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TAUVEX on GSAT4: observational prospects and constraints

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Abstract. In this paper we describe the observational constraints imposed on the TAUVEX space telescope due to scattered light entering its telescopes from outside the field of view. This stray light is a sunlight reflected from various spacecraft components into TAUVEX apertures. Based on these constraints, a basic strategy of observation is suggested, in which the major part of the observational time will be dedicated to sky survey, while the rest will be aimed at specific targets.

Keywords : space vehicles: instruments – instrumentation: miscellaneous – Sun: UV radiation – ultraviolet: Solar system

1. Introduction

Installed on the Mounting Deck Plate (MDP) on the east face of GSAT-4, TAUVEX will scan the sky at a rate of one revolution per sidereal day. This sets the basic method of observation, which is to scan the 'ribbons' of constant declination, δ, for time periods of typically several hours.

The Right Ascension (R.A.) is set by the time of observation while the declination, δ, is the angle commanded to the MDP. During the orbit the Sun illuminates the spacecraft at a varying angle causing a varying stray light noise in the TAUVEX detector. In order to maximize the scientific yield of the mission, it is best to observe when the stray light is minimal and the exposure time (the time a celestial object crosses the field of view (FOV)) is maximal. In addition, for a survey mission, one should try to cover a sky area as large as possible, preferably with a uniform exposure time.

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Fig. 1 shows the TAUVEX as a payload on GSAT-4.

Figure 1. A scheme of TAUVEX on board the GSAT-4 spacecraft (S/C), as seen from south-east direction. TAUVEX (the small box) is mounted on the east side of the S/C, and the solar panels emerge from the north and south sides. The panels are rotating on an axis oriented north-south, while the side with the antennas is pointing towards the Earth. TAUVEX MDP can be rotated on its axis oriented east-west. In this chart TAUVEX is pointing to the North.

The main guideline of observation is that TAUVEX should never have the Sun in a forward angle, namely, the angle between the TAUVEX line of sight (LOS) and the direction to the Sun, the back angle, should be always greater than 90°. This will set the base for the method of observation.

2. Parameters of the orbit

2.1 Changes throughout the year

In Fig. 2 the orbit of GSAT-4 through the year with its characteristics is shown. The Sun is in the centre and the radial solid lines divide the year into months. The numbers

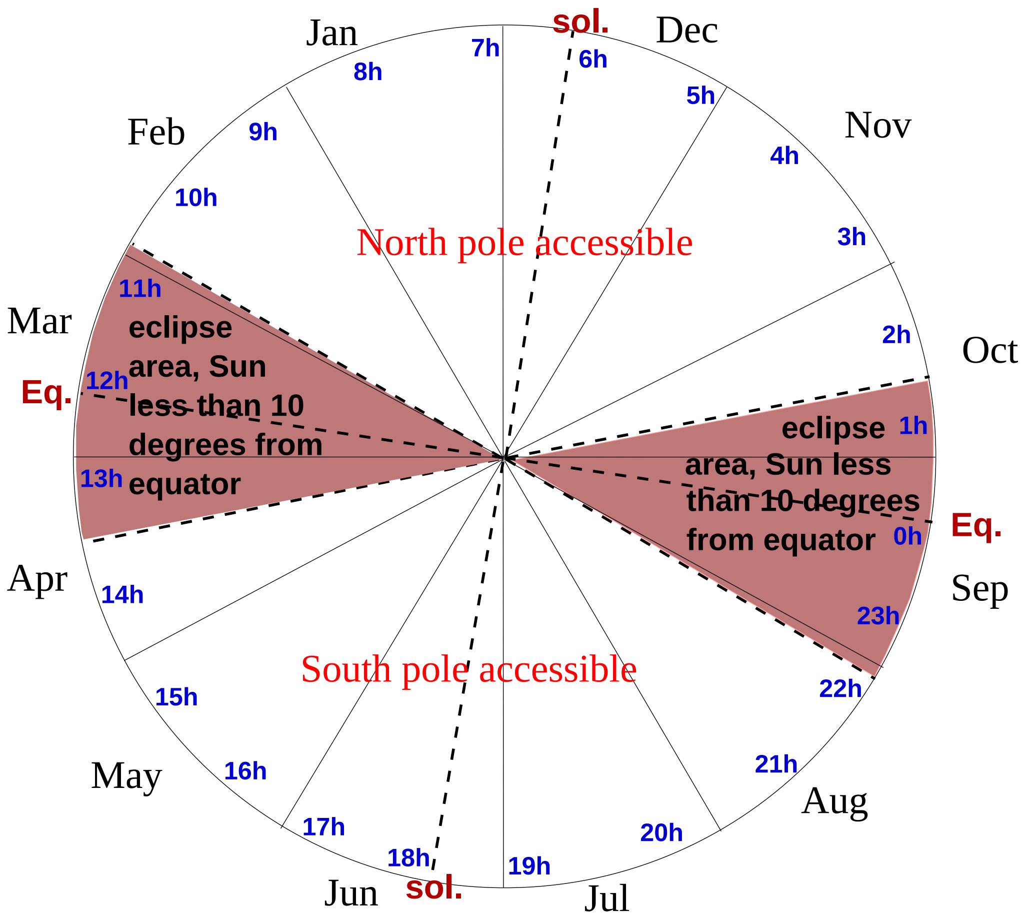

Figure 2. The path of GSAT-4 round the year. Eq. stands for equinox, sol. for solstice.

inside display the R.A observed at midnight. During the months November to February, the Sun is in negative declination at more than 10° from the equator. In this period it is possible to observe the north cap of the sky with the Sun at back angle from the telescopes at all times of the day. During April to August, the Sun is at positive declination and the south cap is visible in the same manner. The dark areas represent the times when the Sun is less than 10° from the equator. At these times the S/C will enter the shadow of the Earth for varying periods of time of up to 70 min. During these periods it will not be possible to observe through all day, but only in a part of the orbit. Around midnight there is no observation due to the power shutdown at the eclipse time.

2.2 Changes throughout the day

Since TAUVEX is rotating together with the satellite, it is pointing generally towards the Sun during one half of the day, while pointing away from it during the other half. Our requirement of the back angle for the Sun limits, therefore, the observation to only a part of the orbit. However, as explained above, when the Sun is relatively far from the equator, it is possible to observe at high δ opposite to the direction of the Sun throughout almost the entire day.

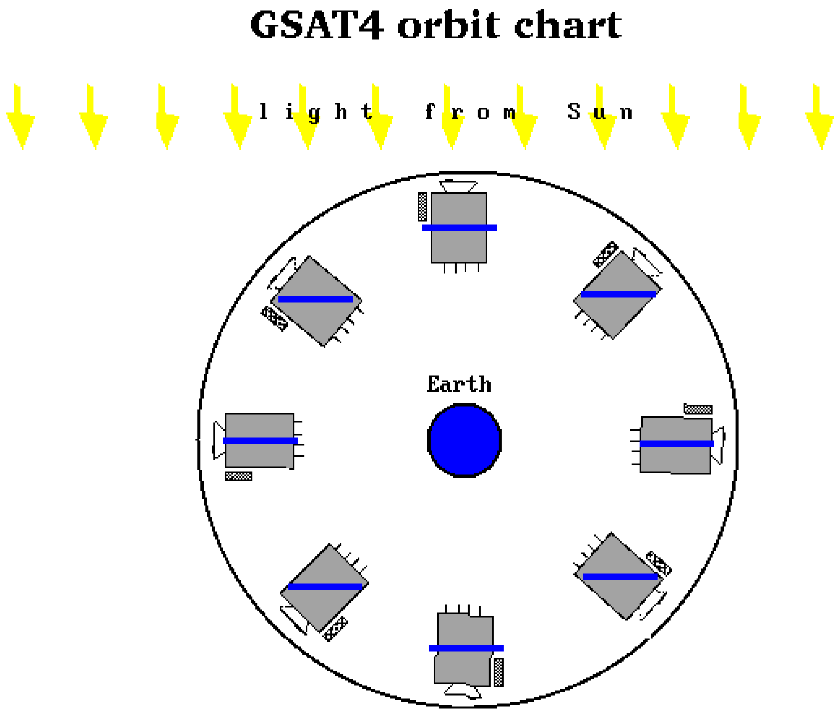

Figure 3. A chart of the GSAT-4 spacecraft in various stages of its orbit. Note that the solar panels (line in the middle of the S/C) are always facing the Sun while GSAT4 is rotating. TAUVEX is the small box attached to the S/C.

Fig. 3 shows schematically the GSAT-4 S/C with TAUVEX as it is orbiting the Earth, as seen from the north pole. The sunlight in the chart comes from the top. The thick line in the middle of the S/C represents the solar panels. These surfaces have a large area and are reflecting a considerable part of the sunlight while aimed constantly towards the Sun.

As previously noted, one should try to minimize the stray light (SL) entering the TAUVEX apertures. This SL is the light that comes from outside the FOV of TAUVEX and scatters off the surfaces of the optics and onto the detector in the focal plane. This includes diffraction from edges of baffles and reflections from mirrors and lenses. The sources of this light may be the Sun itself, if not at back angle, or reflection of sunlight from the various S/C components. Additional SL may come from bright celestial objects like the Moon, when in close angle to the LOS.

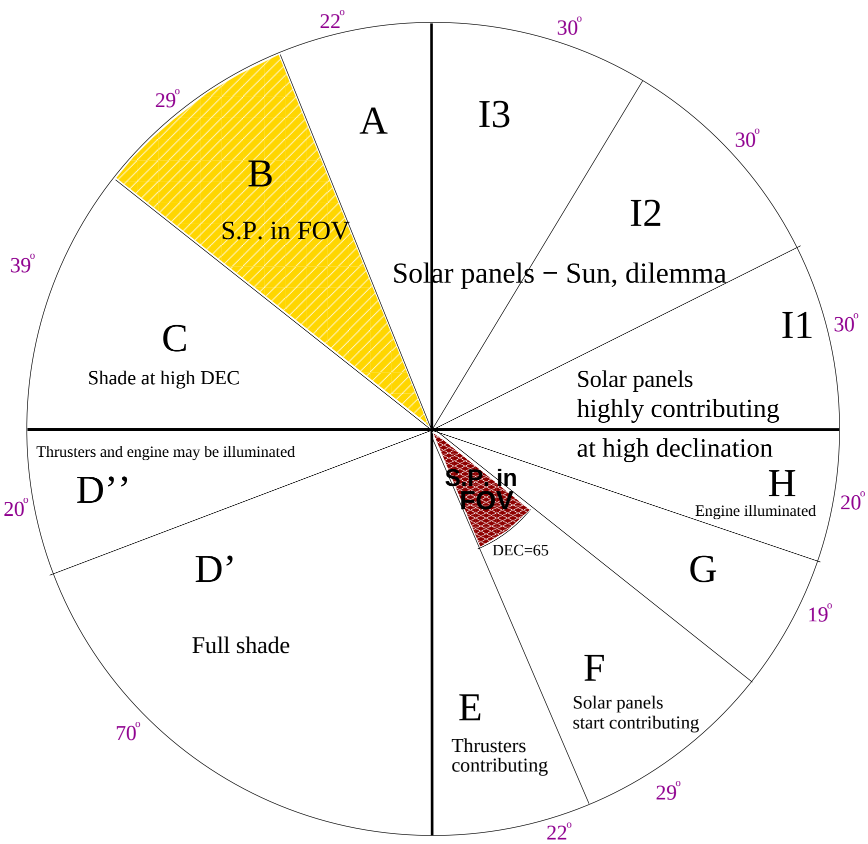

Figure 4. The GSAT4 orbit with its different stages and parameters.

According to the known mechanical and optical parameters of the GSAT-4 S/C, a scheme of the orbit was constructed in which the orbit is divided into regions with different SL parameters. This scheme is shown in Fig. 4, where each region is labeled and its angular size (out of the 360° of the orbit) is marked near its perimeter.

As can be deduced from Fig. 3, there may be a phase in the orbit when the solar panels are in TAUVEX FOV, if it is looking at north or at south. These cases are shown in areas **B** and **F** in Fig. 4. Therefore in phase **B** the observation is not possible at all, since observing at low δ, where the panels are not interfering, would have the sunlight entering the apertures directly, and at high δ the solar panels are in the FOV. On the other hand, it is possible to observe at $\delta < 65°$ in phase **F**, where the panels do not interfere.

In region **C** TAUVEX may be in complete shade of the S/C when looking at high δ, depending on the declination of the Sun. In region **D**$''$ the Sun is at a back angle always, but the thrusters and the engine situated on the anti-Earth side may still be illuminated, and therefore contribute to the SL. The best phase is clearly the phase **D**$'$, where full shade should enable TAUVEX to reach its best performance. In phase **E** the thrusters may be again contributing to the SL. In phase **F** the solar panels start contributing to the SL. In phase **H** the engine is again illuminated by the Sun and contributes to SL. In regions **H** to **I3** the SL is increasing due to the angle of light reflected by the solar panels. As mentioned before, the solar panels are contributing mainly at high declinations, but in these phases one must observe at high δ to avoid the direct sunlight into TAUVEX.

3. Calculation of the Stray Light

The calculation of the expected SL in TAUVEX is based on a few parameters, all of which are modeled according to the known characteristics of the system of TAUVEX and GSAT-4.

One of the basic parameters is the point-source transmission function (PST). This is a dimensionless parameter which relates the illumination of the TAUVEX detector in the telescope focal plane to the light entering the telescope from *outside the FOV*. In contrast to the light inside the FOV which is reflected off the mirrors and designed to fall on a point as small as possible on the detector (for a celestial point source), here the light is scattered off the surfaces of the baffle many times before reaching the detector and eventually creates a relatively uniform noise on it. The ratio of the flux density on the detector (focal plane) to the flux density of the source is the PST. This function is highly dependent on the angle of incidence relative to the LOS. In our calculation the source may be direct sunlight or sunlight reflected off S/C components if the Sun is at a back angle (where, nominally, the PST is zero).

Theoretically, if a detector of TAUVEX with a BBF filter is placed outside the Earth's atmosphere facing the Sun, it will produce $N_{\rm Sol} = 1.036 \times 10^{15} events/s$. If a TAUVEX telescope has the Sun at a specific angle with a non-vanishing PST (forward angle), it will produce a number of counts, N, which is $N_{\rm Sol}$ times the appropriate PST value.

The PST in TAUVEX was modeled for its previous configuration prior to its adaptation for a GSAT4 flight. This was done according to the parameters of all the surfaces of the telescopes with their reflection coefficients, sizes, etc. Variation of the PST with wavelength was not modeled, although in principle the reflection coefficients may depend on it. This is because the wavelength dependence was considered a minor factor among other parameters setting the PST. The old structure of TAUVEX was designed for sunlight at angles larger than 50°, and no light at smaller angles. This is not suitable for the new configuration of TAUVEX on board GSAT-4, where the direct solar radiation will fall at back angles, but light reflected from solar panels may come in at much smaller angles. For this reason an additional baffle was designed and built. The PST for the new configuration of old and new baffles was modeled and is shown in Fig. 5.

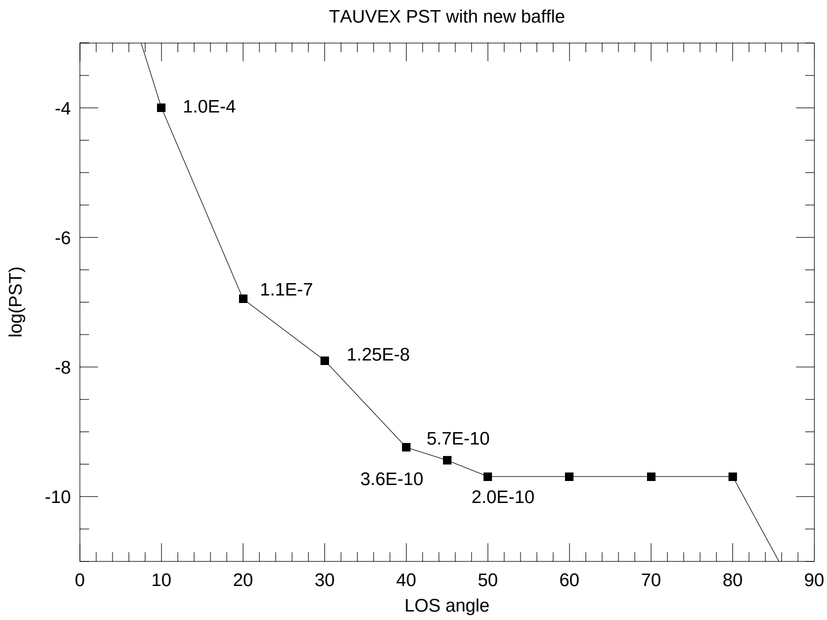

Figure 5. The modeled PST for TAUVEX after the addition of a new baffle.

When considering the contribution of some S/C surface to the stray light one has to take into account the solid angle taken by this surface as seen from the TAUVEX entrance aperture. This is shown in Fig. 6. If, in principle, the surface is infinite (occupies 2π steradians) and is scattering the sunlight in all directions, the total energy entering the TAUVEX aperture will be the same as the solar energy (times the non-specular reflection coefficient). Therefore one has to use, as a first approximation, the solid angle, divided by 2π steradians times the non-specular reflection coefficient, for the calculation of the contribution to the stray light from any specific surface.

This contribution is given by:

$$N_{\rm stray} = N_{\rm Sol} \times R_{\rm nonspec} \times PST(\alpha) \times \frac{\Omega}{2\pi} \times NL_{\rm par}\,, \qquad (1)$$

where N_{Sol} is the number of Solar counts mentioned above, $R_{\rm nonspec}$ is the non-specular reflection coefficient of the surface, $PST(\alpha)$ is the PST at the LOS angle α, Ω is the solid angle taken by the surface from the point of view of the TAUVEX aperture, and $NL_{\rm par}$

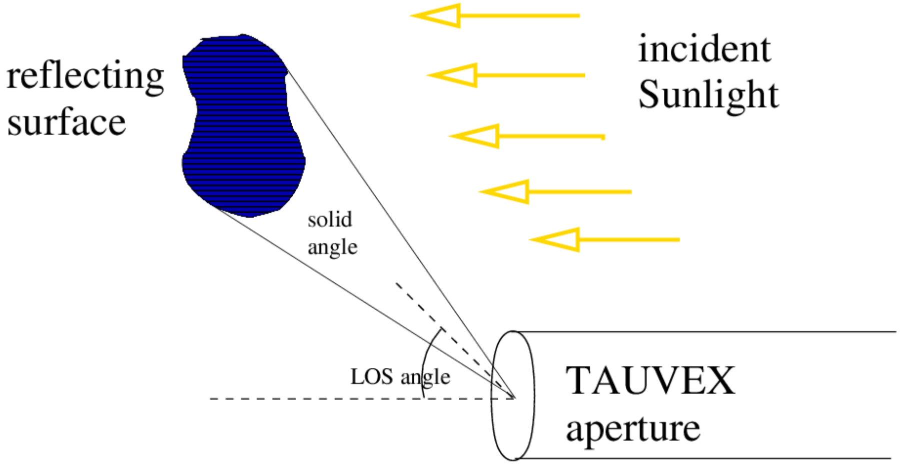

Figure 6. Configuration of sunlight falling on a S/C surface and onto TAUVEX aperture used for the calculation of stray light.

is a parameter describing the deviation from Lambertian (isotropic) reflection. In case of ideal Lambertian reflection, namely, the sunlight is scattered equally in all directions, this value is 1. This parameter was introduced to make the calculation more realistic.

According to these principles, the values of all the parameters were evaluated for every part of the orbit (as in Fig. 4) and for six representative values of δ, each 15° in size, for both North and South directions. Due to uncertainties and the range of parameters inside each 'bin' of δ and orbital stage, two values were assigned to each such bin, representing minimal and maximal values, to enable calculation of best and worst cases.

Based on this set of parameters the values of stray light (number of counts per second) were calculated for every orbit stage and δ. These values are originally for the BBF filter. In order to convert to other filters, the ratio between the solar fluxes in these filters and in the BBF was evaluated using the solar spectrum and the transmission curves of the filters (together with the detector response). This is shown in Fig. 7. The different curves in the figure show the spectral dependence of the filter transmission times the solar flux, so it is largely shifted to longer wavelengths because the solar flux is increasing very rapidly with wavelength. The BBF shows a tail at very long wavelengths. This is due to non zero quantum efficiency of the detectors at optical wavelengths, which was measured to be $\sim$0.04% but with a high uncertainty.

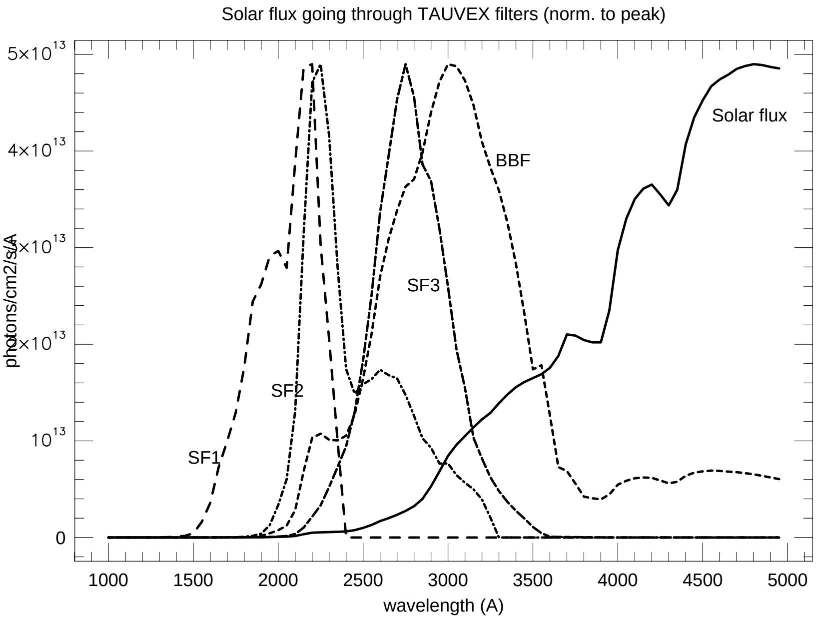

Figure 7. Profiles of the solar flux entering the different TAUVEX filters, together with the solar flux itself. The filter curves are normalized to the peak transmission. The vertical axis labels are for the solar flux only.

4. Calculation of limiting magnitudes

A UV monochromatic magnitude of a source at a certain wavelength λ is defined as

$$m_{\mathrm{UV}} = -2.5 \log F(\lambda) - 21.175 \,,$$

where $F(\lambda)$ is the flux density at λ in units of erg cm^{-2} s^{-1} Å^{-1}. The magnitudes measured by TAUVEX through a given filter will incorporate the averaged $F(\lambda)$ over the filter bandpass. For the calculation of limiting magnitudes at the TAUVEX bandpasses, a relation between monochromatic magnitude and expected number of counts was established for each of the filters. This is based on the optical characteristics of the TAUVEX telescopes, detectors, etc.

For the calculation of the limiting magnitudes, a signal-to-noise ratio, $S/N = 5$, was taken as the detection threshold. The simplest way to measure an object on an image is to sum up its counts in an 'aperture' on the image. In this calculation the S/N is set by both the object counts and the background counts, which depend not only on the background value (number of counts 'per pixel') but also on the size of the measuring aperture. For the evaluation of the S/N, an 'aperture' radius size was assumed based on measurements done with TAUVEX in the past. The assumption that the total SL counts are distributed uniformly in the FOV gives the number of background counts per pixel, which enables to derive how many counts are needed from the object in order to detect it with a $S/N = 5$. This sets the limiting magnitude at this specific bandpass.

The limiting magnitudes for the four main filters: BBF, SF1, SF2 and SF3 were calculated for all the orbital phases and declinations, based on the stray light tables calculated in the previous section. It is notable that this SL originates from solar illumination of the S/C components and does not include other possible sources like zodiacal light, diffuse galactic light, etc. Nor does it include possible light emitted by plasma thrusters, located on the East and West sides of GSAT-4 behind TAUVEX.

For convenience the limiting magnitudes are converted into maps which represent the orbital phase and δ. These maps are calculated for a single scan. They depend on δ not only because of different SL conditions, but mainly due to the varying exposure time as δ changes (the exposure time was taken as the time in which a source crosses the center of the TAUVEX FOV). As in the SL calculations, two maps were constructed for each filter describing the minimal and maximal SL cases.

An example of such a map is shown in Fig. 8, where the limiting magnitude for the SF3 bandpass is displayed. This map is for a minimal SL case in Northern hemisphere. As in Fig. 4 the Earth is in the center and the sunlight comes from the top. The radial direction represents δ. The image is built such that equal areas on the image are mapped to equal sky areas. The colour-code scale shows the limiting magnitude values assigned to the colour.

5. Implications for sky surveys

From Fig. 8 one can see that the difference in limiting magnitude is very large for different declinations. This is because the exposure times vary considerably with varying δ, especially near the polar cap. In addition, the limiting magnitude may not be satisfactory in itself. In order to be able to observe deeper one should repeat the scan of a given sky ribbon and accumulate the photons coming from this area at all the scans. This will increase the limiting magnitude.

If, on the other hand, one wishes to conduct a sky survey, the exposure time of all the sky ribbons at the δ range of the survey should be kept as uniform as possible. This can be achieved by repetitions of the scans with a small difference in δ, which varies gradually with δ. Naturally, the smaller the difference between scans, the longer the accumulated exposure time and depth. Accordingly, the total area coverage (for a given number of scans) will be smaller.

As can be derived from Fig. 2, each polar cap can be observed constantly for a period of not more than about 130 days. During this period the Sun changes its declination. It

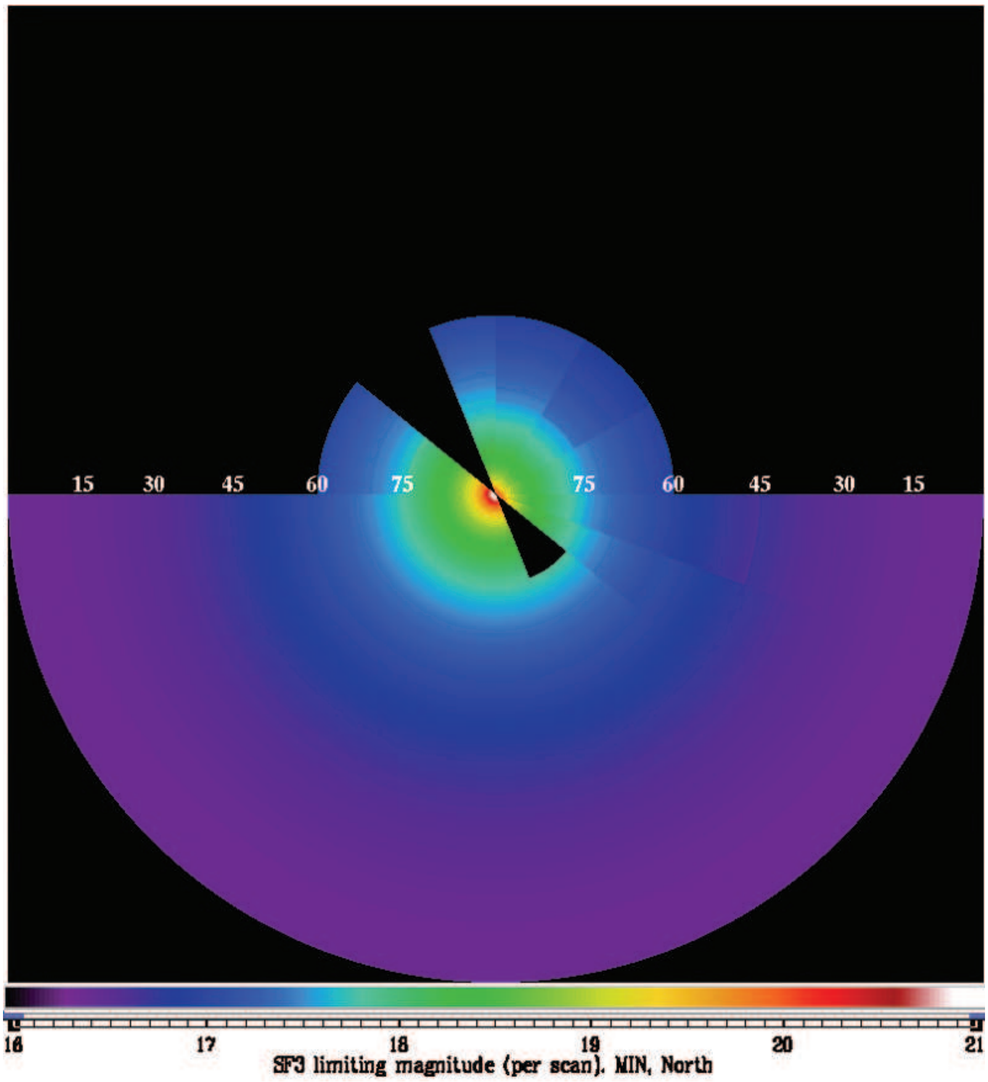

Figure 8. Colour-coded map of limiting magnitude for SF3 filter, Northern sky, minimal stray light case. The magnitude is per scan and different radii represent different δ, with the labels marking δ at specific radii.

is worthwhile, therefore, to divide this to two sets of observations which complement one another. The first set, when the Sun is moving away from the equator, will incorporate observations moving away from the polar cap opposite to the Sun. In the second set, in which the Sun moves back towards the equator, the observations retreat from it, getting back closer to the polar cap.

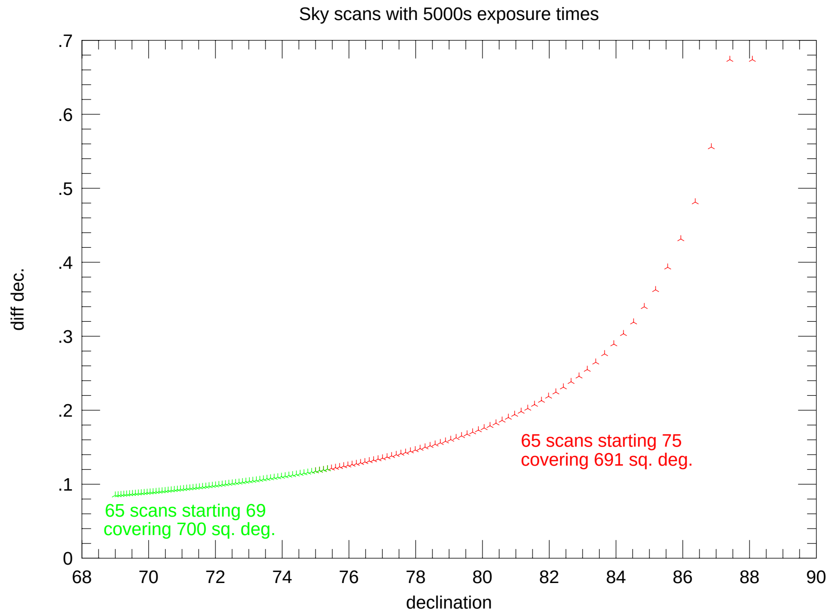

Figure 9. Two sets of scans with a varying declination step. Both sets consist of 65 scans and cover a sky area of ∼700 square degrees. The accumulated exposure time is 5000s for the entire area covered.

In the next half year the same process can be repeated for the other polar cap. With the given conditions it is possible to observe a sky area of 1400 square degrees with an exposure time of 5000s in each polar cap in one year. This is shown in Fig. 9, where each point represents a single scan. One set covers the $\delta \sim 69° - 75°$ and the other covers $\delta \sim 75° - 89°$.

In reality the scenario, depicted in the figure, cannot be followed exactly, since the MDP angle, which is essentially δ, can be set with an accuracy of only $0°.05$, but one may try to optimize the set of observations according to the accuracy available.

In such a case the concept of limiting magnitude per scan is no longer suitable. Instead one should assess the limiting magnitude for a given exposure time regardless of δ. In this case the only parameter that sets the limiting magnitude is the SL at each location in the orbit and δ.

Such maps of limiting magnitude were constructed as before, only that this time the exposure time was constant and was set to 5000s. Maps for SF3 filter are shown in Fig. 10 and Fig. 11.

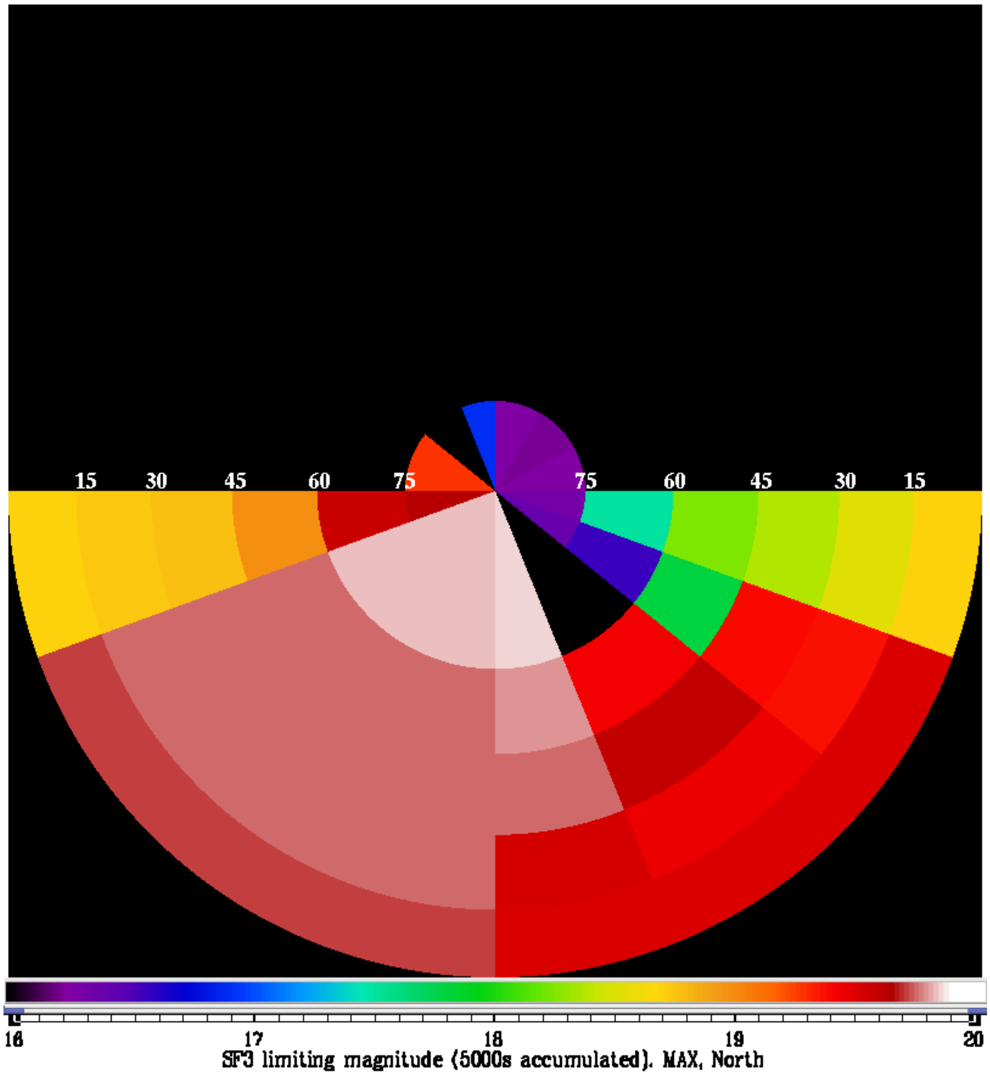

Figure 10. Same as Fig. 8 for a constant exposure time of 5000s, maximal SL case.

6. Conclusions and suggested observational scenario

The stray light in TAUVEX plays an important role in setting the observational plan to be implemented for the best scientific output. In order to make the most of the observational time available, it is suggested to perform a sky survey during the winter and summer times (the white areas in Figure 2), and try to achieve an exposure time as constant as possible.

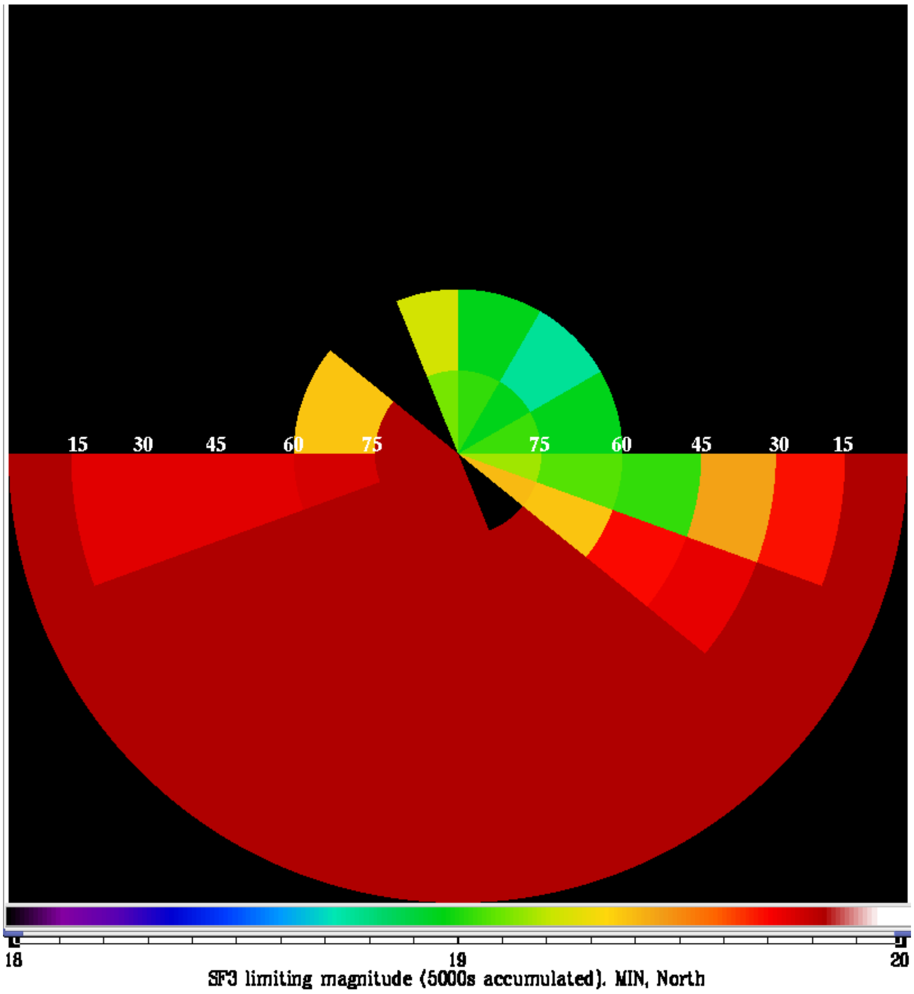

Figure 11. Same as Fig. 10 for a minimal SL case.

In the transition seasons (brown areas in the Figure), one may perform observations of predetermined targets with repetition of observations for several days in order to achieve the required depth. During this time the declination can, probably, be changed several times a day to observe a number of targets.

In this scenario the survey data set is complete after one year. The observations may be repeated in the second year in order to increase the depth, with modified parameters to accommodate the knowledge gathered during the first year.