BRITE-Constellation Science Operations

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BRITE-Constellation is a nanosatellite mission designed for stellar astrophysical research in collaboration between Austria, Canada and Poland. A fleet of six spacecrafts was funded, built and launched, two from each country, all designed to perform precise time-series photometry of the brightest stars in the sky. While the spacecrafts have the same basic design, three satellites host an instrument sensitive in a red bandpass, the others, for a blue wavelength range. From the six satellites launched, five are operational. The sixth one did not separate from the upper stage of the rocket and remains idle. The first pair, the Austrian satellites, started to collect science measurements with their wide field ($\sim 24^{\circ}$) cameras in early December 2013. Since then, more than 340 stars were observed during 16 campaigns, the majority for more than 100 days (up to 168 days) continuously. In total, more than 2.1 million measurements have been collected so far. Originally, the limiting magnitude for target stars was set to $\mathrm{mag}(V) = 4$. However, even stars as faint as $\mathrm{mag}(V) = 6.5$ have been observed with sufficient precision. This is a review of science operations conducted during the past 3.5 years.

1 Introduction

The BRITE-Constellation (where BRITE stands for BRIght Target Explorer) technical layout and science goals have been described in detail by Weiss et al. (2014). The BRITE satellites are 20 cm cubes with a mass of about 7 kg. Hence, they qualify as nanosatellites which are spacecrafts between 1 and 10 kg. One of the key properties to conduct science grade data is that BRITE satellites can be stabilized in three axes to better than 1.5 minutes of arc during at least 15 min while orbiting the Earth. Each satellite hosts an instrument, a 3-cm aperture multi lens refracting telescope, projecting a ~ 24 deg circular sky area on a 4048×2672 pixel size interline transfer CCD (Kodak, KAI 11002-M). The system is deliberately de-focused to spread the light of stars onto about ~ 80 pixels. The optics of each instrument is either designed for a RED bandpass constrained by a filter in front of the telescope to $550-700$ nm or to $400-450$ nm in the BLUE layout. In front of the optics, there is a baffle installed to suppress stray light from the bright Earth, Sun, and Moon. The plate scale is set to about 27 arcsec per pixel in the centre of the field with progression to 30 arcsec at the edges. While the PSFs are circular in the middle of the field-of-view, the shapes get increasingly complex as a function of the distance from the optical axis. All satellites have been launched into so called Low Earth Polar Orbits (LEO), between 600 km and 800 km heights from the Earth surface, leading to orbiting periods of $96-101$ min, respectively. The satellites were launched in the sequence starting with the Austrian pair, UniBRITE and BRITE-Austria (aka TUG-SAT-1) in February 2013 from India, followed by the first Polish satellite BRITE-PL1 'Lem' in November

Country	Name	ID	Launch date	Period [min]	Filter
Austria	UniBRITE	UBr	25-02-2013	100.37	RED
	BRITE-Austria	BAb	25-02-2013	100.36	BLUE
Poland	BRITE-Heweliusz	BHr	19-08-2014	97.10	RED
	BRITE-Lem	BLb	21-11-2013	99.57	BLUE
Canada	BRITE-Toronto	BAb	19-06-2014	98.24	RED
	BRITE-Montréal	*BMb*	*19-06-2014*	*n/a*	*BLUE*

Note: BRITE-Montréal did not separate from the launch vehicle and is not operational.

Table 1: BRITE-Constellation satellites.

of the same year from Russia. Next in line was the Canadian pair, BRITE-Toronto and BRITE-Montréal in June 2014 from Russia and finally the second Polish satellite BRITE-PL2, 'Heweliusz', August 2014 from China. Unfortunately, the separation of the second Canadian spacecraft, BRITE-Montréal, did not work and the satellite is still confined to the upper stage of the launch vehicle ever since. Hence, only five of the six satellites launched are fully operational. Table 1 comprises the affiliations, names and the main properties of all BRITE satellites.

Even though all satellites are of the same base design with the main difference being the installed instrument, either a RED or BLUE type, there are other slight but significant alterations which influence the performance. The Polish and the Canadian BRITE satellites have a different star tracker with enhanced properties compared the model installed in the Austrian units. The consequence is better pointing stability and a wider range of orientations (all sky, instead of limited to the Galactic plane) can be accessed with BHr, BTr and BLb. Right after the first satellites, UBr and BAb, were launched, it became apparent that the CCD detector in the camera is subject to radiation damage in space by building up among other effects 'hot pixels' progressively over time. Since the first Polish satellite was already in the launch preparation phase for Nov. 21, 2013, no sufficient time was left to add more camera shielding to the existing design. However, for the remaining three satellites, BTr, BHr and BMb (although the latter one is for other reasons not functional), more protection was installed prior to their launch.

The main scientific goal of the BRITE-Constellation mission is to survey a large part of sky by measuring brightness variations of the brightest stars on timescales ranging from a few minutes to several months in two colours. Among those are intrinsically the most luminous and massive stars such as O and early B-type stars and supergiants of cooler effective temperatures. However, due to fact that essentially all stars brighter that $\mathrm{mag}(V) = 4$ are measured in any selected field, many other classes of stars (variables) are also included in our program. Therefore, BRITE-Constellation is providing a broad community of stellar astrophysicists with scientific data as is evident when looking at the articles in these proceedings.

2 BRITE organization and observations

The leading authority is BEST, the BRITE Executive Science Team, which decides on observing field selection as well as data distribution. Rules and regulations are written in a 'Bylaws' document which is available on the BRITE-Constellation website (http://www.brite-constellation.at/). The goal of BEST is to select observing fields with a firm list of target stars in general at least one year in advance of the actual campaign, so that ground-based supplementary observing runs can be organized by the groups that proposed the stars.

Mission Control (MC) is in charge of instructing the satellite operations teams. There is one in each partner country, with all relevant information on how to collect science data. This is cast in so called instrument setup files together with the start and end dates of an observing campaign. In return, MC gets access to the collected science data from all satellites on a daily basis in order to check the data quality and integrity. MC reports on a biweekly basis on the status of satellite operations and on the progress respectively issues with observations to BEST.

After an observing run has ended, all raw science data are FITS formatted, which includes image data from the cameras but also relevant spacecraft telemetry such as CCD temperatures and pointing offsets. The data are then made available for data reduction, which delivers light curves from each star observed during a campaign. Those light curve data are checked again for consistency by MC and also by BEST members (very recently even by a subgroup called Quality Control Team, QCT) before they are distributed to the according recipients. The BRITE mission organizational structure is shown in Fig. 1.

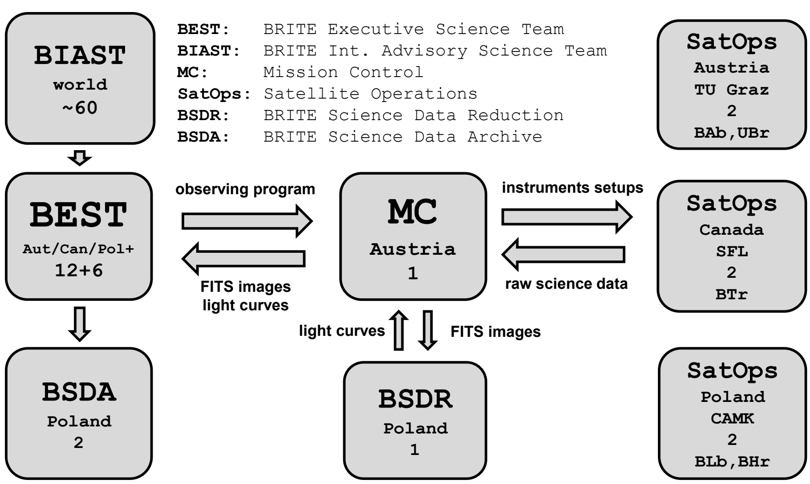

Fig. 1: The BRITE-Constellation organizational structure is drawn up as a block diagram. The numbers in the boxes reflect the number of persons which are mainly involved in conducting the tasks.

Thus far BRITE-Constellation satellites have completed 16 observing campaigns and three are currently ongoing. More than 340 stars have been measured and a subset of them more than once. For example stars in the Orion field are currently

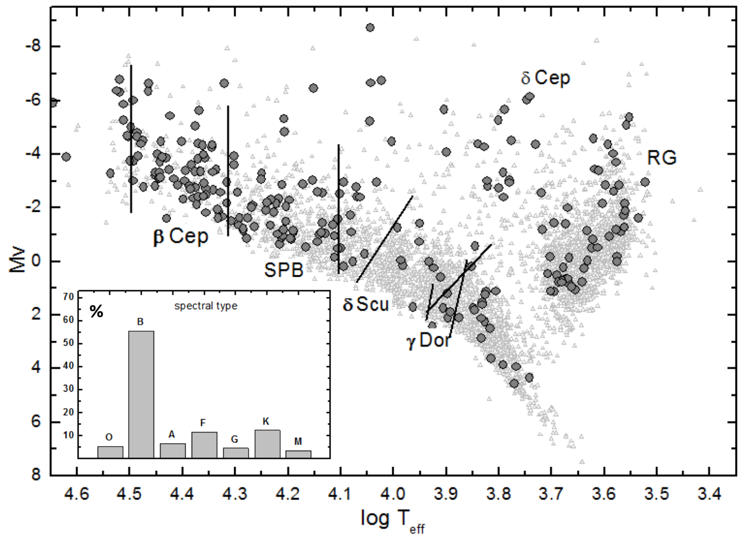

Fig. 2: BRITE target stars plotted on an HR diagram. The small grey triangles are all stars brighter than mag(V) = 6. The filled circles stars observed by BRITE. The inserted diagram on the bottom left shows the percentages broken down by spectral classes.

observed in a fourth campaign by the Austrian satellites and those are also in the observing plan for the upcoming two years.

While at least three of the five satellites can observe anywhere on the sky regardless of how many very bright stars (mag(V) < 3) are in the field of view, most observing fields were selected at or close to the Galactic plane, simply because those fields render many scientifically interesting bright stars. Typically $16-30$ stars are observed by two or more satellites per field. Off the Galactic plane this quickly drops to $5-10$ at the mag(V) $= 4.5$ limit. The star tracker model built in the two Austrian satellites, BAb and UBr, has based on experience a need for about $4-6$ stars brighter than 3.5 mag(V) for operating in accurate (fine) pointing mode. Therefore, stable observations only at or close to the Galactic plane are feasible. The BRITE-Constellation observing plan has been laid out accordingly.

Details about the past, current and futures planned observations can be found openly (no registration required) at a designated Wiki site: http://brite.craq-astro.ca/. This site also includes information about who are the contact Principal Investigators (cPI) for each star and observing campaign.

2.1 Observed stars

As mentioned in the Introduction the BRITE-Constellation science goals were from the onset focused to study hot and massive stars. Hence, many proposals with overlapping target lists were submitted in the past, which included essentially all bright O, early B (OB), and most other B-type stars as well as supergiants from all classes. Figure 2 shows where the observed stars are located in the HR diagram as well as statistics concerning the spectral types.

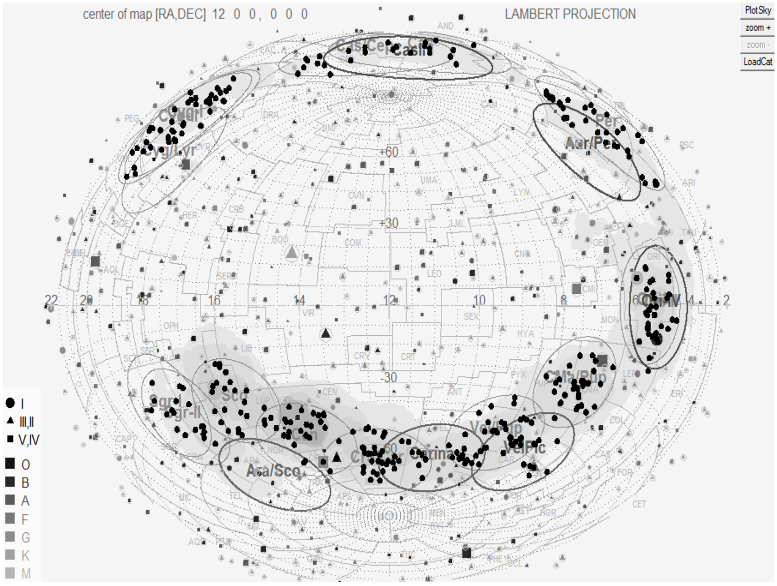

Fig. 3: BRITE past, current, and future planned observing fields are outlined on an all-sky map. The black filled circles are individual stars for which data have been collected and reduced as of yet.

Despite the focus on hot stars, the current sample of stars observed by BRITE is significantly spread across the HR diagram due to the fact that when selecting bright stars in rich fields, many other classes and types are also included. Adding O and B stars together, they account for at about 60 percent of all stars observed thus far. While that fraction will naturally increase in the next years, some well know very bright variable B stars like Spica may never get into the program since it has only few other bright objects nearby ($< 12^{\text{o}}$ distance) and therefore such a field will unlikely be selected. The remaining 30 percent of the current tally are cooler types, either in the instability strip such as δ Scuti and γ Doradus pulsators, or evolved G, K, and M stars (red giants) and also a number of Cepheids even though most of them are relatively faint ($5-6$ mag(V)).

2.2 Observed fields

BRITE-Constellation has to date 16 observing campaigns completed and three more are currently conducted. In addition, the actual observing plan includes three more fields for future observations up to September 2017. Essentially, all observations thus far have been carried out close to the Galactic plane.

Figure 3 shows an all-sky map (all stars brighter than mag(V) = 4.5) and outlines the past, current, and future observing fields which are in the official BRITE observing program right now. Furthermore, all stars are marked which have been observed by BRITE so far and the data have been reduced and released. An extension of the observing program till mid-2019 is currently under investigation by BEST. The public release of this plan can be expected in November 2016 and will be posted on the Wiki site (see above).

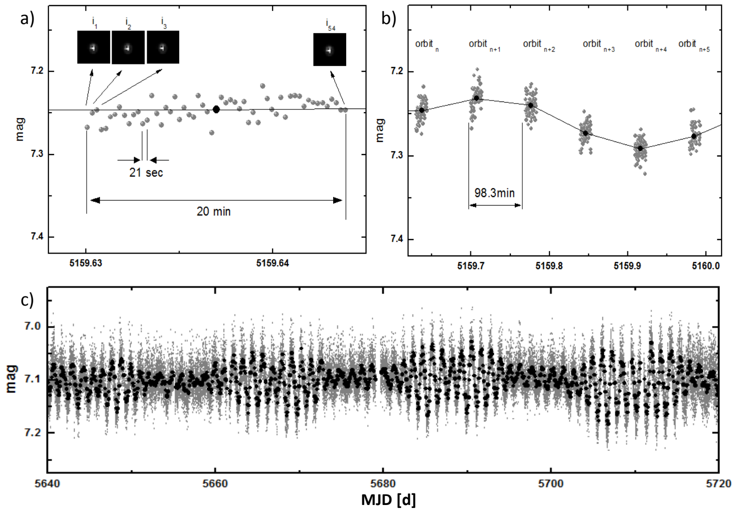

Fig. 4: BRITE typical time-series sampling is presented. Figure a) shows how measurements are timed during one orbit, b) the delay between subsequent orbits and c) 80-day stretch of measurements obtained from a variable star.

3 BRITE photometry

BRITE photometry is space photometry benefitting from the fact that it is conducted outside the Earth's atmosphere and hence are not influenced by its turbulence or weather conditions. The day-night cycle of ground-based photometry is also bypassed and essentially only the close vicinity to the bright Earth, Sun, and Moon are at times disturbing factors.

However, there are also some limitations and challenges going into space like the cost, the size of the instrumentation has to be constrained, no service or alterations can be done (other than for Hubble) and the spacecraft while flying with ∼27,000 km/h around the Earth has to be accurately stabilized to a selected orientation repeatedly every orbit which lasts typically between 96 and 101 min. Also, the radiation environment is harsh and electronics including the detectors needs protection (see the next section).

Furthermore, the amount of data which can be transferred to ground is limited, in the case of the BRITE satellites to about 25 − 50 MBytes per day. The data transmission via the European ground stations is at the lower bracket since most of the time an uplink interference source (likely a military installation) is present. The Canadian ground station in Toronto is not affected by that and can operate essentially on its full technical capability.

3.1 Timeseries sampling

The BRITE-Constellation satellites with their instruments operate all in Low Earth Orbits (LEO) and cannot by default observe target fields/stars continuously each orbit. Typically, during an orbit science data are collected for 15 to 30 min.

After each exposure, which can range from 0.1 to 10 seconds depending on the setup, the full frame CCD image (~ 11 Mpixel) is transferred to a buffer from which only some typically $16-25$ small regions of interest (ROI) of 48×28 pix which include the selected target stars, also called 'rasters', are extracted. Only those image sections are stored together with relevant telemetry data like start time of the exposure and CCD temperatures in a so called Science Data Record (SDR) on board the spacecraft.

The processing of those tasks takes 3 to 6 seconds depending on how many 'rasters' are set. A subsequent exposure can only start once the processing of the previous is completed and the buffer is cleared for the next image. To keep the data production below a manageable average daily transfer rate, the exposures are in general separated by 21 seconds. This cadence is applied for each orbit and throughout, and in general to the whole campaign. Figure 4 shows a typical observing cadence.

When observations are completed on a field during an orbit, the satellite is commanded to course pointing mode either until this field comes back into access range and the transition to fine pointing is started again followed by data collection, or another field is observed during the time when the first field is out of range. Dual field observations are conducted whenever possible to improve the efficiency and scientific output of the mission. A key constraint is that the two observing fields are properly separated on the sky, ideally with no or only minimal overlap in the access period. One recent example of a successful observing fields pairing was the Crux/Carina field with centre coordinates R. Asc. $= 12^{\mathrm{h}}47^{\mathrm{m}}50^{\mathrm{s}}$, Dec. $= -61^{\circ}50'00''$ and the Cygnus/Lyra field at R. Asc. $= 19^{\mathrm{h}}26^{\mathrm{m}}00^{\mathrm{s}}$, Dec. $= +36^{\circ}30'00''$.

3.2 Radiation damage

Two weeks after the launch of the first BRITE-Constellation satellites, UniBRITE and BRITE-Austria in March 2013, when the first images from the CCDs were taken and transferred to ground, it became apparent that there are artefacts which must have been generated in space by radiation. Those artefacts, seen at the beginning of the commissioning phase of the mission, were pixels and even whole columns with elevated dark (thermal) signals, 'hot pixels' and 'warm columns'. They were found across the whole detector, regardless if inside unvignetted FOV or at the very horizontal edges where no light can shine on the CCD. Images taken in the successive weeks revealed an increase of those even at the same operating temperature. 'Warm columns' show only signal values of $100-500$ ADU above nominal background ($\sim$100 ADU). A pixel is considered 'hot' by internal definition when it reveals a dark signal values greater or equal 100 ADU above median background. Their signals populate all levels even up to saturation $>$12,000 ADU (the full range is 16384, 14-bit resolution). Figure 5 shows example images from BAb taken in September 2013.

Later on, also areas starting from a row $100-300$ pixels wide and all the way up to the top the image, did built up with vertical trails where signal are originating either from 'hot pixels' or from stars (PSF) if those were placed inside those regions. Those zones clearly revealed signs of severe Charge Transfer Inefficiency (CTI). Those areas also increased over time and in already affected regions the trails got longer hence the damage got more severe.

As soon as those defects were recognized the progression rate was monitored for each satellite and in parallel concepts were developed on how to remove signals caused by radiation damage in particular if those merge with PSFs from stars. It appeared

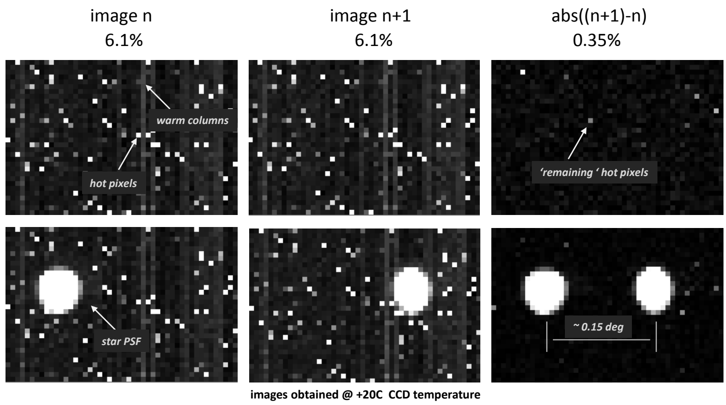

Fig. 5: The top left and middle images are from subsequent exposures without a star rendered in them, so called 'empty rasters'. On the top right is the difference image $(n+1)-n$, with all residual pixel value set positive. The bottom row has a star in the images which is moved between exposures by about 0.15° horizontally. All images have been taken at about $+20^{\circ}$C operating temperature.

that 'warm columns' can be simply compensated for by calculating the median signal value from all pixels of a column and subtracting those values for each column in the raster image. This leaves the 'hot pixels' as the remaining issue. The calculation of the progression rate for the Austrian satellites revealed that about 1.7 percent hot pixels (w.r.t. the total number) are generated per year when referenced to $+20^{\circ}$C CCD temperature. There does not appear to be any structure in the distribution across the detector.

To monitor temporarily the hot pixels in each raster which renders a star, right at the start of the science data collection in December 2013 about three so-called 'empty frames' (the star is moved off the raster) were collected at the end of each observing sequence per orbit. Those provide reference which pixels are 'hot' and merge with the PSF of the star in the raster images and therefore need treatment when reducing the data. However, due to the fact the CCDs are not thermally controlled, the environmental and also self heating of the electronics raise the mean temperature of the detector (measured with four sensors under the chip) by $5-8^{\circ}$C during the observations on each orbit. Hence, we only get this 'hot pixel reference' at systematically hotter or cooler conditions if those 'empty frames' are taken before regular observations start.

In the late summer 2014 a concept was proposed to address the 'hot pixel' issue in a more sophisticated operational way by following a strategy that has been applied in infrared astronomy for decades, called 'chopping' or 'nodding'. This is based on the fact that those measurements are in general conducted with high background/detector noise. Applied to BRITE, the strategy is to change the position of the star, from one

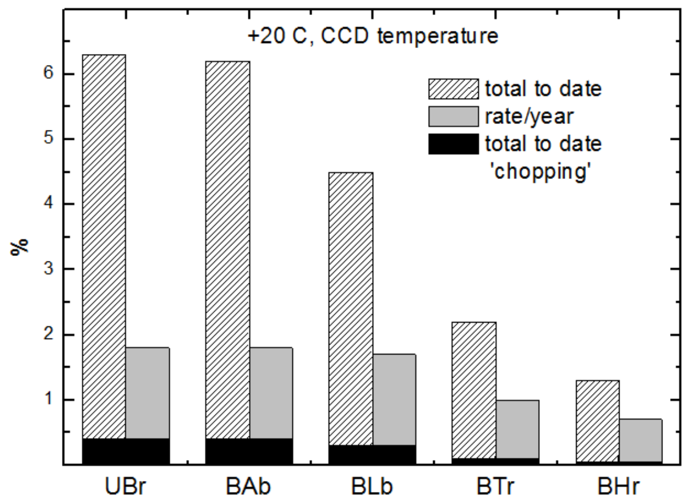

Fig. 6: The bar diagram shows for each satellite the total number of 'hot pixels' (bars with diagonal lines), yearly progression rate (grey bars) and the percentage of pixels (black bars) exceeding the mean background signal value by 100 ADU after taking the difference of the subsequent images.

exposure to the next and throughout the whole observation time per orbit, sufficiently that the PSFs do not overlap. This allows the subtraction of a close to instant background for each image taken and processed at similar temperatures. Figure 5 demonstrates that for a set of images without and with a star included.

When calculating differences of subsequent images, the amount of pixels which reveal residual signal values above or below the background is reduced very significantly. Raw images from UBr and BAb, which currently show a total accumulated 'hot pixel' fraction of 6.1 percent during 3.6 years in space, in the difference image only about 0.36 percent remain and need treatment in the reduction. This 'chopping' mode of operation was tested first on UBr from October 2014 and fortunately the Attitude Control System (ACS) of the satellite was capable to apply this strategy in a stable and consistent manner even though it was by no means designed nor required to cope with that. Starting early February 2015, all satellites have been set to operate in the 'chopping' mode.

A cure for the CTI effects was also investigated and tested. It is based on the fact that vertical charge transfer time was initially set to only 3 μs per shift, which apparently is too short to move all charges in those areas from one pixel to another in radiation-damaged areas. When extending that period up to 20 μs, the upper limit recommended by the manufacturer, all CTI-affected areas essentially disappeared. This timing change was applied to all instruments in August 2015.

Figure 6 summarizes the current hot pixel statistics for all satellites. The instruments with protection beyond the base design reveal a significantly lower damage rate, like only 0.65 percent per year for BHr, which has the most extra shielding installed in the fleet. But even at the high total hot pixel fraction, the 'chopping' scheme mitigates the impact on the science data quality by a large degree in particular when stars are observed at high signal-to-noise regime.

3.3 Data reduction and de-correlation

Once an observing run of a field is completed by all participating satellites, the whole bulk of raw image data is supplemented by spacecraft telemetry and transferred to FITS format. For each raw science data record, one FITS file is created. In sum, typically 50,000 to 60,000 files are produced from one satellite after a full campaign lasting about 160 days or more.

All FITS files are submitted to an archive which can be accessed by persons conducting the data reduction. After the first observation run from early December 2013 till late March 2014, three independent teams were organized to developed optimized science data reduction methods, which apparently was much more challenging than expected, due to the radiation damage of the imagers. During a designated workshop held in Warsaw in September 2014, results were compared and decided that the routines developed by Adam Popowicz lead to the best scatter values. Those tests were done on 'normal' (no-chopping) data collected early on as described above, hence his scheme was tailored to that. Once chopping was introduced by default in early 2015, his routines were extended and optimized to this mode of operation. A description of his specifically developed aperture photometry reduction can be found in Popowicz (2016).

The outputs of the data reduction are light curves for each star. Occasionally, even two stars are in a single raster. In such a case, two data sets are extracted. Those light curve files are supplemented with a header containing auxiliary information about the setup and data collection. A heliocentric time correction is applied and reduction parameters are also included. The final files are then checked for consistency before distribution to the recipients.

The reduced and formatted light curves still contain outliers and typically show evidence of instrumental effects. Among those is most prominently a brightness value correlation with the mean CCD operating temperature. Also correlations with positions, the x and y PSF centre of gravity, is often present and those values are also included for each entry in the light curve file. It is highly recommended that those dependencies are de-correlated, in series or in combination from the data before further analysis steps are applied. In a so called 'Cookbook' written and updated by Andrzej Pigulski this is demonstrated with examples and steps and routines are suggested and explained. The latest versions can be found and downloaded on the BRITE Wiki site at: http://brite.craq-astro.ca/doku.php?id=cookbook.

4 Summary and outlook

Science data collection with BRITE-Constellation satellites have been going on close to three years by now. All spacecrafts successfully launched into orbit (five of six) are working well even though the nominal (design) lifetime of two years has elapsed for them by now. Despite issues with progressive radiation damage of the detectors, the performance is good and well worth to continue the mission, since the introduction of the 'chopping' mode in regular operations reduce the ageing effect significantly. The progressive increase of 'hot pixels' made the data reduction difficult and it took about one year to develop proper routines which subsequently were optimized also for the ‘chopping’ data. Therefore, the publication rate started quite slow but has in particular since the first science conference in Gdańsk, in September 2014, picked up strong momentum. The second conference in Innsbruck will boost that further in the next 12 months. BEST is currently casting an extension of the current observing plan from September 2017 until the middle of 2019. A third BRITE Science Conference will be organized in the summer of 2017 in Canada.

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References

Popowicz, A., *Image processing in the BRITE nano-satellite mission*, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Proc. SPIE, volume 9904, 99041R (2016)

Weiss, W. W., et al., *BRITE-Constellation: Nanosatellites for Precision Photometry of Bright Stars*, PASP **126**, 573 (2014), 1406.3778