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Calibrating TAUVEX: turning space hardware into a scientific instrument

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Abstract. This article explains the basic philosophy of calibrating TAUVEX on the ground at the El-Op facilities in Israel, and in space after launch. We refer the reader to historical articles describing TAUVEX, its design and calibration, and update the knowledge base as to the modern testing and calibration procedures. We explicitly point out the products expected to result from the calibration process.

Keywords : telescopes – techniques: photometric – methods: observational – ultraviolet: general

1. Introduction

The TAUVEX space telescope array, constructed for Tel Aviv University with funding from the Israel Space Agency (Ministry of Science, Culture and Sport), consists of a bore-sighted assembly of three telescopes with 20-cm apertures mounted on a single bezel and imaging the same ∼one-degree field of view in the vacuum UV. The mission and payload have been described by Brosch (1996), Brosch et al. (1994, 1996), Leibowitz (1995) and Topaz et al. (1993a, b) and the optical design of TAUVEX was presented by Nir & Freiman (1993).

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TAUVEX is mounted on the side of the GSAT-4 satellite on a plate (Mounting Deck Plate=MDP) free to move the line of sight to different declinations from δ=+90° to δ=-90°. As GSAT-4 orbits the Earth on its geo-synchronous orbit, the TAUVEX line of sight scans a sky ribbon. The data transmitted to the ground station is reconstructed into a set of UV images of the sky ribbon scanned by the experiment. The purpose of the calibration procedures is to allow the transformation of the stream of information into useful scientific data.

In designing the calibration process we relied on previous experience, mainly from TD-1 (Humphries et al. 1976), GALEX (Martin et al. 2005) and from the HST imagers (Holtzman et al. 1995), and partly from Clementine (Hillier et al. 1999) and IMAGE (Mende et al. 2000a, b). The ultimate goal of all calibration processes is to remove completely the signature of the measuring instrument from the results and to provide accurate locations and fluxes for all sources, including the sky background. The preliminary ideas about the TAUVEX calibration were described by Braun et al. (1993); this has been significantly modified a number of times since then.

There are two basic sets of calibrations; the first one is obtained on the ground as part of the performance testing of TAUVEX and is somewhat limited. The other will be derived post-launch and will be based on targeted as well as on science observations by TAUVEX. The purpose of the present document is to explain the various tests and calibrations, and to point a way to space refinement of the ground-based calibrations.

Note that the ground-based process is mostly included in the testing of the payload and is a contractual obligation of the TAUVEX Prime Contractor, El-Op, Electro-Optical Industries, Ltd., part of the ELBIT Systems Group. These tests verify the compliance of the payload to the pre-determined and agreed-upon performance required for the performance of the scientific tasks. The results of many of the compliance tests provide the investigator teams with measurements that are, essentially, calibrations of the instrument. The space calibrations, on the other hand, are the responsibility of the two investigator teams, Indian and Israeli, and will be performed as part of the performance verification (PV) phase of the flight, as well as from time to time during the scientific operation.

2. Testing and calibration on the ground

2.1 General

There are, in principle, nine different tests that will be performed at El-Op: a life test, a measurement of the line-of-sight (LOS) and field-of-view (FOV), a measurement of the dark pattern of the detectors, an evaluation of the “flat field” response, a measurement of the image distortion, measurements of the resolution and linearity, an evaluation of the spectral response of the payload, and a measurement of the stray light rejection.

The life test is performed with the built-in light sources of each telescope (see below) and produce a specific pattern and response on each detector. Since this test can be performed in space, this offers an additional possibility to compare the flight performance of TAUVEX with that measured during the ground tests and calibrations.

Some of these tests will be performed a number of times, and in different environmental conditions. They will all be done with the Flight Model (FM) of TAUVEX, in the clean room of El-Op which is a Class 10,000 environment. Since there are very stringent requirements to prevent molecular and particulate contamination of TAUVEX, the FM will be protected throughout the testing and calibration process that is expected to last 6-8 weeks.

At this point it is worth-while to describe briefly the special equipment that is available for the tasks described below. This is part of the standard infrastructure available at El-Op, though some items have been purchased specifically for the use of the TAUVEX project.

The two main equipment pieces are two 55-cm f/10 collimators. These use a reverse-Newtonian arrangement to project images of objects at their focal plane onto the entrance apertures of telescopes. The TAUVEX telescopes focus the beams of light that arrive from the collimator as from infinity onto the detectors at *their* focal planes so that the quality of the images can be evaluated. The collimators illuminate the payload under test that is mounted on gimbals that tilt, translation and rotation, so that the angle between the incident beam and the telescopes' LOS can be changed. The targets in the focal planes of the collimators can be illuminated by a variety of lamps, with pan-chromatic or monochromatic capability, and can even be moved or modulated to simulate various observing conditions.

Note though two shortcomings of the El-Op collimators in regard to the TAUVEX testing: the angular width of the collimator beam is narrower than the TAUVEX FOV, which implies that the illumination of the entire FOV is not possible at a single orientation of the telescopes, and the illuminated area near the telescopes' entrance apertures is equal to the beam diameter, 55-cm, while the distance between the extreme ends of the two outer TAUVEX telescopes is 80-cm. This implies that if the central telescope is fully illuminated, the two outer telescopes are only partly illuminated.

The Newtonian arrangement implies that the beam projected toward the telescopes has a central obscuration; the illuminated pattern is therefore an annulus. In addition, the two Newtonian mirrors of the El-Op collimators have coatings optimized for the visible band of the spectrum, thus their reflection efficiencies is rather low in the UV with the efficiency decreasing toward the lowest wavelengths. One of the collimators illuminates the tested payload in the ambient air of the clean room. Since the inner part of the collimator is pumped to high vacuum, that collimator is equipped with protective windows at its input and output entrances that are transparent to only the long wavelength part

Figure 1. Clean room of El-Op. The thermal vacuum chamber is on the right. Its collimator extends out of the clean room into a laboratory. The ambient (clean room) collimator is on the left.

of the UV spectrum. The collimator attached to the thermal vacuum chamber, whose light source is located outside the collimator, is illuminated through a UV-transparent window.

One of the collimators operates in ambient air; the other one is coupled to a thermal vacuum chamber (TVC) with a diameter of 2m and a length of 5m. It is possible to change the temperature of an internal shroud between -40C and +70C, and the vacuum within the chamber is better than 0.001 mili-torr with cryopumping. This unique ca-

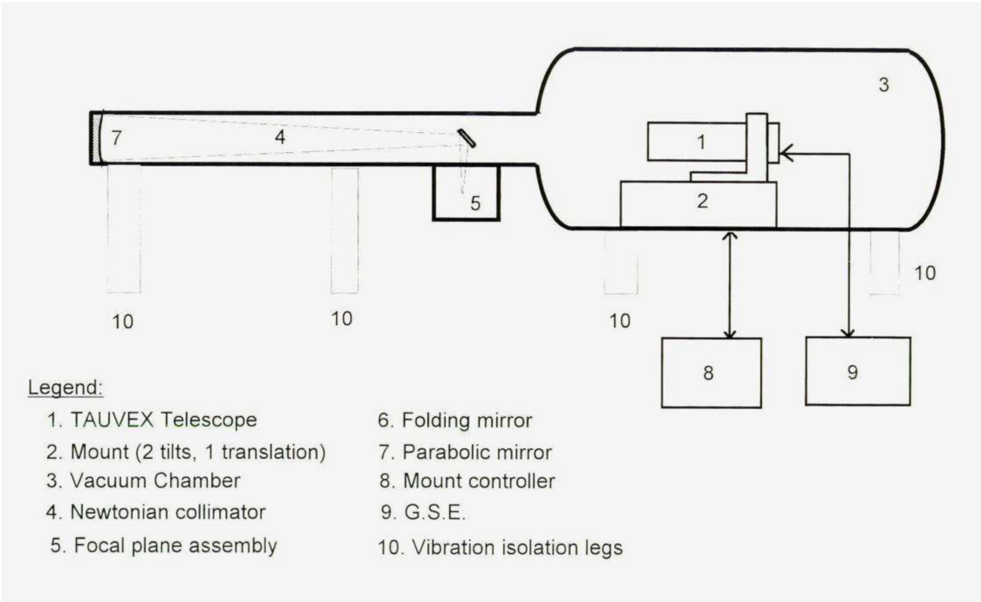

Figure 2. Schematic diagram of the thermal vacuum chamber with collimator for TAUVEX calibration.

pability implies that a space imaging payload can be tested end-to-end at its extreme operating conditions, its behavior can be compared to the design (see Blasberger & Levi 1993), provided it is installed in the chamber without its thermal blankets. While it is tested in the TVC, TAUVEX will also have its thermal interfaces connected to heat exchangers; this will allow a faster equilibration of the telescopes with the chamber at test conditions.

A large set of cables and vacuum feed-throughs allow the connection of the payload and of ancillary measuring equipment within the chamber to test equipment installed near the chamber for command uplink and data recording.

Some of the calibrations described below will be performed using a wide-aperture integrating sphere (WAIS). This has an 80-cm aperture and is illuminated by 14 tungsten-halogen lamps for the visible and the near-UV part of the spectrum. A 15th lamp (Xenon) provides illumination at shorter wavelengths. The WAIS provides illumination that is uniform to 98%, is equipped with a monitor of the internal illumination, and its internal reflectivity was spectrally calibrated.

It is important to stress that some of the tests cannot be performed in air because of the strong attenuation of the UV photons by scattering off the air molecules and by

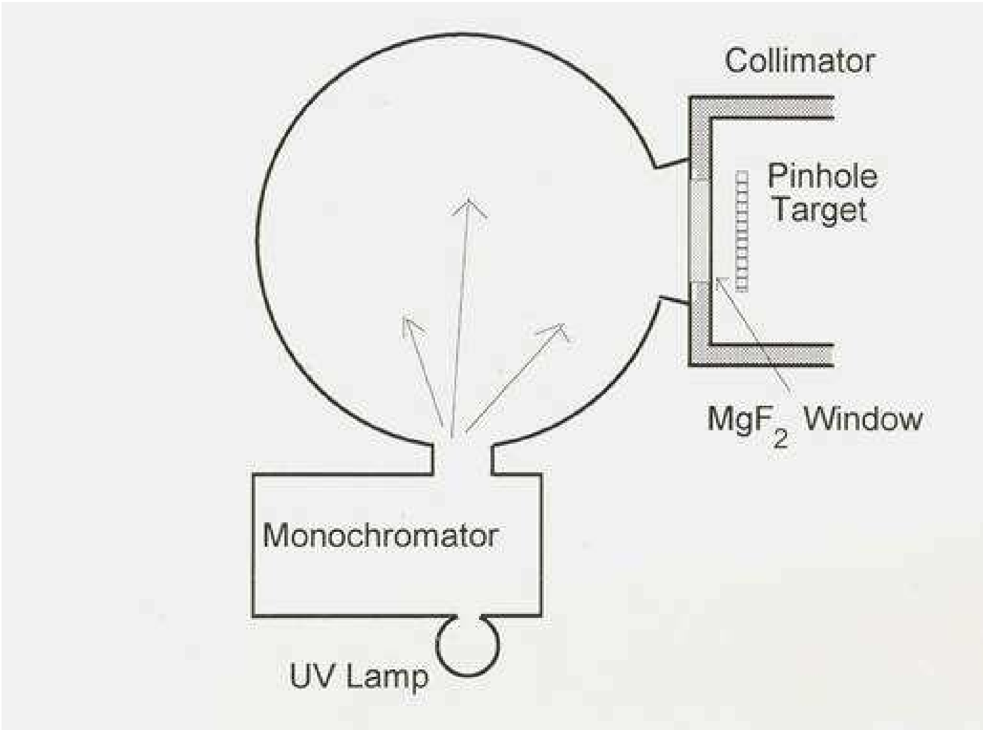

Figure 3. Focal plane assembly of collimator with integrating sphere, monochromator, and lamp. The pinhole targets are at the collimator focal plane, in the high vacuum.

absorption from the ozone molecules formed near a strong UV light source; these tests will be performed in the TVC under vacuum.

Another important and specific part of the test and calibration task is the Electrical Ground Support Equipment (EGSE) that has been specifically constructed to allow the full operation and testing of TAUVEX under a wide variety of regimes. The EGSE accompanies the TAUVEX FM during all its tests at El-Op and will accompany it when delivered to ISAC for integration with the satellite. The EGSE contains a GSAT-4 simulator for the specific functions required by TAUVEX. It issues commands to TAUVEX as GSAT-4 will, it acquires engineering and scientific telemetry, and can display the acquired data in a variety of formats.

For the specific purpose of this paper, the EGSE is the interface between the experimenter and TAUVEX; the data files acquired by it can be processed as will the actual data from TAUVEX be, and the calibration parameters can be derived from these files.

2.2 Life test

This test can be performed in ambient atmosphere on the ground, in a clean room, in the thermal vacuum chamber, with TAUVEX as a stand-alone unit connected to its EGSE, or with it integrated with GSAT-4, or in space while operating. The purpose of this test is to verify the adequate operation of TAUVEX without any test equipment except the EGSE or the GSAT-4 computer (BMP).

Since this is a stand-alone test that can be performed even when TAUVEX is on GSAT-4 and the satellite is integrated with the GSLV and on the launching pad, this test performs the most basic functions that would indicate that TAUVEX is "alive". The test checks the detector operation by exercising the three detectors through illumination with the built-in lamps in each of the telescopes. These lamps are installed behind each secondary mirror and illuminate the detector directly through the field corrector lenses and the filter (no mirror reflections).

Images are taken with the three telescopes simultaneously. The images are compared with baseline images taken before tests, or during the ground calibration, and differences are examined and evaluated. Synthetic data is also transmitted, to evaluate the performance of the electronic chain. Finally, all three filter wheels are rotated to the next position and then back. There is no pass/fail criterion for this test.

2.3 Line of sight and field of view

This test checks the TAUVEX Line of Sight (LOS) and Field of View (FOV). The calibration is performed using a single-aperture target in the collimator focal plane. The purposes of the test are to verify that at each of the TAUVEX telescope the FOV is according to the TAUVEX specification, to calculate using the FOV results the exact direction of the LOS of each telescope, and to measure the LOS of each telescope relative to the reference mirror mounted external to TAUVEX, which is used to align TAUVEX on the MDP and with the GSAT-4 axes.

The test is performed in ambient air and with white light. The illuminating source is a pinhole and positions are measured using a theodolite. The reference is the external TAUVEX mirror. The detectors of each telescope are used to image the pinhole, and the TAUVEX mount is driven so that the pinhole image reaches the edge of the field. The mount is then driven to put the pinhole image to the opposite edge of the field. This measures the FOV in one direction and the center of the field (the LOS) is defined as the location mid-way between the two edge measurements.

The requirement for the FOV diameter is to be at least 0.9°. The difference in LOS parallelism between the central telescope and any of the other two telescopes must not exceed 6 arcmin.

2.4 Dark

This test checks the TAUVEX dark noise characteristics while the system is installed in the thermal vacuum chamber or is in the ambient clean room (with the TAUVEX technological covers in place and with the test room darkened). The test is performed without illumination. The purpose of the test is to measure the dark noise count rate in each telescope of the TAUVEX system. Two images will be taken for each telescope (all 3 telescopes simultaneously). Each image is a 30 minute exposure.

The requirement is that the count rate should not exceed 110 events/second over the entire field of view. The hot spot pattern and total count rate for each detector were supplied by the detector manufacturer, Delft Electronische Producten (DEP) in Roden, the Netherlands.

2.5 Built-in light source test and calibration

The test is performed without external illumination in order to measure the internal light source (BIT lamp) image characteristics while the system is installed in the thermal vacuum chamber or in ambient clean room. The purpose of the test is to create BIT lamp maps for each telescope of TAUVEX. Two images will be taken for each telescope (all three telescopes simultaneously) in order to allow their comparison with BIT lamp images taken periodically in space.

The BIT lamp voltage is set so as to provide a maximal count rate (as close as possible to a nominal 24000 events/s in all three telescopes together). A set of images is recorded simultaneously with all three telescopes of TAUVEX. The exposure should continue until at least 7 million events are accumulated in each telescope, or up to 30 minutes. The test is performed once using the BBF, SF3, SF3 filters in the three telescopes, and again with the SF2, NBF3, SF2 filters in front of the detectors.

The result is an image for each detector recording the illumination pattern for the specific detector and filter combination. There is no pass/fail criterion for this test.

2.6 Flat field

This test examines the TAUVEX flat field characteristics while the system is in the ambient clean room. The test is performed under uniform illumination by the WAIS or in the vacuum chamber for the short wavelength filter SF-1. The purpose of the test is to create non-uniformity maps for each telescope of TAUVEX and for all the filters.

The test is performed sequentially for each telescope and filter, while each is tested separately. The goal is to collect images that contain some 280 million events so that the statistical accuracy of the flat field should be as high as possible (expected accuracy is better than 5% per "pixel" or 2% per resolution element). Note that while the degree of illumination can be adjusted, the maximal count rate from TAUVEX should be kept below 24000 events/sec so that the event rate will match that of the data transmission from TAUVEX (in order not to fill up the on-board data storage). This implies that calibrating each telescope-filter combination would require some 3.5 hours of data collection for the BBF, SF-3, SF-2, and NBF-3 filters.

The flat field calibration of the SF-1, with the shortest bandpass, cannot be performed in air and with the WAIS. For this purpose, TAUVEX will be operated in the vacuum chamber so that the central telescope is fully illuminated and the side telescopes are partly illuminated. The illumination source shall be a high-power Deuterium lamp (with strong continuum emission from 120 to 180 nm) with the small integrating sphere in the collimator focal plane.

Since the collimator is not able to fully illuminate the TAUVEX FOV, the telescope array will be aligned so that at least half of the FOV is covered in its lower part. The intensity of the illumination will be adjusted so that the count rate of the telescope and filter in use is nominally 24000 counts/sec. Images containing about 180 million events will be recorded, which will require some 2.2 hours (expected accuracy 3% per resolution element).

The procedure will be repeated with the second filter of the same telescope, following which TAUVEX will be moved so that another telescope will be fully illuminated. The procedure will be repeated until all telescopes and all filter combinations except BBF will be calibrated, then TAUVEX will be moved to illuminate the other half of the field and the entire procedure will be repeated. The two flat field images (from the two alignments) will be combined to make a full field map for all the "pixels".

The TAUVEX motion is not performed for SF-1. Using the ratio between the image of the SF1 filter and that of the other filter (for each of the two telescopes), and combining with the reference image taken in air, an image of the flat field of each telescope will be created for each alignment.

2.7 Distortion

This test checks the TAUVEX distortion pattern. The distortion is primarily the result of electrostatic fields in the detector, but some might arise from the optics. The test is performed using a ∼200-hole target located at the collimator focal plane. The purpose of the test is to map the distortion of the TAUVEX telescopes and detectors, and to verify that this is according to the TAUVEX specifications.

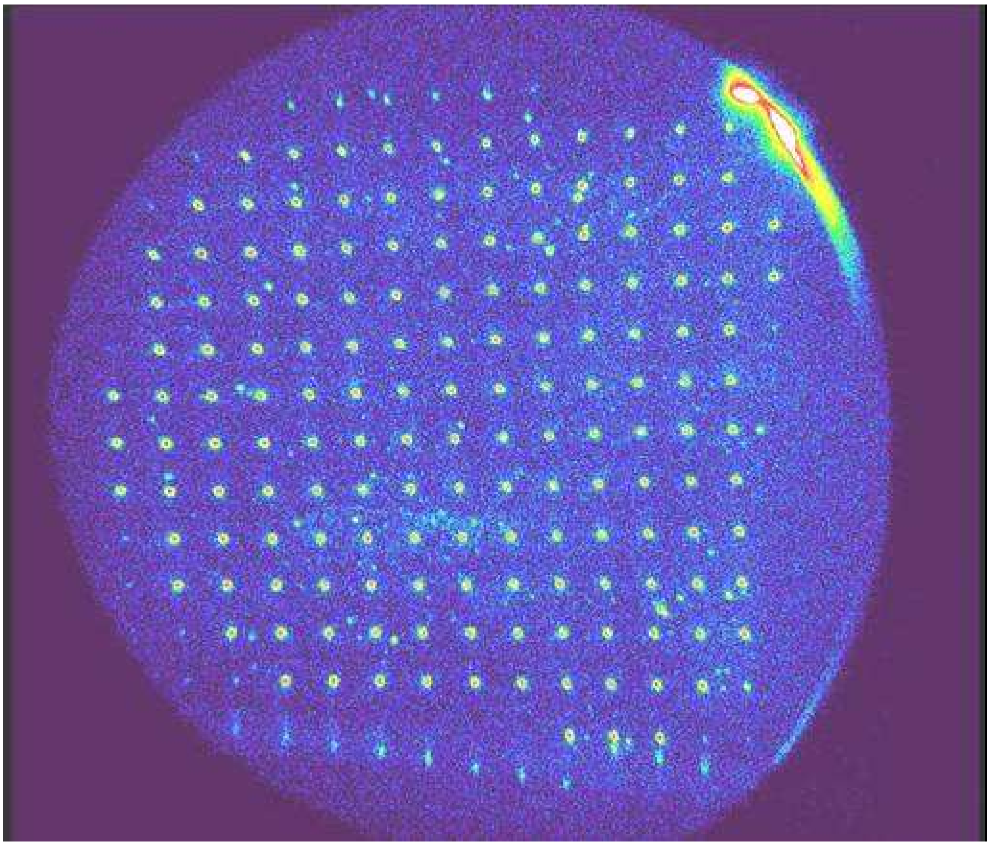

Figure 4. Image of distortion matrix obtained during the TAUVEX qualification by combining images from two different TAUVEX orientations.

The test is performed with TAUVEX in the TV chamber under ambient air pressure, and with the light source for white light illumination (a xenon lamp and integrating sphere) set to illuminate all the holes in the target. The pinhole pattern is approximately square with 50μm diameter holes that are reduced to 15μm on the TAUVEX focal plane.

TAUVEX will be aligned for full illumination on the central telescope and partial illumination on the other two telescopes. The focal plane of the collimator with the target in place will be illuminated and the TAUVEX LOS will be aligned so that the target image will be in the lower part of the FOV, filling at least half of it.

Images will be recorded with all three telescopes, requiring at least 200,000 total events per telescope. Following this the filters will be changed in all telescopes and the procedure will be repeated. Then TAUVEX will be re-aligned so that the target image would be in the upper part of the FOV, filling at least half of it. The full procedure will then be repeated to complete the full FOV mapping.

The image will be displayed on the image screen of the EGSE for visual evaluation. The image will consist of a pattern of spots corresponding to the ∼200 holes of the target. The two images recorded in each filter will be merged to produce a complete image of the target. Each spot will be analyzed to find its centroid. The coordinates of the spot positions will be matched to a best fit array of equally spaced points, and the deviation of each spot from the corresponding spot of this array will be measured. The r.m.s. value of the ratio of deviations to the distance to the center of the image will be determined. The map of the deviations will be recorded for use in correcting images.

The map recorded for the second filter in each telescope will be compared to the first one in order to evaluate the spectral dependence of distortion. The average value of spacing between the best-fit array of equally-spaced points will be compared to the actual angular distance between the target points, which is 5mm/5.5m≈3 arcmin. Based on this, corresponding parameters for the construction of the TAUVEX images will be established for each telescope so that an angular extent of 0.9 degrees falls on the central 960 pixels of each image.

For distortion, the r.m.s. distortion ratio should reproduce the DEP results for the individual detectors and should not exceed 10%. No significant difference in the distortion should occur between any two filters (3 arcsec rms) in the same detector. For the science calibration, distortion matrices will be derived for all filters and detectors.

Note that during space operations we expect an additional source of distortion due to "image pulling" by instantaneous electrostatic fields arising on the anodes in the immediate vicinity of bright stars. This distortion cannot be calibrated on the ground but would be removed by an iterative process post observation.

2.8 Resolution

This test checks the TAUVEX resolution performance in air and in the thermal vacuum chamber. The test is performed using a 25 aperture target in the focal plane of the collimator. The purpose of the test is to verify that at each of the TAUVEX telescope focal planes the FWHM spot diameter is according to the TAUVEX specifications.

The light source for white light illumination, the xenon lamp and integrating sphere, are used to illuminate all the holes in the target. The TAUVEX LOS is aligned to be parallel to the collimator optical axis and TAUVEX is aligned for full illumination on the first telescope. The focal plane of the collimator is illuminated with the 25 pinhole target in place while the event rate is adjusted so as not to exceed 300 events/second for each spot in the image. Two images in this telescope are recorded with each of the filters

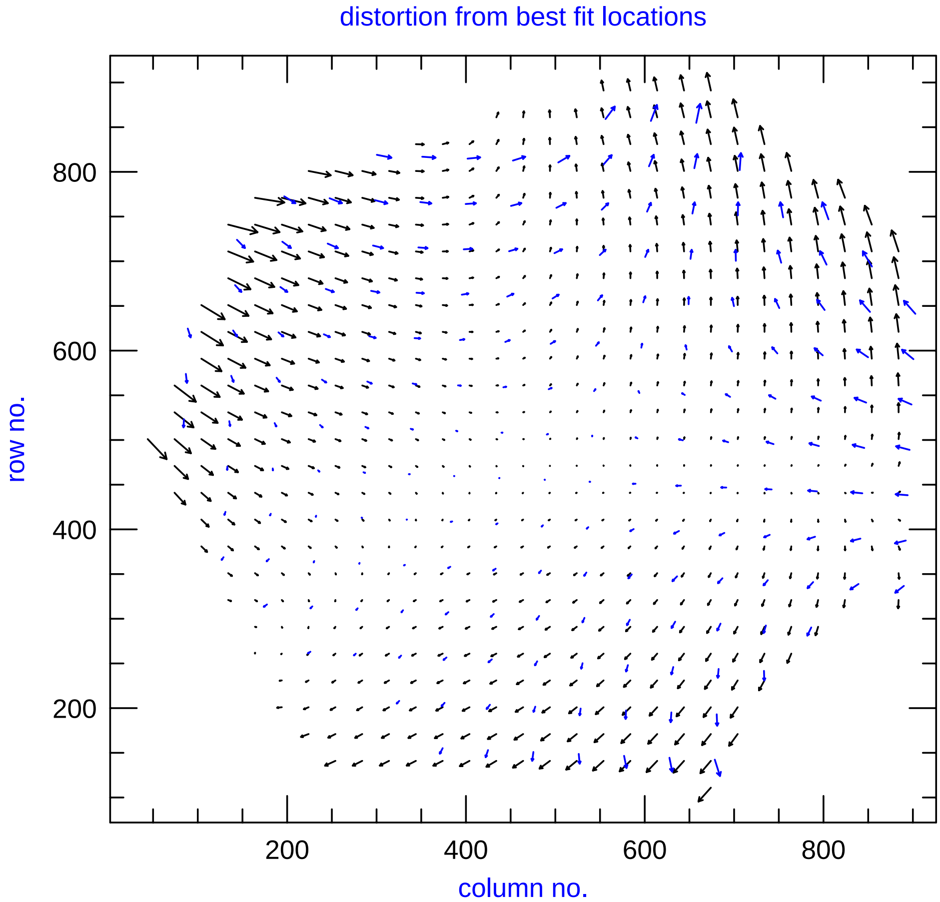

Figure 5. Approximation of the TAUVEX distortion during qualification. Detector D13 and 6th order polynomial fit.

then TAUVEX is re-positioned for full illumination on the second telescope. The steps are repeated as before, and then again for the third telescope.

The image is displayed on the image screen of the EGSE for visual evaluation. The image will consist of a pattern of spots corresponding to the 25 pinholes in the target. The pinholes deproject to 10μm, much smaller than the virtual pixel size. Each spot will be analyzed using the image analysis software of the EGSE to find the diameter of the image FWHM in the vertical and horizontal directions. For resolution determination, the FWHM, converted into radians, is the spot size at each of the points. Conversion should be made from detector coordinates to arcsec via the angular conversion factor.

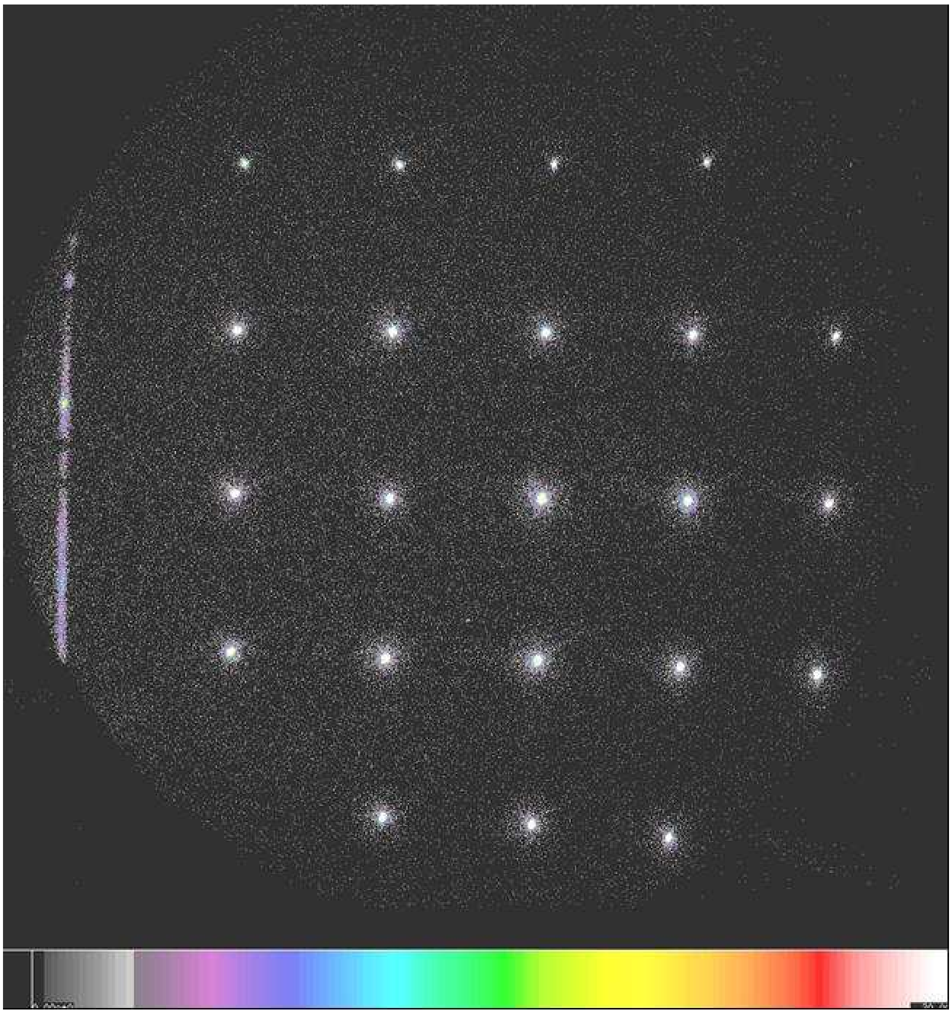

Figure 6. Image of the 25 pinhole resolution target obtained during the TAUVEX qualification.

The FWHM of a pinhole spot image is given by FWHM = W×K, where W is the FWHM measured from the image (in software units) and K is conversion factor from software units to angle (to be obtained from the angle calibration test). This test is repeated in the vacuum chamber for the SF-1, SF-2, and SF-3 filters using the Deuterium lamp, and without using an integrating sphere for the short wavelength filter in order to increase the light throughput. For resolution, the value of spot FWHM should be the same as the values obtained in the tests carried out at the acceptance of the detector pre-amplifier design. The comparison will be made for the average and standard deviation of all the spots.

2.9 Linearity

This test evaluates the TAUVEX linearity performance in ambient conditions. The test is performed using a three-position light attenuator in the collimator focal plane to adjust the illumination level in a known manner. The purposes of the test are to determine the linear portion of the TAUVEX response and to evaluate the non-linear portion of TAUVEX response and its saturation level.

The light source for this test is white light illumination, using a halogen lamp and an integrating sphere at the collimator focal plane. This illuminates the entire FOV of TAUVEX. A three-position attenuator plate will be fitted between the lamp and the sphere. This is a mechanical device that allows only a known fraction of the incident light from the lamp to pass into the collimator.

TAUVEX is positioned for full illumination on the central telescope and partial illumination on the other telescopes. The BBF filter is selected in telescopes 1 and 2, and SF3 filter in telescope 3. The attenuator is set to the minimum illumination position and the event and count rates are recorded for all three telescopes simultaneously. The attenuator is opened to the next step and the procedure is repeated, and again for the last attenuator position (fully open). This yields three measurements with light intensities whose ratios are well known.

The attenuator is reset to the minimum illumination position and the lamp illumination level is adjusted by changing its voltage and/or by selecting a different filter in each telescope so as to obtain a higher count rate. The illumination level is adjusted so that the count level will be equal the level obtained with the fully open attenuator at the previous illumination level. This measurement yields two additional measurements in the plot of illumination vs. count level that extend the measurements of the first stage of the test.

This is repeated again with an even higher level of illumination; this provides two additional points in the plot. The final calibration plot will have seven points at widely different illumination levels, from very faint to rather bright, covering a range of $(4.5)^6 \simeq 8300\times$ in intensity from the faintest to the brightest light levels. The plot is expected to be linear, but some effects could be discovered at high illumination levels due to count pileup in the electronics. The test is repeated with a two-hole plate in the focal plane of the collimator.

2.10 Spectral response

This procedure tests the TAUVEX spectral response characteristics with the system installed in the thermal vacuum chamber. The test is performed under monochromatic illumination with no target at the focal plane of the collimator. The purpose is to determine the absolute sensitivity of each TAUVEX telescope with the different filters at a number of discrete wavelengths.

This test uses the UV McPherson monochromator of El-Op equipped with a 30W deuterium lamp and located in front of the focal plane window of the collimator, so that light emerging from the monochromator slit illuminates the collimator mirror. The collimator target holder is set in the fully open position. A slightly defocused image of the monochromator slit will be projected onto the TAUVEX detectors.

Since the test requires good knowledge of the illumination of the TAUVEX telescopes, it is necessary to map this pattern in front of the FM as installed in the thermal vacuum chamber before performing the test. This is done with the calibrated photomultiplier (PHTM=secondary NIST-traceable detector) with the monochromator set to output a wavelength of ∼220 nm or longer. The illumination pattern is measured by locating the PHTM at pre-established locations and measuring the count rate. The pattern is found by interpolating among the measured locations.

TAUVEX is installed inside the vacuum chamber and its position is adjusted using the gimbals so that the central telescope would be fully illuminated while the other two telescopes would be symmetrically illuminated. The slit image is adjusted to be in the center of the image of the central telescope. The wavelengths to be set on the monochromator for each telescope and filter are listed below in nm. The monochromator bandwidth is nominally 4 nm, but in each case it will be set to the minimum which gives a useful count rate in TAUVEX (significantly above the dark count rate). The actual absolute illumination is measured with the calibrated PHTM in a pre-set location, or with a NIST-traceable diode at a similar location, with the diode and the PHTM having been cross-calibrated.

The measurements are performed with TAUVEX in one of the following three configurations and at the following wavelengths:

Configuration 1: filters BBF, SF3, BBF

Wavelengths (nm): 120, 160, 190, 210, 230, 245, 260, 275, 290, 310, 350, 400

Configuration 2: filters SF1, SF1, SF2

Wavelengths (nm): 120, 140, 160, 175, 190, 205, 220, 235, 250, 270, 300, 400

Configuration 3: filters SF2, NBF3, SF3

Wavelengths (nm): 120, 160, 190, 200, 210, 220, 230, 245, 260, 275, 295, 320, 400

At each configuration and wavelength images are collected until 10000 counts have accumulated for each telescope. Note that for the throughput calibration there is no

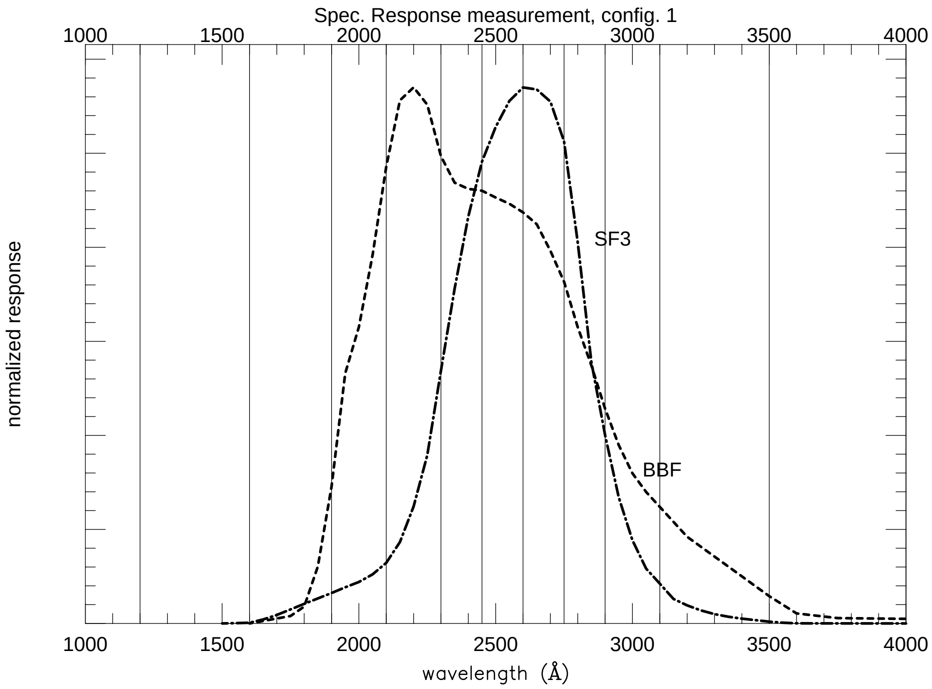

Figure 7. Filter profiles and wavelengths to measure for the throughput calibration of BBF and SF3.

need to know the exact shape of the slit image on the detector; the total collected counts suffice. For each image taken during the test, the total number of events in the field of view as recorded in the image is compared to the total number of events collected by the calibrated photomultiplier in the same period. The relative illumination profile map which was created previously is used to calibrate the images.

In order to derive the sensitivity or throughput, the used algorithm is:

$$Throughput = N \times Fi \times A \times QEph/Nph \tag{1}$$

where *Nph* is the number of counts in the calibrated photomultiplier (measured during the test), *N* is number of events in the image in any telescope, *A* is the active area of the photomultiplier, *QEph* = Quantum efficiency of calibrated photomultiplier at the specific wavelength (from the calibration curve), and *Fi* is the ratio between the number of counts in the calibrated photomultiplier at the image location (which is the average value across the entire TAUVEX aperture) and the number of counts in the calibrated photomultiplier at the photomultiplier location measured during the mapping step.

This test has a pass/fail criterion: the derived efficiency should be at least 90% of that calculated for TAUVEX using the individual detector and filter characteristics as supplied

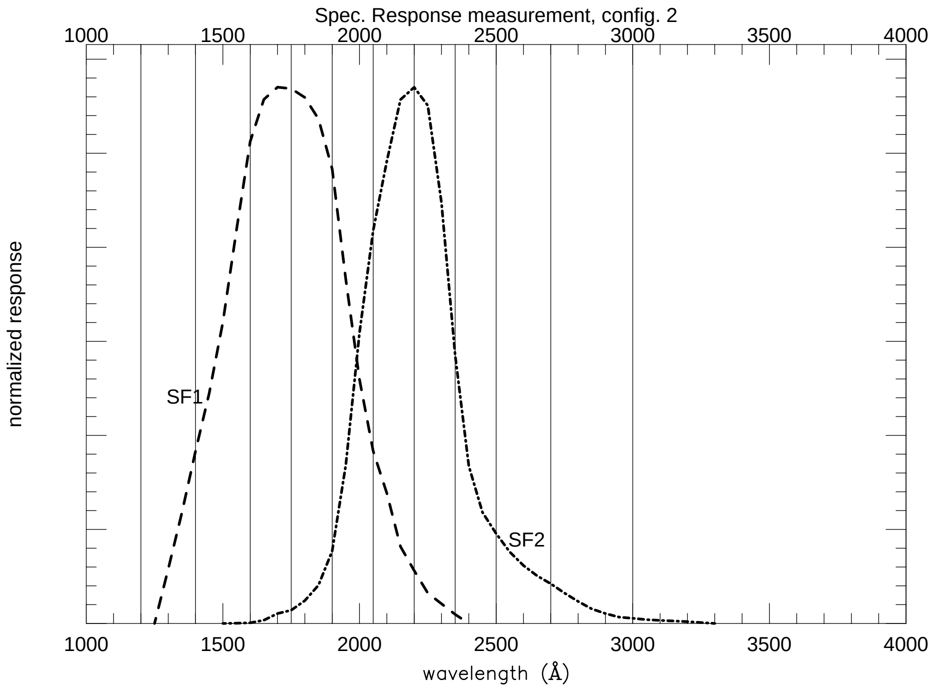

Figure 8. Filter profiles and wavelengths to measure for the throughput calibration of SF1 and SF2.

by the manufacturers, and generic reflectivity and transmission values. For calibration purposes, we expect to derive the throughput to 2% at each measurement point.

2.11 Stray light rejection

This procedure tests the TAUVEX stray light rejection while the system is in the ambient clean room and with the additional TAUVEX baffles mounted in front of the telescopes. The test is performed using illumination from a collimator. The purpose of the test is to determine the attenuation of stray light as a function of angle to the optical axis. Although TAUVEX will be used at 90 degrees or more from the direction of the Sun, the testing must be done at lower angles because sunlight will be scattered into the optics by the solar panels at angles less than 90° from the TAUVEX LOS.

A light-trap box will be constructed such that when placed in front of the TAUVEX telescope under test, no light will be seen over the entire field of view. A collimator with a 20-cm aperture having a tungsten halogen lamp near the focal plane will be mounted

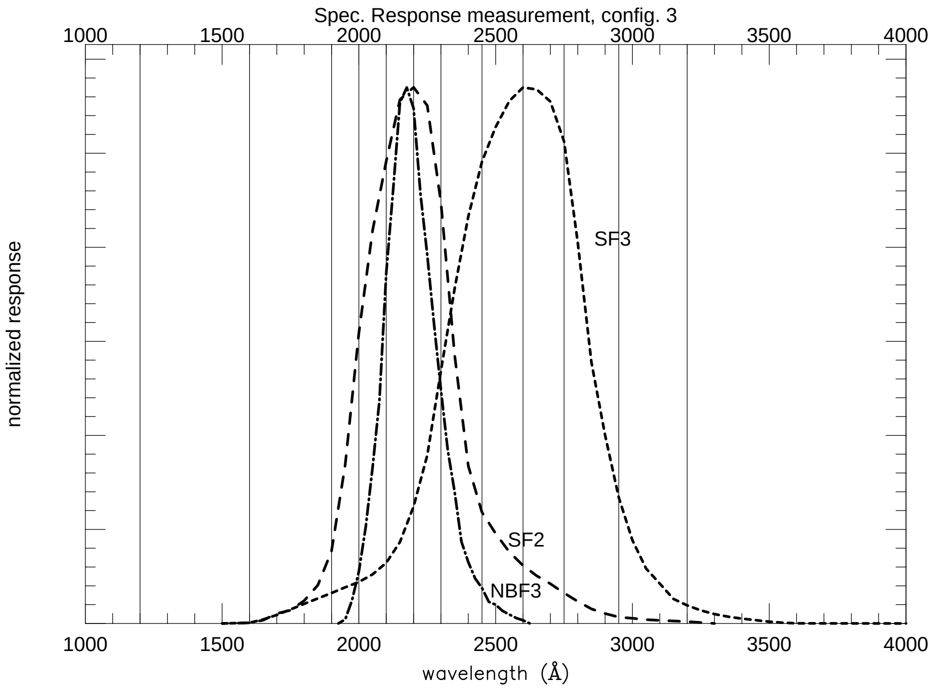

Figure 9. Filter profiles and wavelengths to measure for the throughput calibration of NBF3, SF2 and SF3.

so that it can be pointed at TAUVEX from the desired angle, with a calibrated photodetector to determine the intensity of the beam.

The test will be performed so that the TAUVEX telescope under test (the central one) points to the entrance aperture of the light-trap box. TAUVEX will be fully covered with black curtains so that no light emitted by the collimator or reflected from TAUVEX or the room walls will be able to illuminate TAUVEX. All light sources in the clean room will be switched off and the collimator will be pointed to the TAUVEX entrance aperture at the desired angle to the LOS. Measurements will be taken at three angles: 20°, 40° and 50° (TBR) and will be compared with the calculated values for these angles.

The pass/fail criterion is the result for the measurement at 50° from the LOS; this should be identical to that calculated for this angle. Measurements at for the lower angles should be better by a factor of 2-3.

3. Calibrations in space

The purpose of the calibrations in space is to verify and refine the ground calibrations. In planning for the TAUVEX space calibrations we again relied on previous experiences, such as that from GALEX (Morrissey et al. 2005).

For a number of tests, it is expected that the space calibrations will surpass in accuracy those calibrations done in the lab. However, the space calibrations are costly in terms of TAUVEX operational time. The intention is, therefore, to minimize the need for special observations to derive the calibrations. These will be derived preferentially from the science observations.

3.1 Flat field

It is possible to derive a one-dimensional flat field map just by following a source as it transits the FOV. Assuming the source does not change its brightness during the detector passage, its count rate is expected to be constant. Deviations from a constant rate are attributed (in first instance) to vignetting and non-uniform detector response, i.e., flat field corrections.

The negative side of this test is that the count rates are expected to be low for most of the imaged sources, so that TAUVEX remains in its linear regime, thus any individual correction will carry a high statistical noise level. To derive a good flat field correction it will be necessary to add up many source transits for the same detector location. In order to cover the entire TAUVEX FOV it will be necessary to repeat this for many sources, at different locations on the detector.

This calibration does not require special observations but can be derived from the routine science observations. It is likely that the processing of the first data sets will use the ground calibration. During the performance verification phase of the mission a first cut at flat field calibration in space will be made. The calibration will be refined as more observations will be gathered.

3.2 Distortion

The space calibration of the distortion requires special observations of a stellar field with bright enough sources so that their centroids can be determined for each 128 msec subframe interval. The sources have to be very accurately astrometrically-measured and present an unambiguous picture to the investigator. A preferred choice is to observe a nearby open cluster; such targets are rich in bright, early-type stars that would be easily recorded by TAUVEX.

One possibility is to use the Pleiades star cluster. Since the cluster contains some very bright 2nd magnitude A stars that can bring the system into a non-linear regime, the distortion calibration should be done using intermediate, i.e., SF filters, or even the NBF-3 filter. The advantage of such a choice is the relatively large number of stars that will be imaged in each 128 msec sub-frame. The disadvantage is the necessity of scheduling a special observation.

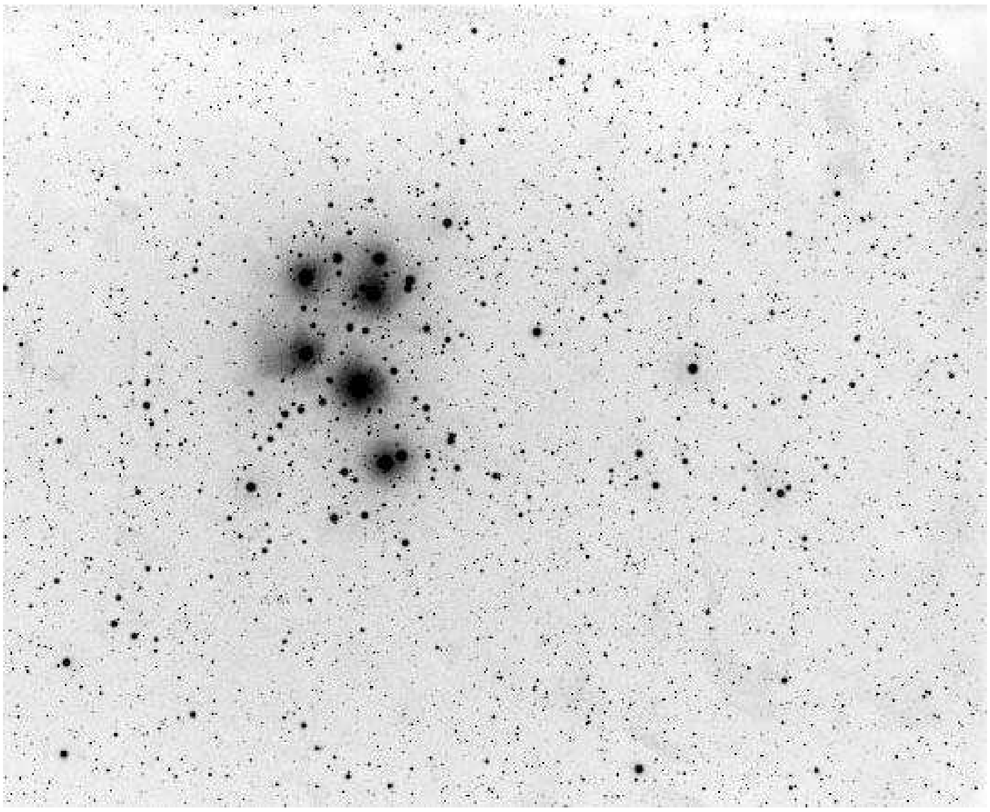

Figure 10. The Pleiades star cluster (depicted as negative). Note that the field of view of TAUVEX is larger than the extent of the seven bright stars.

In principle, distortion corrections can also be derived from observations of any star field with accurate astrometry. We shall prepare UV strip catalogs of Hipparcos/Tycho stars at the same declination, which have very good astrometric measurements, by transforming their optical magnitudes to the UV. These stars will be "traced" during TAUVEX scans and will allow a separate derivation of the distortion correction.

3.3 Spectral calibration

The issue of spectral calibration has been considered by the HST and by GALEX; we shall adopt a similar strategy and use dedicated observations of UV spectrophotometric standard stars (Bohlin et al. 2001, 2004; Strongylis & Bohlin 1979). These will have to be scheduled outside the regular observations, since only short scans will be required across each calibrator.

The first GALEX calibrators were the white dwarfs (Morrissey et al. 2005): HZ21, HZ43, HZ44, BD+33°2642, LDS749B, and G93-48. These are objects with UV magnitudes [AB] 10-13, with the exception of LDS749B that is 15 mag, and are perfectly well observable by TAUVEX.

However, in order to provide a more densely sampled calibration, it will be necessary to derive secondary calibrations from among the regular observations. These will be based on the brighter stars that will be contained in each scan; since scans will be repeated a number of times in order to achieve sufficient exposure depth, it is likely that this would yield also secondary calibrators to account for even small changes in the absolute calibration.

3.4 Linearity

The linearity calibration can be performed on-the-fly, with the science data gathered routinely. The calibration is originally based on the ground tests and is refined as space data are gathered.

The only necessity is that the sources to be used for this test be measured in the UV; we shall use a combined catalog of UV sources with entries from TD-1, FAUST, IUE, and GALEX augmented by lists of stars whose UV magnitudes will be predicted from their optical properties.

3.5 Stray light rejection

The stray light rejection will be verified during the PV phase in order to set the necessary parameters for observation scheduling. There is no intention to "calibrate" the stray light; just to quantify its influence for various TAUVEX orientations with respect to the Sun, so that the stray light can be factored in the target scheduling process.

4. Conclusions

We devised a comprehensive program to calibrate TAUVEX both on the ground and in space. The program allows a derivation of all the necessary parameters required to convert the collected count rates into accurately fluxed measurements.

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