a magnesium fluoride substrate and the remaining UV filters are on quartz substrates. A narrow band UV filter for the C IV lines at 1548 and 1550 Å is deposited on crystalline quartz (as is a narrow band filter peaking at 1570 Å). The filter for the continuum at 1600 Å is made with the same deposition coating on a fused quartz substrate. This substrate sharply attenuates the C IV lines and makes it possible to subtract the longwave transmission of the 1550 Å narrow band filter. Normally

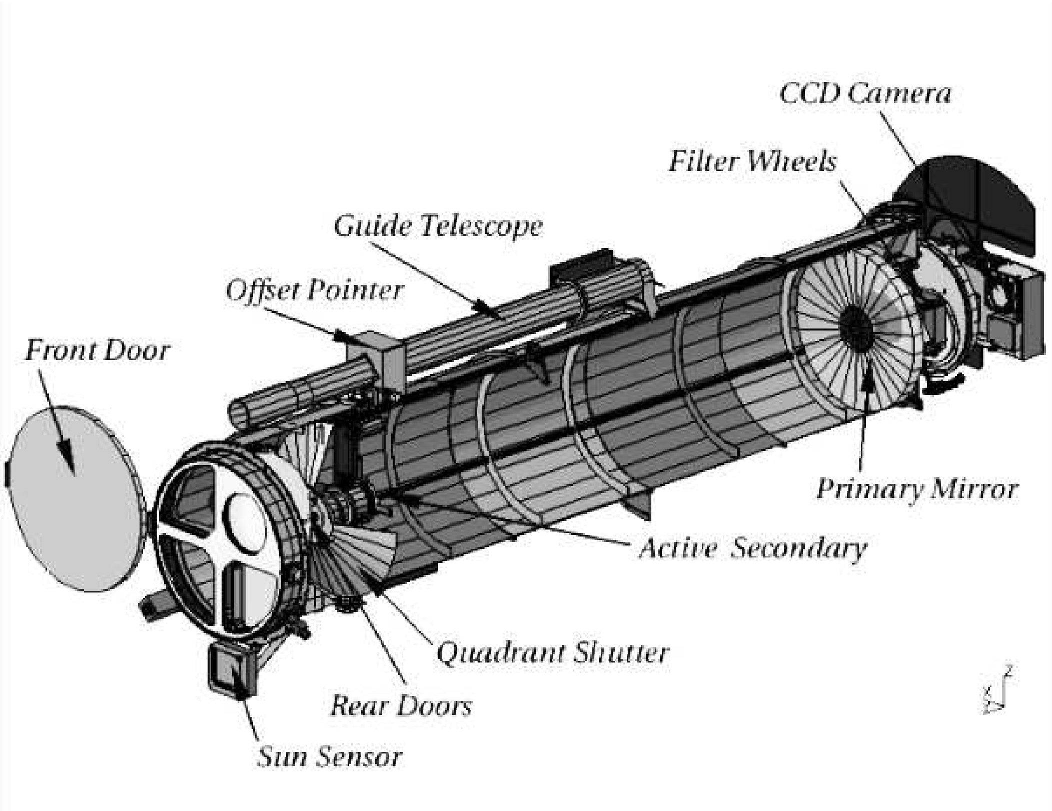

Figure 3.1: Cutaway drawing of the TRACE instrument

Mirror Quadrant	FW 1 (FWD)	FW 2 (AFT)
A: 171 Å (EUV)	1: Open	1: Open
B: UV and WL	2: 1600 Å	2: 1216 Å
C: 195 Å (EUV)	3: Aluminum	3: Aluminum
D: 284 Å (EUV)	4: 1550 Å	4: Fused Silica

Table 3.1: The TRACE Filter Wheel and Mirror Quadrants

one filter wheel is set at open; the other selects the spectral region. To observe in the 5000 Å band, one filter wheel is open and fused-silica is selected on the other.

Radiation passing the filter wheel assembly next encounters the focal plane shutter. The shutter mechanism consists of a disk mounted directly on the shaft of a brushless DC motor. Two apertures are provided in the disk, wide for exposures longer than 20 msec and narrow for exposures that are multiples of 1.6 ms. The final element in the optical train is the Lumogen-coated CCD camera. Its 21 micron pixels each subtend $0.5 \times 0.5''$ at the focus of the telescope. Ray traces of the optical system show that optical aberrations are smaller than one pixel throughout the field of view, even with maximum secondary mirror tilt.

#	Quadrant	FW 1	FW 2	Name	Comments
0	A (171)	1 (open)	1 (open)	171oo	
1	A (171)	1 (open)	3 (Al)	171oa	
2	A (171)	3 (Al)	1 (open)	171ao	* Baseline
3	A (171)	3 (Al)	3 (Al)	171aa	
4	C (195)	1 (open)	1 (open)	195oo	
5	C (195)	1 (open)	3 (Al)	195oa	
6	C (195)	3 (Al)	1 (open)	195ao	* Baseline
7	C (195)	3 (Al)	3 (Al)	195aa	
8	D (284)	1 (open)	1 (open)	284oo	
9	D (284)	1 (open)	3 (Al)	284oa	
10	D (284)	3 (Al)	1 (open)	284ao	* Baseline
11	D (284)	3 (Al)	3 (Al)	284aa	
12	B (UV)	1 (open)	1 (open)	UVoo	alternate white light
13	B (UV)	1 (open)	2 (1216)	1216	* Lyman alpha
14	B (UV)	1 (open)	3 (Al)	UVoa	pinholes
15	B (UV)	1 (open)	4 (FS)	WL	* White Light (FS = fused silica)
16	B (UV)	2 (1600)	1 (open)	1600	* Continuum + C IV + other lines
17	B (UV)	2 (1600)	2 (1216)	1216L	L for long wavelength leakage
18	B (UV)	2 (1600)	4 (FS)	1700	* Continuum + weak lines
19	B (UV)	3 (Al)	1 (open)	UVao	pinholes
20	B (UV)	3 (Al)	3 (Al)	UVaa	pinholes
21	B (UV)	4 (1550)	1 (open)	1550	* C IV + other lines + continuum
22	B (UV)	4 (1550)	4 (FS)	1550L	L for long wavelength leakage

Table 3.2: The TRACE Channels as defined by combinations of the filter wheels and mirror quadrants - the baseline channels are denoted by "*". (Note: 23–30 are spare; 31 is dummy and moves no mechanisms)

3.1.2 Spacecraft Orbit, Attitude Control and Pointing

TRACE is a 3-axis stabilized, Sun-pointing spacecraft. It is in a Sun-sychnronous (98°) orbit of 600×650 km.

The TRACE **attitude control system (ACS)** includes three reaction wheels, three electromagnetic torquers, a 3-axis magnetometer, a gyro system, coarse sun sensors, and a fine sun sensor. High sensitivity pitch and yaw error signals are provided to the ACS by the TRACE **Guide Telescope**. The ACS uses these signals to limit pointing jitter to $<20''$; the Image Stabilization System (ISS) removes residual jitter using higher frequency signals from the guide telescope.

Within the guide telescope, a pair of independently rotatable wedge prisms mounted between the entrance filter and the objective lens allows the optic axis of the telescope to be deflected in any direction within a cone of 1 degree half-angle centered about the optic axis of the main telescope. The spacecraft is maneuvered by offsetting the optical axis of the guide telescope such that the main telescope points to the desired portion of the solar disk.

The ISS drives the active secondary mirror to compensate for spacecraft pointing jitter to a level of $0.1''$. It is an open-loop control system in the sense that the error signal is derived from the guide telescope rather than from motion of the image in the main telescope.

TRACE does not use a star tracker. The roll axis is defined using Earth's magnetic field; the gyro system provides error signals for roll stabilization. Steady slow drifts in roll ($\sim$0.7 degree/hr) can be accepted without degrading the science.

3.2 TRACE Instrument Properties

3.2.1 CCD Camera

TRACE uses a flight spare CCD from the SoHO MDI instrument - it was designed by Loral for MDI. It is a 1024$\times$1024, 3-phase, Multi-Phase Pinned (MPP), 21 micron pixel design which incorporates dual serial registers for redundancy; is front-illuminated, and is not thinned. The pixels each subtend $0.5\times0.5''$ at the focus of the telescope.

The CCD is phosphor-coated to give it UV sensitivity. The material used was **Lumogen**, made by B&K, and deposited by Lorel. The sensitivity of the Lumogen-coated CCD is about 0.08 at the EUV wavelengths, 0.09 at 1216 Å, 0.15 at 1600Å, and $\sim$0.40 in the visible. The **system gain** of the camera is **$\sim$12 electrons/Data Number (DN)** when using the A amplifier (which is normally the case); the B amplifier system gain is $\sim$45 electrons/DN. The response of the camera is very linear with exposure; weak pixels are also linear.

The 12-bit ADC tops-out at 4096 counts - count levels in excess of this return this value. This represents only 20% of the full-well capacity of a pixel, so unless the countrate is extremely high there is little spreading from (ADC) saturated pixels.

The CCD is designed to operate at temperatures below -55 °C. It is cooled by an aft-facing passive radiator system located at the rear of the spacecraft. The detector runs cold to reduce dark current, and mitigate radiation damage effects.

The **peak data rate** of TRACE is theoretically limited by the time taken to read the CCD, and practically limited by signal level considerations. The amount of time required to obtain a 1024$\times$1024 image is determined by the CCD read rate of 500 Kpixels/s to be 2.2 seconds. N$\times$N subarrays can be read out faster by a factor of almost 1024/N; there is usually some fixed "overhead". On-chip summing and/or binning of pixels in the image processor can be used to invoke compromises of spatial resolution, FOV, signal level and peak image rate. The 12-bit pixels are compressed in cells using a JPEG algorithm.

3.2.2 CCD Detector Properties

Flat field correction maps have been derived but show little departure from unity - for white light typical excursions across the field show $\sim$1.5% peak-to-peak. To date, the flat field correction are not applied.

Calibration images of the **CCD dark-current** are taken roughly every two weeks. The dark current is essentially zero ($\sim$0.1 DN/sec), has changed little during the mission, and varies slightly with temperature. The routine **trace_prep** presently uses a fixed dark current for all exposures, but will soon use a temperature dependant value.

There is a **readout pedestal on the CCD** of almost 87 DN (in non-summing mode). This varies for different summing modes and when different parts of the CCD are readout (e.g. the middle 256$\times$256), but is not dependent on exposure time. It increases in magnitude and becomes less uniform over the CCD with progressively higher summation modes (2$\times$2, 4$\times$4, 8$\times$8). The pedestal decreases slightly as the temperature increases. The routine **trace_prep** presently removes a fixed pedestal but will soon use a temperature dependant value.

The **CCD readout noise** is typically less than 2–3 DN/sec. This is probably electronic in origin and includes a herring-bone pattern on the image. The pattern is modulated by vertical

Bandpass	X-axis (arcsec; WE)	Y-axis (arcsec; NS)
EUV	-2.15	3.60
1600 Å	0.60	-0.60
1700 Å	0.60	-0.90
1550 Å	0.25	-0.65
1216 Å	3.10	-1.25

Table 3.3: Typical TRACE channel alignments with respect to white light. These values were determined on September 24, 1998 - in this case, images in the EUV channels are offset 2.15″ E and 3.60″ N of the white light image. The analysis software applies these, or more current offsets to the data.

stripes that may be caused by the CCD maufacturing process. CCD readout noise is discussed further in the section on image quality.

The TRACE CCD experiences a lot of problems with **orbital background** (i.e. SAA and HLZ's). The effect is greater than was anticipated before launch for HLZ's and data are no longer taken in the (longer exposure) EUV channels when TRACE is in the radiation belts. The problem takes the form of spikes or tracks left in the CCD image. The effects of orbital background are discussed further in the section on image quality (see Section 3.2.7). The approximate timing of passages through the belts can be determined from the *fdss* files (see Section 2.1.2).

3.2.3 Image Coordinates and Pointing

The **pointing coordinates** included in the TRACE index records are for the White-light channel. The EUV channels, and the UV Lyman-α (1216 Å) channel, are offset slightly from the white light and other UV channels - a set of measured offsets is given in Table 3.3. For alignment with data from other instruments, the index record needs to be adjusted - this is done by the routine **trace_wave2point**.

Because of slight differences in the optics, it is necessary to change the **focus** between exposures for the different TRACE channels - an adjustment of ±5 mm in the position of the secondary mirror is provided for this purpose. The focus of each channel has been determined since launch by imaging solar features with fine structure at several focus adjustment positions and determining the best focus by examining the sharpness of each image - e.g. solar prominences were used for the 1216 Å channel. **Note**, a new set of inter-channel offsets has been derived for the new set of focus positions adopted on September 24, 1998 - these are given in Table 3.3. The new focus adjustment positions brings the 1216 Å channel closer to the positions used for the other channels than was the case prior to then.

The **pointing accuracy** of TRACE is probably good to 5–10″ - this may improve when a better wedge calibration is available. The **pointing stability** within a stream of images is very good - better than a few tenths of a pixel. Movements of the quad-shutter causes a ~4″ disturbance that takes a few seconds to damp down, and can leave a residual change of 0.5″ or less.

There is a small **pointing wobble** over the course of an orbit, of the order ±1″. This correlates well with temperature and may be caused by a slight flexing between the guide telescope and the main TRACE telescope; it will be removed by the analysis software once it has been characterized. In movies, an apparent pointing drift can occur if the roll of the spaceraft is not properly aligned to Solar north-south - a 1° error in the roll axis would represent $17''$ at the limb. Since TRACE does not have a star tracker, data from the SOHO/MDI instrument are needed for an absolute **roll calibration**.

Although TRACE collects images over a 8.5×8.5 arcminutes field-of-view (FOV), the images are vignetted by the telescope optics. The **vignetting** is caused by the filter-wheel, is not symmetric about the center of the FOV, and is different for each channel because each uses a different mirror quadrant. For the UV passbands, since the same mirror quadrant and filter wheel position are used, the vignetting should be the same for all channels, although the different focus position for the 1216 Å channel has some effect.

3.2.4 Image Exposure and AEC

TRACE often uses a simple **Automatic Exposure Control (AEC)** algorithm, very similar to its predecessor on Yohkoh/SXT. The algorithm adjusts the exposure index based on a 128-bin histogram of the previous CCD image, which is taken after the removal of bad pixels and the CCD readout pedestal. For most applications, the AEC is programmed to maximize dynamic range while avoiding saturation of the CCD. Simply stated, the approach is to choose the greatest exposure time that will not saturate pixels in the highest percentile of intensity. AEC behavior is controlled by several adjustable parameters which are stored in the AEC table - this contains entries for each wavelength and target class that define thresholds and amounts by which the exposure should be adjusted in case of over- or under-exposure.

Details of the **TRACE Automatic Exposure Control** algorithm, including a description of the parameters used to control it, can be found on the TRACE Web pages at MSU.

3.2.5 Image Timing

The **image time** downlinked in telemetry is the **time that the shutter closes**. The start of the exposure can be determined by subtracting the exposure time. There is an uncertainly of $\sim$0.1 secs in the timing.

3.2.6 Image Resolution

The **plate-scale** of the white-light TRACE images have been determined by J.-P. Wuelser to be:

$$\mathbf{0.4993 \pm 0.0001}\ \text{arcsec/pixel}$$

The plate scale is thought to be effectively the same for all channels, if they are in focus. The **resolution** of TRACE is therefore very close to its planned $1''$.

3.2.7 Image Quality

TRACE uses a modified 12-bit JPEG algorithm for **data compression**. The algorithm has a nearly lossless mode that preserves 12-bit data with a maximum error of 1 count and a wide range of lossy options which are tailored to different image characteristics. The image is compressed in cells of 8×8 pixels - these can clearly be seen if a decompressed TRACE image is closely examined.

In itself, JPEG compression affects an image in a manner that is well understood, but for TRACE there are some additional effects described below:

Orbital Background
The TRACE CCD is significantly affected by orbital background (i.e. the SAA and HLZ's). The problem takes the form of spikes or tracks left in the CCD image. It is most acute with the long exposures in the EUV channels; the shorter exposures of the UV channels are much less affected. Because the spikes are not removed on-board, the intensity distribution of the spike is spread by the JPEG compression leaving a residual signature that is hard to quantify and which affects the accuracy of the diagnotics.

CCD readout noise
The CCD image is affected by readout noise that is probably electronic in origin. It takes the form of a herring-bone pattern on the image; the pattern is modulated by vertical stripes that may be caused by the CCD maufacturing process. Although its amplitude is small (typically 2–3 DN), the noise creates spikes in the image FFT; this can be removed with Fourier techniques.

Filter Mesh Diffraction Pattern
TRACE uses a standard design entrance filter in which the support mesh is an electroformed metal fashioned as a regular grid of fine wires in a rectangular pattern. This mesh acts as a diffracting element, which has a regular, well characterized pattern in the focal plane. It is most noticable if a bright, compact flare kernel is in the TRACE field of view. The pattern can be removed during data analysis by straight forward Fourier techniques. A **detailed study of the diffraction pattern** is available under the instrument section of the TRACE Web pages at Lockheed-Martin.

Atmospheric Absorption
For several weeks either side, and while TRACE is in its eclipse season, the signal observed by TRACE is attenuated by the Earth's atmosphere during parts of its orbit and the response of the EUV lines is compromised. This effect is present in each orbit for several minutes either side of the actual eclipse (see Appendix B.4). While the images are still fine for morphological studies, they should only be used for diagnostic purposes with extreme caution.

For the most part, these effects can be corrected by routines called by the analysis routine **trace_prep** (see the User Guide, Section 2.4). The CCD readout noise and mesh diffraction pattern can both be removed by Fourier techniques (using **trace_knoise**), and although this would be better done before compression, it is still remarkably effective. The spikes and streaks are removed by a number of techniques (using **tracedespike**, etc.) - unfortunately any image that is badly affected by particle spikes has a residual pattern that makes it impossible to use for quantitative analysis.

3.3 TRACE Instrument Response

3.3.1 Sensitivity

The characteristics of the TRACE channels are given in Table 3.4, where the sensitivity is defined as:

$$\text{Mirror Reflectivity} \times \text{Filter Transmission} \times \text{CCD Quantum Efficency}$$

Wavelength Å	Ion Indentification	Bandpass Å	Sensitivity	Temperature Log (K)
5000	Continuum	broad	.00010	3.6 – 3.8
1700	Continium	200.0	.00006	3.6 – 4.0
1600	C I, Fe II + cont.	275.0	????	3.6 – 4.0
1550	C IV + cont.	20.0	.00068	4.8 – 5.4
1216	H Lyα	84.0	.00055	4.0 – 4.5
171	Fe IX	6.4	0.017	5.2 – 6.3
195	Fe XII	6.5	0.011	5.7 – 6.3
284	Fe XV	10.7	0.0035	6.1 – 6.6

Table 3.4: TRACE Channel Characteristics

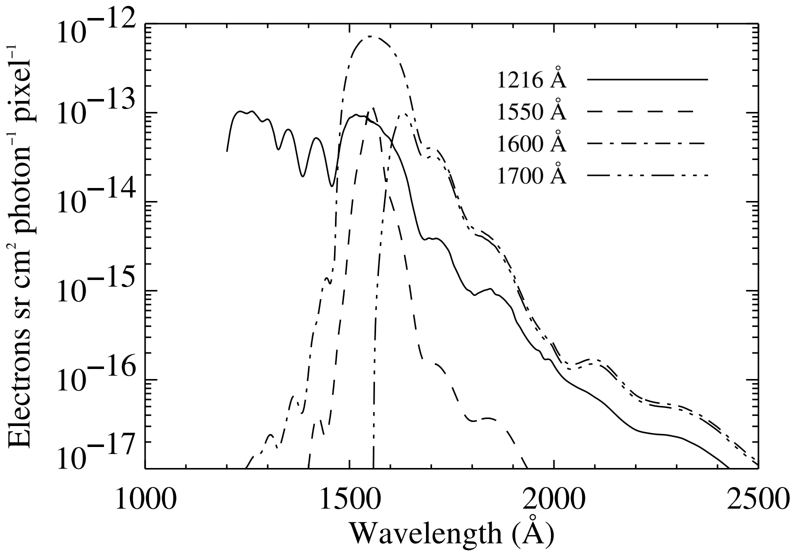

Figure 3.2: The combined TRACE optical and UV response.

The wavelength response of the TRACE optical and UV channels is shown in Figure 3.2, and of the EUV channels in Figure 3.3. The temperature response of the TRACE EUV quadrants are shown in Figure 3.4.

Details of the **manufacture of the TRACE mirrors and filters**, and the **sensitivity of the TRACE channels**, and the **calibration of the instrument** are given on the TRACE Web pages at SAO and Lockheed-Martin.

3.3.2 On-orbit characterization of the Flat Field Response

On-orbit flat fields of the TRACE CCD and optics in WL and 1700 Å wavelengths have been generated using the the Kuhn-Lin flat-field algorithm. This algorithm uses a number of images at slightly shifted locations on the CCD, with the images out of focus to reduce contrast.

The **WL flat field** is quite flat and of good quality (in the sense that it corrects WL images to high accuracy). The flatness and quality has changed very little since launch, with a difference image of two flat fields taken 7 months apart showing $\pm 1.0\%$ peak-to-peak variations,

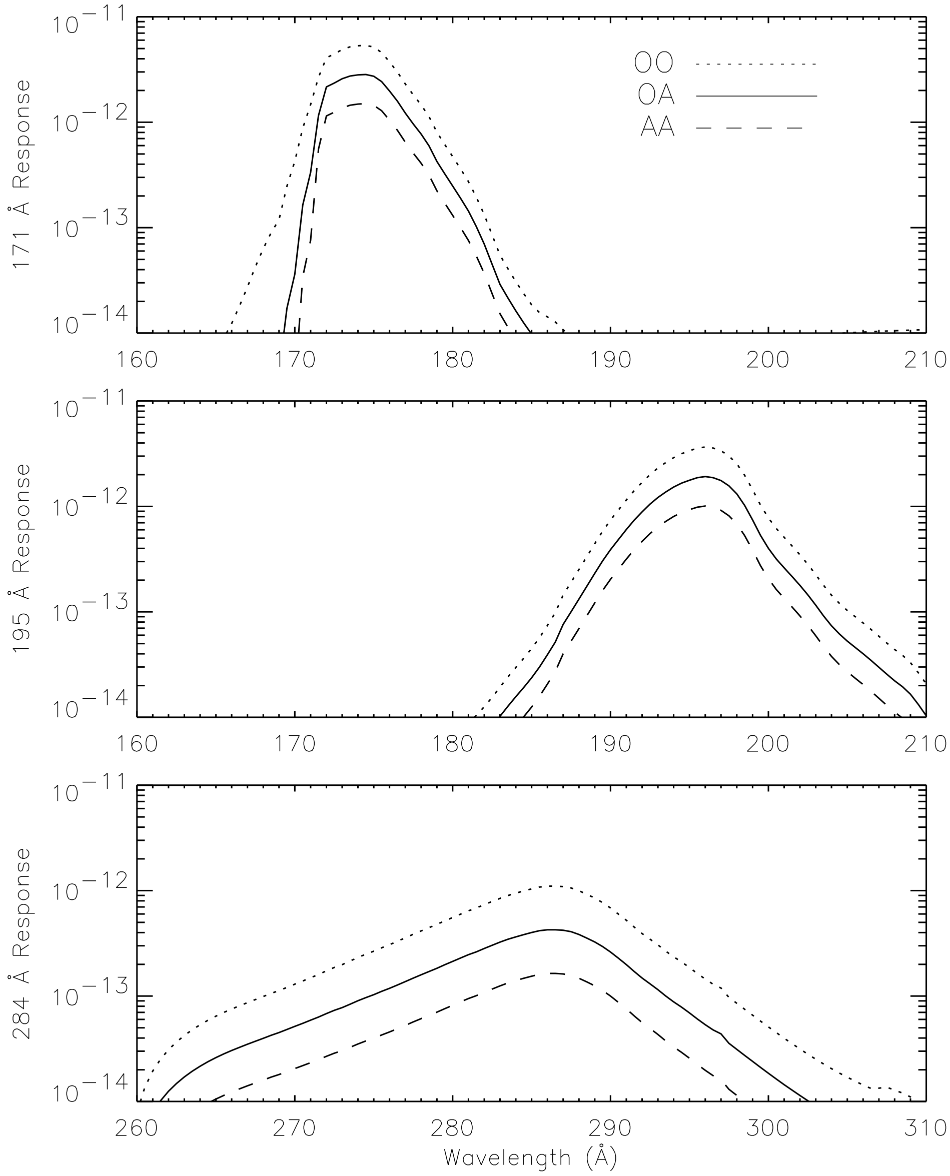

Figure 3.3: Spectral response in the TRACE EUV quadrants, in units of electrons sr cm^2 photon^{-1} pixel^{-1}. The different line styles show the filter combinations defined in Table 3.2

the same range as the flat fields themselves.

Several features are evident in the WL flat field of Figure 3.5a. There are many small dark spots of ∼1–3 pixels across with intensities of 20–80% of the normalized field. These were present on the CCD prior to launch and correct well in the WL images. Because the spots interact poorly with the JPEG data compression algorithm, most of them are treated on-board as bad pixels and are replaced by a good nearest neighbour.

Larger spots (∼50–60 pixel diameter with an intensity of ∼96–98%) are also evident on the WL flat field. These are most likely shadows of dust particles on the fused silica filter in the aft filter wheel. They disappeared when a WL flat field was generated from images that did not use the fused silica filter. In these flat fields, another set of larger (∼80 pixels), less well focused, and lower contrast (∼97–99% intensity) spots became apparent as a regular array on

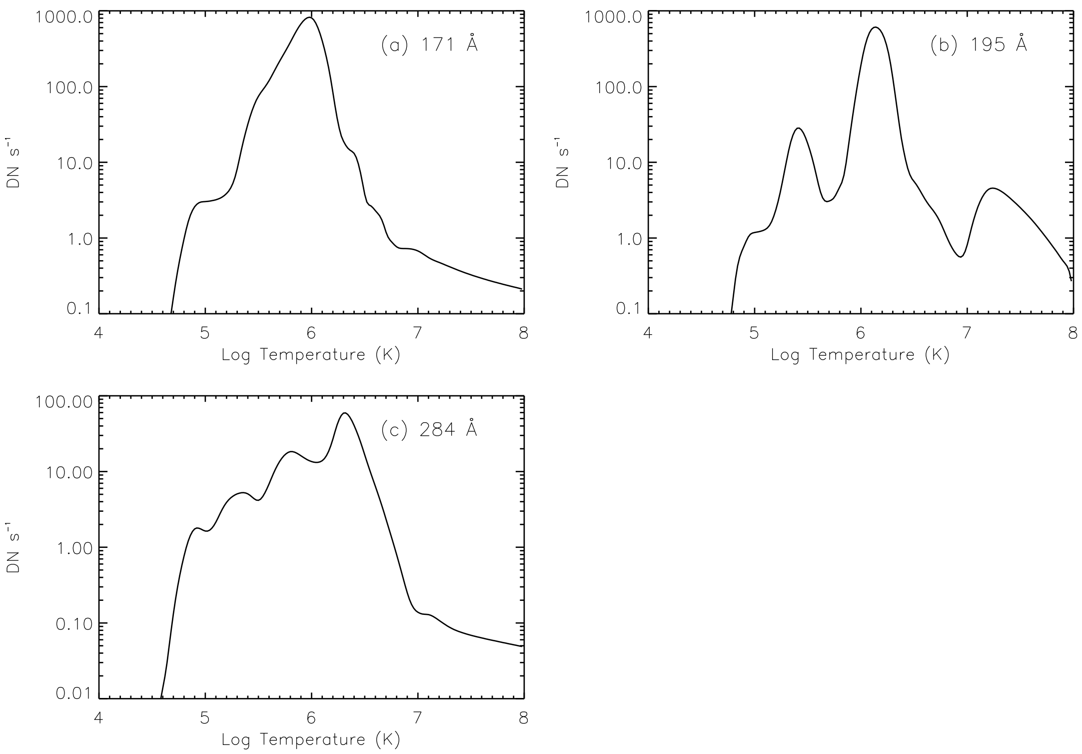

Figure 3.4: Signal at the CCD for each of the TRACE EUV quadrants as a function of source temperature for an emission measure of 10^{44} cm^{-3}.

the CCD. This array was seen at several wavelengths during CCD testing prior to launch and is believed to be a CCD fabrication artifact. All of these features correct well in the WL images.

A pair of bad partial rows (CCD columns actually) are visible in the WL flat field. In addition, vertical and horizontal dark lines are seen every 24 pixels at very low contrast. These are a CCD fabrication artifact.

The **flat field at 1700 Å** (Figure 3.5b) shows some degradation in the relative response across the field of the CCD in the center. Although 30 images were utilized in the analysis of the flat field, most of the CCD structure is not resolved at this wavelength due to higher contrast, lower count rates, and changing structure in the original images when compared to those in WL. Despite defocusing, the 1700 Å images in quiet sun have network features three times brighter than average intensity. However, the pair of bad partial pixel rows observed in the WL flat field is also present in the 1700 Å flat field.

The 1700 Å flat field for 7 January 1999 demonstrates a degradation of about 5–8% in the center region of the CCD with a small portion degrading up to ∼10%. A 1700 Å flat field from 9 October 1998 displayed about a 2–5% relative degradation in the same region. This relative degradation in response across the field is probably occurring in the Lumogen coating on the front of the CCD. A similar loss has been noted near the CCD center in EUV images of loops on the limb when compared to images with the limb moved to regions near the outer, non-degraded portions of the CCD area. The decrease in **Lumogen sensitivity** near the center of the CCD is probably a result of damage by the accumulated EUV dosage. However, the degree of degradation is less than was anticipated.

Efforts are ongoing to generate satisfactory flat-field images for the other lines. The EUV

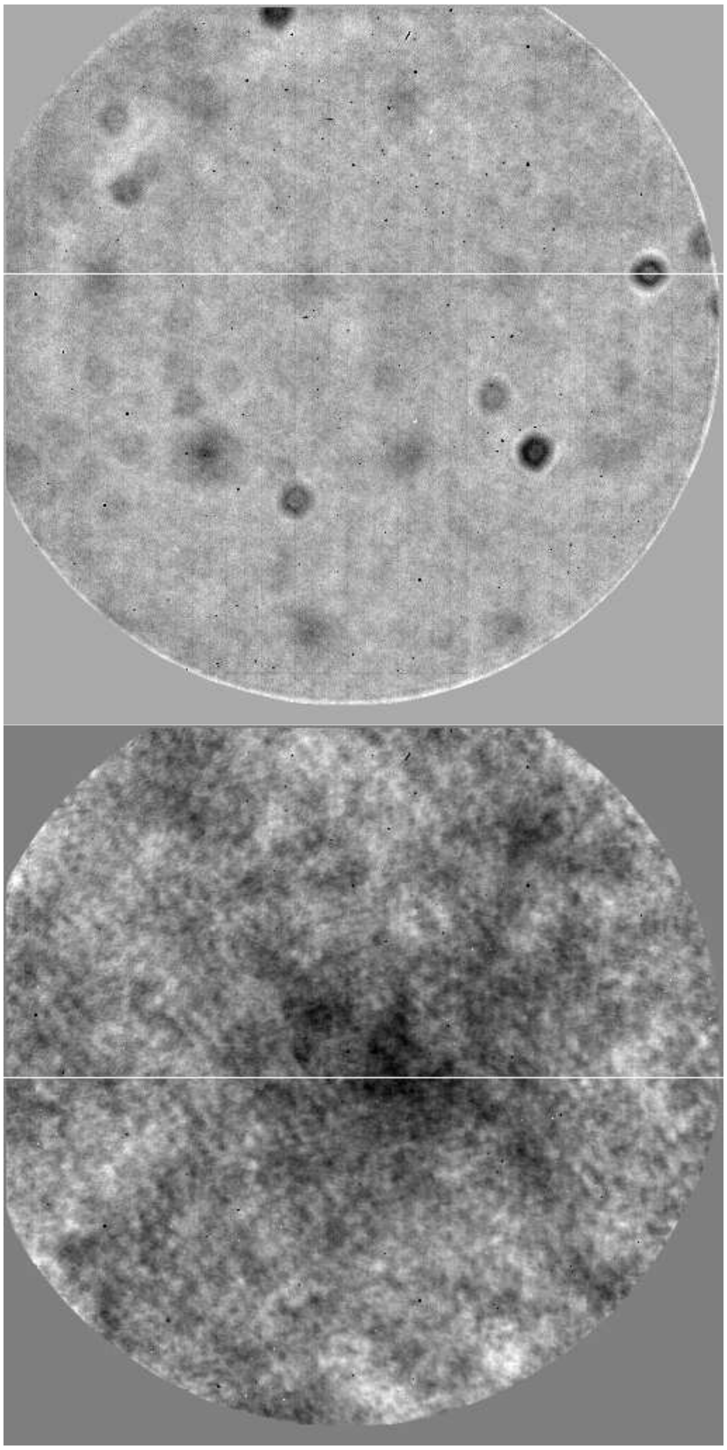

Figure 3.5: The TRACE flat fields measured on 13 January 1999. a) White-light (WL) flat field (top). Typical excursions across the field show variations of $\sim \pm 1\%$ peak-to-peak. Some of the large blobs are dust particles on the fused silica filter; others are intrinsic to the CCD. b) Flat field in the 1700 Å channel (bottom). The somewhat mottled appearance is caused by the photospheric network.

wavelengths are particularly resistant to this method, as they are of extremely high contrast with much of the image at a very low count rate. Flat field data taken in the 171 and 195 Å channels in May 1999 suggests that the degredation in sensitivity in the EUV is similar to that at 1700 Å.

For the **most recent information on flat field measurements**, see the TRACE Web pages at Lockheed-Martin.

3.4 TRACE Diagnostic Capabilities

TRACE can provide information on the morphology of the magnetic field directly from its images and can also provide a number of other diagnostics.

When TRACE is in or near its eclipse season, care should be taken when using data for diagnostic purposes because of the effects of **atmospheric absorption** – see Appendix B.4.

3.4.1 Temperature

The three EUV channels overlap in temperature coverage and can be used to investigate the temperature of the coronal plasma. As all the EUV wavelength bands are dominated by different ionization stages of iron, ratios do not depend on a knowledge of iron abundance. The band ratios are extremely sensitive to temperature changes, varying by factors of up to 40 over typical coronal temperature ranges. This compares favorably with broad-band temperature diagnostics (e.g., factors of 2–4 for Yohkoh/SXT temperature ratios).

Figure 3.6 shows the relative contributions of the three EUV bands. Ratios of the bands are multivalued and are ambiguous for certain temperatures. Obtaining images in all three EUV channels can help to resolve the ambiguity if the plasma is nearly isothermal. In practice, this is only likely to work if careful background subtraction is done. Without background subtraction, temperature ratios yield inconsistent or nonsensical results in nearly all cases.

It is surprisingly easy to derive differential emission measure distributions from TRACE data, primarily because there are few channels and so an inversion by linear techniques is well-behaved. There are, however, several pitfalls:

1) The DEM is meaningful only under the assumption that most of the emission measure is in the range 0.4–3 MK. Thus, it is applicable mainly to non-flaring active regions, quiet sun, and polar plumes.

2) There are only three channels, so the DEM must be composed of just three basis elements. The choice of basis can have an effect on the properties of the result.

3) The resulting DEM curves are not always positive for all temperatures. This may result from excessive noise (if the DEM is done for a single pixel) or simply a choice of basis that is ill-suited to representing the actual temperature distribution. Integration over tens or hundreds of pixels will virtually always yield a positive DEM.

3.4.2 Emission Measure/Densities

For the optically thin lines, a simple emission measure is derived by merely dividing the emission function into the count rate at the calculated isothermal temperature. This is dependent on the abundance of iron for the EUV channels and the abundance of carbon for the C IV channel, which can vary in space and time by factors of up to 4. Hence unless there is an independent abundance measurement (e.g., from SoHO/CDS or SoHO/SUMER) the true emission measure

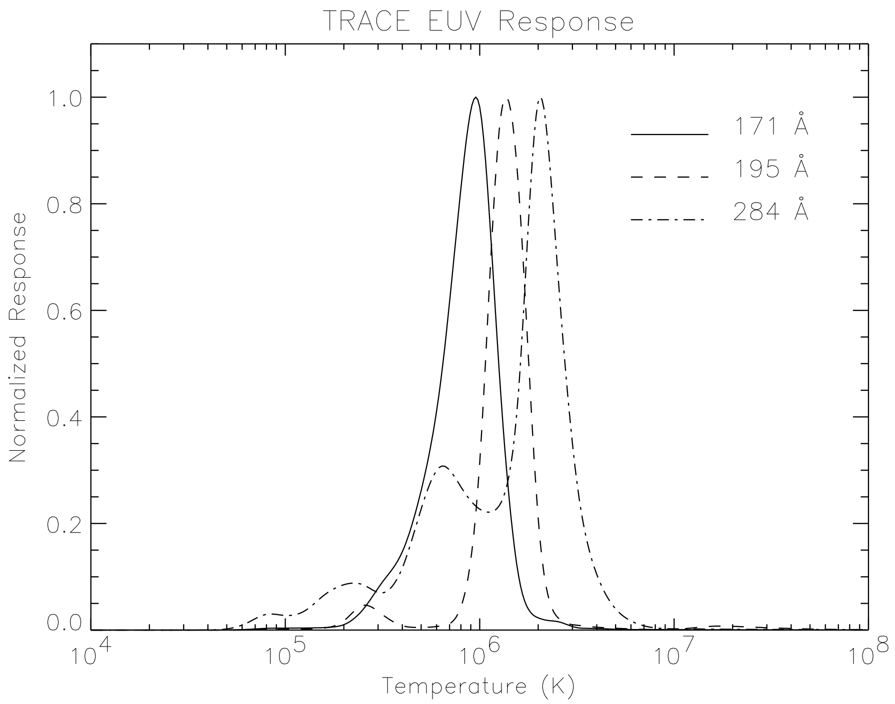

Figure 3.6: Relative contribution versus temperature in the three EUV bands

is uncertain by the same amount as the abundance. Similarly, density estimates based on the emission measure/volume technique are uncertain by the root of the abundance uncertainty and any filling factor. The X-ray Polychromator on SMM found filling factors of 0.01 to 0.001 when density diagnostics were available during flares. However, the XRP pixels were about 15″ FWHM and so TRACE has about 900 pixels for every 1 pixel of the FCS. Since TRACE therefore has much larger filling factors, density estimates are significantly improved.

3.4.3 Observing C IV Lines

Although the C IV resonance lines at 1548 and 1550 A are both strong and relatively isolated, the current technology of interference filters is not quite good enough to isolate them in a single image. The filters used in previous rocket instruments at LMSAL have a full-width at half maximum (FWHM) of about 30 Å and allow a sizable contribution from nearby C I and Fe II emission lines. They also have a weak secondary maximum at about 1700 Å and a long wavelength tail that admits troublesome amounts of near-UV radiation These effects must be evaluated to get reliable results, especially in quiet regions and the chromospheric network.

TRACE uses a set of three filters to observe and correct the C IV images (Handy *et al*, 1998). The filters characteristics are:

1) 1550 Å filter - 30 Å FWHM, centered at 1550 Å. Observes C IV + C I, Fe II lines + continuum.

2) 1570 Å filter - 30 Å FWHM, centered at 1570 Å. Observes C I, Fe II lines + continuum.

3) Continuum only - Same interference coatings as 1), but made on a substrate that rejects light below 1700 Å.

Reduction of a set of three observations uses simple matrix methods. Let P(i) represent the image made with the ith filter. Let I(j) represent the intensities of the C IV lines (j=1), the chromospheric contribution (j=2) and the long wavelength continuum (j=3), respectively. Then the matrix representation of the set of images is:

$$[P] = [A][I]$$

where [P] and [I] are column vectors and [A] is the matrix A(i,j) representing the transmission of the ith filter to the jth wavelength. The formal solution is:

$$[I] = [a][P]$$

where [a] is the inverse of [A]. The transmissions A(i,j) is measured during instrument calibration; the matrix solution is expected to be well behaved because of the nature of the problem. (Note that A(3,1) and A(3,2) are both zero and that A(l,j) and A(2,j) are linearly independent because of the way the filters are designed).

The reduced observations provide images of the chromosphere (from the C I and Fe II lines) as well the transition zone. The long wavelength continuum image is probably formed somewhere between the high photosphere and the temperature minimum, based on the work of Foing (1986). Finally, images taken through the UV entrance filter only are dominated by wavelengths near 2500 Å, which arises in the photosphere. These images are used extensively for co-alignment with SoHO and other observations.

3.4.4 Aeronomy

Since it is in a Sun-synchronous, polar orbit, at certain times of the year, as the declination of the Sun changes and the orbit precesses, TRACE will look through increasing amounts of the Earth's atmosphere. The TRACE line-of-sight will make a series of cuts at different heights through the atmosphere over a variety of latitudes and longitudes producing an attenuated signal at the detector. The absorption will primarily be due to oxygen (O_2) and ozone (O_3) at UV wavelengths (>1000 Å), and nitrogen and water vapour at XUV wavelengths (171–284 Å). The ratio of thermospheric oxygen to mesospheric ozone can thus be studied by TRACE - similar studies were made by the SMM/UVSP instrument.

See Aiken et al., 19?? for more information on this type of science.

3.5 References

TRACE Investigation and Technical Plan (Phase III & IV), August 1994, LMSC P017270P-1
"The Transition Region and Coronal Explorer", 1999, Handy et al., Sol. Phys., in press.
"UV Observations with TRACE", 1998, Handy et al., Sol. Phys., 183, 29
"Thermospheric Molecular Oxygen??", 19??, Aiken et al., ???.

A Useful TRACE Software

TRACE Calatog and Ephemeris	
trace_cat	read TRACE catalog (via setup/call to 'read_genxcat')
view_trace_mosaic	View TRACE mosaic for date closest to selected date
rd_fdss	To read the FDSS files and put the data into structures
pr_fdss	Print an FDSS files for the selected time interval
TRACE I/O	
read_trace	Read TRACE data image files, headers or headers & data
trace_cat2data	use catalog entries to get the data (or filelist/dset)
read_analist	Reads a list of files and frame indices created by the ANA Browser
write_trace	write trace index/data to specified type of FITS or WWW file
trace_sswhere	Select subset of TRACE images with widget interface
struct_where	filter a structure array; return SubScripts which satisfy
grid_data	return gridded subset of input (fixed cadence if no gaps)
tim2dset	Given a structure (roadmap or index), find the dataset with the time closest to an input time.
read_trace_fov	Reads selected sub-image, etc.
trace2x	Ingests the ANA Browser's Fav Img file and reads each image and writes out as gif files or creates an IDL array.
open_anacube	Opens ANA data cube for reading with WINDOW_ANACUBE
window_anacube	Read ANA image cube opened with OPEN_ANACUBE; windowed region selectable by cursors.
close_anacube	Close ANA data cube opened with OPEN_ANACUBE
Plotting TRACE Data	
slide_image	Create a scrolling graphics window for examining large images.
utplot	Plot X vs Y with Universal time labels on bottom X axis.
plot_trace	N.A.
lcur_image	To display a normalized light curve plot for image data.
plot_arc	To allow a user to mark an arc on an image and the intensity along that arc will be plotted
index2map	Make an image map from index/data pair
plot_map	Plot an image map
ssw_track_fov	Extract a sub-field from the SSW-compliant (2D) image data based on the reference time and reference coordinates.
xstepper	Widget interface/ X-Windows data cube reviewer
trace_special_movie	TRACE movies -> WWW
image2movie	convert an image file sequence (3d, gif, jpeg) to mpeg or gif animation URL Reference: http://www.

Calibration, etc.	
trace_prep	Process TRACE image(s).
tr_dark_sub	Subtract a previously averaged, 1 second exposed dark current image, which includes an ADC offset, from a TRACE image after selecting and reading in the closest dark fits file for the first image.
tracedespike	despike an image using a median filter (default) that eliminates spikes exceeding 'threshold' percent (detault = 15%), or using a statistical correction that corrects pixels diviating by more than
trace_unspike	N.A.
trace_destreak	N.A.
trace_cleanjpg	N.A.
trace_knoise	Remove readout noise from TRACE images by identifying and zeroing spikes in the FFT.
trace_unspike_time	temporal despiking of TRACE images using neighbor images
trace_wave2point	apply wavelength dependent adjustments to trace pointing tags
Diagnostics and Modelling	
civ_subtract	Given an arbitrary set of UV images from TRACE out of the 1550, 1600 and 1700 Images, generate a "Clean" C IV image, per Handy et al.
trace_t_resp	Returns TRACE EUV response to a solar plasma at temperature T.
trace_dem	Calculate differential emission measure and EM weighted average temperature for a set of TRACE images in all three EUV wavelengths (171, 195, 284).
trace_dem_setup	Calculate and invert the temperature response matrix for a 3-component model of the differential emission measure.
trace_tbasis	Implement three DEM basis functions, indexed 0, 1, 2, for use with TRACE_DEM and TRACE_DEM_SETUP.
trace_tmap	Compute temperature and emission measure maps based on an isothermal model.
trace_isothermal	Create temperature and emission measure maps from TRACE EUV images, assuming an isothermal plasma along the line of sight for each pixel.
trace_t2em	Given an array of possible temperatures and one, two, or three pixel values in DN for any of the TRACE EUV passbands, calculate the corresponding
trace_disp_tem	Create a map of temperature and emission measure.
trace_teem	calculates temperature and emission measure from a wavelength pair of 2 TRACE images (e.

Utilities	
trace_files	return trace reformatted file names between t0 and t1
trace_list_index	produces listing of TRACE index structure
trace_colors	return TRACE wave dependent RGB; optionally loadit
trace_scale	scale TRACE images (SSW wrapper for Karel Schryver routines)
tr_ext_subimg	To extract a sub image out of a TRACE image with no change of the image resolution
trace_data_filter	return subscripts of 'good' or 'bad' trace data
tr_get_disp	Given a datacube of images, measure the rigid displacement between each image and the first in the cube and optionally shift each image to coalign the entire cube.
align_cube_correl	align a data cube via cross correlation; update coordinates
normalize_cube	empirically normalize cube of data from relative signal levels
grid_data	return gridded subset of input (fixed cadence if no gaps)
trace_uniq_movies	identify uniq movies from input structures (index or catalog)
GTT Functions	
gt_tagval	return value stored in specified tag - (nested N-deep struct OK)
gtt_orbit	To read the FDSS files and output an array of answers corresponding to the array of input times based on code
gtt_info	To extract information from the TRACE index information.
gtt_ccd_cen	To compute solar coordinates of the CCD center for a trace image index
gtt_mnem	TRACE routine to extract mnemonic information from data
gtt_pnt	N.A.
gtt_sciplan	N.A.
gtt_shutter_exp	Compute and return shutter exposure time from index of an image.
gtt_wave_tru	Compute and return wave length name from index of an image.

B TRACE Instrument Items

B.1 Amount of Instrument Data per day

On average, TRACE has generated just over 3 GBytes of data per week – by the end of the first year of operation it had produced just over 161 Gbytes of data. A detailed breakdown of the **data generated each day by TRACE** can be found on a page in the Web version of this document.

B.2 Missing and Lost Data

TRACE data may be lost for a number of reasons: data overflow in the on-board memory, missed downlink, etc. Often, the data is just missing as the result of a bad or missed transmission from the ground-station. Where possible, the TRACE team attempt to recover this data by retransmission and reformatting, and update the TRACE data archive when this is done.

The first major data gap was at the start of the first **eclipse season** when TRACE was shutdown from 17:00 on 7 November 1998 to 12:00 on 11 November 1998. Each year there is a gap of several days when TRACE was switched off as a precaution during the **Leonid meteor shower** (16–19 November 1998; 17–19 November 1999).

A list showing the status of **missing TRACE data files** can be found on a Web page at Lockheed-Martin (**<http://vestige.lmsal.com/TRACE/Data/Missing/>**).

B.3 Searching for TRACE Data

There are several ways of searching for particular **TRACE** data.

The **TRACE DATA CENTER** uses a **Search Engine based on the TRACE Data CATALOG**. The user select parameters in a web-based form and submits the request; an IDL task linked to the page generates quicklook images and allows the selection to be refined before creating a FITS file of the selected modes. See URL:

<http://vestige.lmsal.com/TRACE/trace_cat.html>

Alternatively, you can use a **Search Engine based on the TRACE Observing PLANS** provided by the **TRACE EOF**. The user enters search parameters (e.g Objective/Science, Date, JOP or Campaign No., FOV center, etc.) and is presented with a list of the planned observations that match the parameters. See URL:

<http://chippewa.nascom.nasa.gov/cgi-bin/trace_announce/db.cgi>

There is also a **TRACE Event List** - sorted by **event type** that has been assembled by team at the **TRACE EOF**. The user selects a type of event and a time interval and is presented with a list of the dates that such events were observed. See URL:

<http://chippewa.nascom.nasa.gov/~despres/data_archive/datarch1.html>

B.4 The Eclipse Season

The TRACE spacecraft is in a Sun-synchronous orbit. Every year, for about 6 weeks either side of the Winter Solstice, TRACE is eclipsed for part of its orbit. The timing of the eclipse may be determined from the ephemeris files (see Section 2.1.2). The first eclipse season started on 7 November 1998 and ended on 5 February 1999; the second covered a similar interval (7 November 1999 to 5 February 2000).

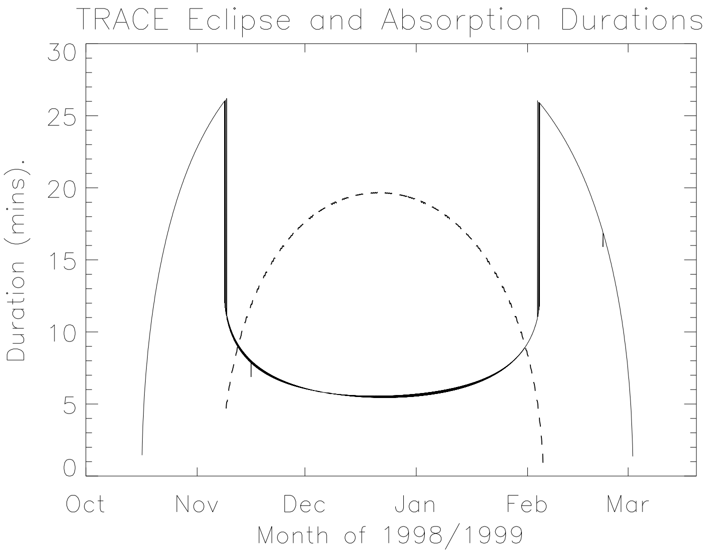

Figure B.7: Duration of the eclipse (dashed) and absorption periods in each orbit

While TRACE is in its eclipse season, and for several weeks either side, care should be taken when using TRACE data. In each orbit, for several minutes either side of the eclipse, the signal is still attenuated by the Earth's atmosphere and the response of the EUV lines is compromised. The attenuation on successive images changes rapidly and the effect is very difficult to predict. While the images are still fine for morphological studies, they should only be used for diagnostic purposes with extreme caution.

The effects of **atmospheric absorption** are present for several weeks either side of the interval when TRACE is fully eclipsed and extends from mid-October to the beginning of March. The durations of the eclipse and absorption for each orbit are shown during the first eclipse season in figure B.7 - the eclipse duration is the dashed curve in the centre. The routine **trace_prep** warns users if the data they have selected were taken during these times.

C Installing SolarSoft

SolarSoft is described on Web pages hosted at Lockheed-Martin in Palo Alto, California - see the URL **<http://www.lmsal.com/solarsoft/>**. Pages referenced from this home page describe the **Installation** and **Upgrading** of the **SolarSoft** tree - the steps necessary to **configure your system** are also described. Another page describes **some of the concepts of SolarSoft**.

It is not necessary to install the whole of **SolarSoft** to analyse TRACE data. For TRACE, when requesting an installation through the **SSW Installation Form**, you should request **TRACE** under **Others...**, and request **binaries** and **ANA** under **Packages...** Once you have made your **SolarSoft** installation, it is recomended that you update it regularly.

In order to use some of the TRACE software, e.g. **trace_prep**, you need some of the ancillary TRACE files and therefore need to install **$tdb** branch of the **SolarSoft DataBase (SSWDB)** tree. This is a separate tree to **SolarSoft** and will require a separate mirror package - see the web page at Lockheed-Martin describing **SolarSoft DataBase (SSWDB) Installation** if you wish to install the database branch. **Note**: Take care when requesting the *mosaics/* sub-branch, it is quite large.

D ANA and the ANA Browser

A **description of ANA**[1], together with an on-line manual and instructions on how to install it, can be found on one of the Lockheed-Martin Web sites on URL **<http://ana.lmsal.com/>**. The latest version merges two strands of **ANA** that had evolved (developed by Dick Shine and Louis Strous), and is backwardly compatible with both earlier versions (with some minor exceptions).

If you need more information about **ANA**, or have any questions, contact Zoe Frank (zoe@lmsal.com), Louis Strous (strous@lmsal.com), or Dick Shine (shine@lmsal.com).

E Web and Others Versions of the TAG

The **TRACE Analysis Guide (TAG)** may be viewed as a Web document on the URL's:

- **http://www.lmsal.com/~bentley/guides/tag/**
- **http://umbra.nascom.nasa.gov/~bentley/guides/tag/**
- **http://surfwww.mssl.ucl.ac.uk/guides/tag/**

The **TAG** is available as a **PostScript document**; it is in two formats: for **A4 paper**, and for **US Letter paper**. Choose the one appropriate for your printer - it is designed to be printed double-sided. If you want a printed copy of the **TAG**, the PostScript version is recommended since the screen representation of special characters in the Hypertext version does not produce good printed output.

The **TAG** was prepared at the **YDAC** (located at the Mullard Space Science Laboratory, University College London) by **Bob Bentley**. The Hypertext version was translated from LaTeX using **TtH**, and further formatted using **IDL**.

In the Web version of the **TAG**, the **changes between versions** are listed.

This version of the **TAG** was prepared on: **January 27, 2001**

[1]ANA - A Non Acronym

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