I. Objective :

The objective of this code is to provide a tool for assessing the importance of the stray light component contained in spectroscopic solar data. It has been conceived initially to treat data of the CDS and SUMER instruments, but it can be applied to spectral data from other spectrometers or imagers (EIT, TRACE, etc.), as long as one knows their instrumental spread function. It is essentially designed for observations of very dark regions such as coronal holes, observed beyond of the solar limb.

II. Principle of the calculation method :

Stray light results from small imperfections (small compared to wavelengths) of telescope mirrors. These shortcomings are characterized by an instrumental diffusion function (PSF, Point Spread Function) or instrumental function. This function gives the law of distribution of the energy spread according to the angle of diffusion. It means that the image of a point source on a detector after reflection on the mirror of the telescope is not ponctual but forms a spot, brilliant in its center. In the case of the CDS and SUMER instruments, the energy is mainly distributed within an angle lower than 2 arcsecs that corresponds to their spatial resolution; for details concerning the specifications and the performances of these instruments we refer to publications of Harrison and al. (1995) for CDS and Wilhelm and al. (1995) for SUMER. This seems to indicate that one should be able to neglect this component in spectral measurements. But, we observe an extended source, the Sun. It is composed of a multitude of ponctual sources. In these conditions, the stray light on any point of the image of the Sun reflected by the telescopes, is the sum of the contributions of all other points. Besides, the emission that comes from the Sun is not distributed in an uniform manner. There are strong contrasts in emission according to whether one observes an active region or a coronal hole, on the disk or beyond. The survey of a polar coronal hole from observations obtained with CDS and SUMER showed that this component of stray light can not be neglected, reaching up to 80 % of the measured emission (David and al. (1998) and David and al. (1999, submitted)).

As said previously, stray light in a point of the image of the Sun (point of reference) formed at the level of the detector is the sum of the contributions of all the other points of this image. Therefore, its evaluation consists in determining stray light from every point. For that, it is indispensable to know:
- the law of distribution of the spread energy in function of the angular distance, given by the PSF function.
- the brightness associated to every pixel of the image of the Sun (without component of stray light).

These two quantities constitute the main input parameters of the procedure of calculation of stray light.

• <u>The PSF function</u> :

CDS :

Initially this code has more especially been conceived for the CDS instrument.
The PSF of the CDS telescope has been measured before the launch by Bernd Aschenbach of the Max-Planck Institute of Garching (private publication), with a monochromatic source at 68 Å. Because of the intrinsic spatial resolution of the detector used for this measurement, the PSF function is only determined for $r > R_{min68} (R_{min68} = 25\ arcsec)$; r is the angular distance from the optical axis. PSF depends on r and the azimuthal angle ϕ that define the position of a point in the plane of detectors. The normalization used here is given by

$$\int_0^{2\pi} \int_0^{\infty} PSF_{68}(\phi, r)\, d\phi\, r\, dr = 1$$

which means that we consider the quantity of incident energy equal to one. The calibrations showed that this function can be described solely in function of r (circular symmetry). That is

$$2\pi \int_0^{\infty} PSF_{68}(r)\, r\, dr = 1$$

Because of the strong dependence of the diffusion function with the wavelength of the source, we cannot use this function directly, but an extrapolation in the range covered by the spectrometers of CDS. The method of extrapolation has made the object of an in-depth survey and has been validated by observations (David et al. (1999), in preparation). One could thus reduce the indetermination of the function to $10 arcsec$, instead of $25 arcsecs$ for the calibration measurement. Also, in the case of CDS, while introducing as input parameter the wavelength of the measured line, a procedure calculates automatically the corresponding PSF.

<u>Other instruments</u> :

This code can be applied to other instruments. In this case, the PSF function becomes an input parameter. It should be analogous to the one of CDS, that is, normalized to one as previously and supposed to depend only on r. As for the wavelength dependence, it cannot be taken in account by this code ; it depends on the instrumental features (type of mirror).

Table 1: Stray light contribution computed from and EIT image, in regions beyond the North pole limb

E-W position (arcsec)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S-N position (arcsec)	980.0	1000.	1050.	1100.	1150.	1200.	1250.	1300.00	1350.
distance from limb (arcsec)	10.	30.	80.	130.	180.	230.	280	330.	380
S*(%) (CDS)	11.14	7.63	3.56	2.14	1.51	1.19	1.03	0.94	0.88
S*(%)(SUMER)	6.56	3.2840	1.67	1.24	1.06	0.96	0.91	0.88	0.86

S* the difference (in percentage) between the straylight contribution calculated with the whole EIT image and the one determined by taking account only a portion of that same image (as shown in figure 1).

- Solar brightness :

To determine the contribution of each point of the image of the Sun upon the reference one, it is necessary to know its brightness without component of stray light, because the PSF function gives the proportion of energy spread according to the distance to the reference point solely. The above-mentioned study of a polar coronal hole showed that the stray light is important only for regions with very weak emission, that is beyond the limb. One can safely consider therefore as negligible the diffusion in brightness measurements made on the disk.

In this case, the regions that contribute are the most brilliant, the corresponding emission measure is not very polluted by the instrumental diffusion. To calculate the instrumental component, it is therefore necessary to dispose either of an image of the Sun at the wavelength considered, or of a model giving the brightness distribution as a function of the distance to the center of the disk (coronal or chromospheric model). Therefore, it can be sufficient to have only a portion of the brigthness of the solar disk, the nearest one from the region that one studies. For example, we calculated the straylight at different distances from the center of the solar disk, beyond the limb (North pole) in two cases (for more details see the annex A):
- with the whole image of sun (EIT image, at 171 Å, figure 1),
- only by considering a portion of the disk, 20 degrees of angular area, centered in the direction of the region considered. In this last case one used this portion to get an average profile (brightness as a function of the distance to the center of disk, see figure 1). For points near 10 arcsec of the limb the difference between these two methods is about 12%. This difference decreases rapidly with distance, it is less than 4% at 80 arcsec (see Table 1). Moreover, the proportion of stray light in the emission measured, inside 100 arcsec is less than 10 %. In summary, it seems sufficient to know only a portion of the solar disk brightness to determine the stray light of a region beyond the limb.

III. Description and utilization of the code :

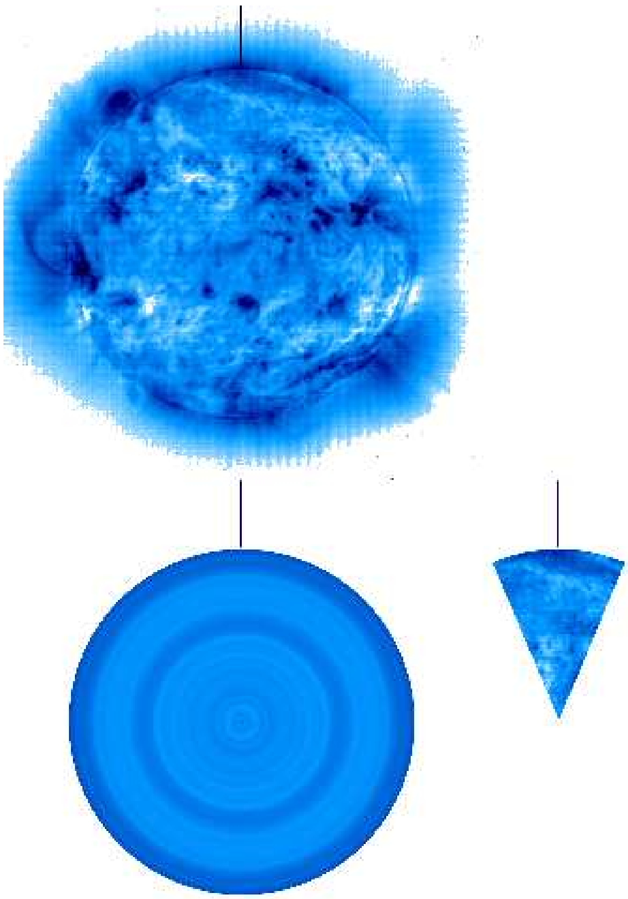

Figure 1: EIT image used in the calculation of straylight contribution and the average model obtained with only a portion the solar disk (angular extension of 20 degrees). The vertical lines represent the position of the reference points considered for the calculation.

<u>CAL_STRAYLIGHT</u> :

The calculation of the stray light component is assured by this function. We are going to describe now what are the different input and output parameters.

Input parameters :

• The first parameter of entrance is **POSITION_REFPOINT**. It is the only obligatory parameter. It contains the position of the location where one wants to determine the instrumental component. The position can be expressed in two manners: position of the point (or points) for which one wants to determine the instrumental component. The input parameter is a 2D array t(2, *), where t(0, *) corresponds to the coordinates in the East-West direction and y in the South-North direction (Cartesian coordinates). These values are expressed by default in arcsec in a heliocentric system.

They can be given in the image pixel device (by including U_PIXEL); the size of the images is 1024 x 1024 pixels.

- Function of instrumental diffusion (**PSF**) :

This parameter contains information on the instrumental diffusion function. Its content depends on the instrument considered.
- in the case of CDS, this parameter contains the wavelength to which these data correspond ; a function called **CAL_CDS_PSF_COEFF_WAVE**, computes the corresponding PSF function.
- in the case of SUMER, this parameter is not called. The function is already integrated in the function (for a wavelength between 1000 and 1500 Å).
- for other instruments, the PSF contains parameters describing the function of diffusion. They are the coefficients of the polynomial (PSF=[a,b,c,..]) describing the function in a log-log scale. That is:

$APSF(R)=a+bR+cR^2+dR^3+......$ $\qquad$ $APSF=\log(psf(r))$ and $R=\log(r)$.

Of course this function must be normalized as the one of CDS (to see section II).
To select the CDS or SUMER instruments, one will add **/CDS** parameter or **/SUMER**. By default it is the third case that is taken in account (other instrument).

Distribution of solar brightness :

As it has been explained in section II the other parameter important for the calculation of stray light is the model of solar brightness. Two choices are possible :

- one considers circular symmetry for the solar brightness . In this case, one provides solely a radial profile of brightness in an array of two dimensions: (2, *). the column (0, *) containing the radial coordinate (in relation to the center of the disk), expressed in arcsec, and the column (1, *) to the corresponding brightness (the unit is not important). The parameter containing that profile is **MODEL**.

- one has a picture of the Sun at the (1024,1024) format. In this case one uses the parameter **SUN_IM**. If the center of the disk is not at the address [511,511] (center of the image), one can precise this address in the **POS_CENTDISK** parameter. If the size of a pixel is different from the one used by default, which is $2.92969 arcsec$. One can specify it in the **S_PIXEL** parameter. It is necessary to note that this last parameter can be used whatever the chosen option to describe the brightness of the Sun.

Remark :

In the case where one doesn't give the solar brightness, the program considers that the brightness of each pixel of the solar image is equal to 1. In order to reduce computing time, it is preferred to introduce a picture (**SUN_IM** parameter), because in the case of the model, the function is going to build the corresponding picture at the (1024,1024) format.

Limitation of the calculation :

• **MIN_LIMIT** :

This parameter permits to define the minimal distance of the point of reference from which one considers the contribution to stray light. By default, MIN_LIMIT is equal to $10 arcsecs$. This value corresponds to the minimal distance for which the PSF function of the CDS instrument is known with good precision. Anyway, it cannot be lower or equal to the spatial resolution of the instrument or to the size of a pixel in the array defining the Sun picture.

• **MAX_LIMIT** :

As explained above, the component of stray light, in the brightness measurements of disk regions, can be neglected. But beyond the limb (after the jump in emission observed in the case of a coronal line), it is not true. So, it is not necessary to consider all pixels of an observed picture of the Sun, in particular those corresponding to the regions beyond the limb which are fainter, because their measured emission contains an important part of stray light. This would lead to errors in the calculation. The MAX_LIMIT parameter permits to insure that such false contributions are not taken into account. It corresponds to the maximal radial distance (in arcsec) taken from disk center, which defines the border of the regions that contribute to stray light at the given point of reference. If this parameter is not introduced, there is no limitation (beyond the distance defined by the MIN_LIMIT parameter).

Output parameters :

• The CAL_STRAYLIGHT function gives the value of the stray light component corresponding to the point of reference.

• **CONTRI_IM** :
It is possible to get the respective contribution of every pixel of the picture for every point of reference, by introducing the CONTRI_IM parameter. When you use it, it is advisable to limit the number of reference points, so that the size of CONTRI_IM (nbre _refpoint,1024,1024) is not too important (limitation of the IDL capacity).

• **SUN_MODEL** :
In case you use the MODEL parameter, you can get the corresponding image with this parameter.

IV. The limits of utilization of the program:

This code applies mainly to observations made beyond the solar limb, sufficiently distant from active regions (at least 20 arsecs).

ANNEX A

The results have been obtained with the following data :

- p, positions put in Table 1.
- EIT image at 171 Åobtained in September 1999 (seit_00171_fd_19990929_2013.fts)
- position of the center of the disk in that image (in pixel): centre=[507.81,519.35]
- MAX_LIMIT=ray_sun (solar radius=969.41 arcsec) - S_PIXEL=2.64 arcsec.

• For CDS (λ =171 Å):

for the whole image:
stry=cal_straylight(P,PSF=171,/CDS,SUN_IM=eit_image,POS_CENTDISK=centre,$
S_PIXEL=2.64,MAX_LIMIT=ray_sun)

for a portion of the image of the disk:
stry=cal_straylight(P,PSF=171,/CDS,MODEL=model_s,POS_CENTDISK=centre,$
S_PIXEL=t_pixel,MAX_LIMIT=ray_sun,SUN_MODEL=im_model)

model_s is the average profile of a portion of the solar disk.

• For SUMER :

for the whole image:
stry=cal_straylight(P,/SUMER,SUN_IM=eit_image,POS_CENTDISK=centre,$
S_PIXEL=t_pixel,MAX_LIMIT=ray_sun)

for a portion of the image of the disk:
stry=cal_straylight(P,/SUMER,MODEL=model_s,POS_CENTDISK=centre,$
S_PIXEL=t_pixel,MAX_LIMIT=ray_sun,SUN_MODEL=im_model)