The BRITE Space Telescope: A Nanosatellite Constellation for High-Precision Photometry of the Brightest Stars

Norman C. Deschamps, C. Cordell Grant, Dan G. Foisy, Robert E. Zee
Space Flight Laboratory, University of Toronto Institute for Aerospace Studies
4925 Dufferin Street, Toronto, ON, Canada M3H 5T6: (416) 667-7700
normand@utias-sfl.net, cgrant@utias-sfl.net, dfoisy@utias-sfl.net, rzee@utias-sfl.net

Anthony F. J. Moffat
Département de physique, Université de Montréal
C.P. 6128, succ. centre-ville, Montréal, QC, Canada H3C 3J7: (514) 313-6682
moffat@astro.umontreal.ca

Werner W. Weiss
Department of Astronomy, University Vienna
Tuerkenschanzstrasse 17, A-1180 Wien, Austria: +43 (01) 427751870
weiss@astro.univie.ac.at

ABSTRACT: The BRITE-Constellation is a group of Canadian/Austrian nanosatellites that will examine the apparently brightest stars in the sky for variability using precise differential photometry. The constellation consists of four low Earth-orbiting nanosatellites, divided into pairs, with each member of a pair having a different optical filter. Each BRITE satellite will observe a region of interest for up to 100 days or longer, allowing measurement of stellar variability on the order of hours to months. Each BRITE satellite utilizes a number of new, innovative technologies including reaction wheels, star tracker and optical telescope, all sized and designed around Space Flight Laboratory's 5-kilogram, 20x20x20 cm CanX nanosatellite bus. The BRITE science instrument is a low power CMOS detector coupled with a lens system designed to provide a telecentric, slightly defocused image optimized for observing stellar intensity with an accuracy of 1 mmag per data point per orbit down to a visual magnitude of +3.5. Photometric measurements will have an error amplitude spectrum no greater than 20 ppm over measurement periods longer than a month. The optics will have a small (30 mm) aperture and a maximum length of 100 mm in order to fit within the nanosatellite bus.

INTRODUCTION

Life Cycle of Matter

Stars are the cosmic engines of the Universe; all elements heavier than beryllium are produced in stars, and without those heavy elements life would not be possible. Most of these heavy elements are produced in stars that are among the intrinsically brightest objects in the Universe. The apparently brightest stars in Earth's sky are also among the intrinsically brightest stars.

There are two broad groups of stars responsible for the production and dispersal of heavy elements in the universe. The first group is known as Asymptotic Giant Branch (AGB) stars. These are stars of intermediate mass that have evolved off the main sequence of a star's life cycle into red giants and red supergiants. At this stage of the star's life, its primary fusion process is burning helium into other heavy elements. These stars have a large part of their mass removed by strong stellar winds only during this final phase of their evolution. They contribute almost half of the carbon in the Universe, as well as over 200 neutron-rich isotopes of elements such as cadmium, tin, and lead.

The second group of stars are those that begin their lives with greater than eight solar masses. These most massive stars, classified as hot OB stars (including dwarfs, giants and supergiants), and cooler supergiants, represent a small fraction of the stars in the Milky Way, but are important far beyond their small number and in fact, along with red giants and AGB supergiants, dominate the bright stars seen in the night sky. Massive stars are brighter and have much shorter life spans because they burn their fuel at a much higher rate than smaller stars. As a result, hundreds to thousands of generations of massive stars have existed since the Big Bang.

Massive stars enrich the interstellar medium (ISM) with heavy elements in two ways. The first is through blowing strong stellar winds during the star's entire lifetime, as opposed to intermediate stars that do this just at the end. Stellar winds can represent a large fraction of the star's dispersed mass, although the amount of heavy elements ejected by winds will be marginal, since the outer layers of the star lag behind the core, where nuclear burning takes place. The second method of dispersal is through a supernova, which literally blows most of the star apart and generates even more heavy elements in the process. These massive stars are the primary source of carbon, nitrogen, and oxygen in the ISM.

It is well known that these massive and AGB/red-giant stars experience periodic, semi-periodic and irregular variations in intensity. These variations can be due to changes in the magnetic field of the star, density changes and rotation within the star itself, or fluctuations in the surface temperature of the star. The variations can differ greatly in both time and intensity, with periods ranging from minutes to months and intensity changes as small as a few parts per million.

Oscillations generated by seismic phenomena within the star are excited in many different modes simultaneously. By identifying the frequency associated with each mode, information about the density of specific layers within the star can be modelled and analyzed, i.e. we can learn about the internal structure of the star without actually probing it directly! Mode association with frequency can be considerably enhanced by measuring photometric variations using different colour filters.

Science Objective

There are many questions about the life cycles of bright stars that remain unanswered. Some of these questions will begin to be answered with the upcoming BRIght Target Explorer (BRITE) Constellation mission. The primary goal of BRITE-Constellation is to constrain the basic properties of intrinsically luminous stars – i.e. stars that most affect the ecology of the Universe – by measuring their oscillations on minute to month timescales, based on dual-broadband, ultra-high precision photometric time-series from space.[1] Roughly speaking, the fundamental vibration mode of a star is inversely proportional to the square-root of its mean density. Observing this mode and its harmonics thus gives information on the density profile within the star.

Observations of stellar oscillations will give new insights into the inner workings of O and B type stars and help to constrain models of surface fluctuations in red giants and supergiants. In both cases, this knowledge will help answer important questions concerning the ecology of those stars most important to the life cycle of matter.

Achieving the Science Objective with BRITE

The BRITE-Constellation is a joint Canadian/Austrian project that is currently developing a constellation of four nanosatellites to answer the science objective. Each nanosatellite will observe a subset of the 286 apparently brightest stars with limiting visual magnitude V=3.5. The satellites will use a small-aperture telescope and CMOS detector capable of taking images with a differential brightness measurement accurate to at least 0.1% per sample. The telescopes will have a 24° field of view (FOV) and will be capable of using either a red or a blue optical nearly square bandpass filter.

Pairs of nanosatellites, one with each type of filter, will take images during a 15 minute window once per orbit (typically 100 minutes), for time periods up to 100 days or longer. These images will encompass regions of interest that contain anywhere between 2 and 15 of the bright stars under study (Figure 1). Having multiple bright stars in a region of interest will allow for high precision differential brightness measurements of those stars. These brightness measurements, mapped out over time, will give the variability of each of the stars. Table 1 outlines the mission parameters required to achieve the science objectives.

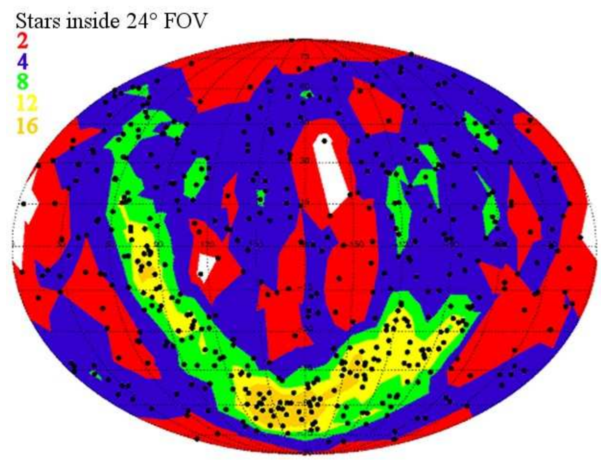

Figure 1: Number of Stars with Limiting Magnitude V=+3.5 Visible Across the Whole Sky for a 24° FOV.

The reasons for using a constellation of nanosatellites instead of a single satellite are twofold. First, multiple satellites observing the same region of interest will increase the overall duty cycle of observation beyond what a single nanosatellite can provide. Because the stars that we want to observe with BRITE are located in all parts of the sky, a continuous viewing zone for all targets of interest is not possible. Each BRITE satellite's view of any given region of interest will be occulted by the Earth for some period of time, depending on the star's position and the actual satellite orbit. Having two BRITE satellites in two slightly different orbits that have different viewing times for the same region of interest doubles the duty cycle and significantly improves the spectral window.

Table 1: Science Requirements

Science Requirement	Minimum Requirement
Visual magnitude limit	+3.5
Positional constraints	None, all parts of the sky except for sun and moon exclusion zones
Field of view	> 24° diameter
Differential photometry error per single observation	< 0.1%
Error of amplitude spectrum for > month	< 2×10^{-5} (20 ppm)
Cadence (repeat of the same field)	< 100 minutes
Duration of the mission	> 2 years

Secondly, each telescope will be optimized to work with only one colour filter. By collecting colour as well as intensity data from at least two different BRITE satellites, each with a different filter, the science capacity of BRITE is greatly enhanced. To minimize development costs, the BRITE telescope is being designed to have no moving parts. This means that we cannot change between filters using one BRITE telescope in orbit.

By having two nanosatellites in the same orbit, each with a different filter, we can minimize the development costs by ensuring that each BRITE satellite is identical except for the telescope and thus help to eliminate nonrecurring engineering costs.

BRITE DESIGN

Satellite Design Requirements

Table 2 gives an overview of the major design requirements for the BRITE satellites to achieve the science objective. The primary design requirement of the satellite bus comes in the attitude control. The strict photometric error-tolerance places a high precision requirement on the ACS system to ensure BRITE will always keep regions of interest surrounding each star within the same pixel areas on the imager.

Spacecraft Platform

The BRITE satellites will use the Generic Nanosatellite Bus (GNB) developed by Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS), Canada (Figure 2). The first BRITE satellite, UniBRITE, is being built by SFL for the University of Vienna. The second BRITE satellite, BRITE-Austria, is being developed by the Graz University of Technology with mentoring and components from SFL. The BRITE team has asked the Canadian Space Agency to complete BRITE-Constellation with two Canadian BRITE nanosatellites.

Table 2: BRITE Platform Specific Mission Requirements

Mission Requirement	Minimum Requirement
Field acquisition	< 0.5°
Field re-acquisition accuracy	1.5 arcminutes
Attitude error during observation	2 pixels over 15 minutes
Data transfer/day	> 180 KB
Onboard memory storage	> 360 KB
Window of observation per orbit	> 15 minutes
Detector temperature	< 20 °C

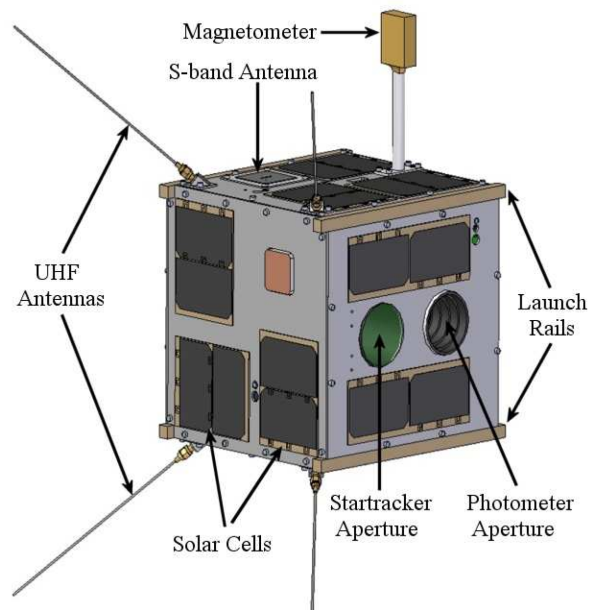

Figure 2: One of Four BRITE Satellites

The GNB is a modular spacecraft bus designed around a 20x20x20 cm cube form factor that provides all basic satellite functionality. The GNB incorporates a direct energy-transfer power system utilizing up to six solar cells on each face and battery storage to supply 10 W peak and 5.6 W nominal for the satellite. Attitude sensing is provided by coarse and fine sun sensors located on each face of the satellite, and a magnetometer on a pre-deployed boom.

Many of the technologies being used for BRITE will have space heritage through use on CanX-2.[2] CanX-2 is SFL's technology demonstration satellite, planned for launch in mid 2007. Some of the components that will benefit from the space heritage provided by CanX-2 are the sun sensors, magnetorquers, magnetometer, UHF receiver, S-band transmitter, and reaction wheels.

Attitude Determination and Control

The generic nanosatellite bus includes coarse and fine sun sensors, as well as a magnetometer, to achieve attitude determination of +/- 2°. To achieve the error requirements for the photometry measurements, however, arcminute attitude determination is required. To accomplish this, BRITE will use the nanosatellite sized startracker currently being developed by Dynacon Inc. and Defence Research & Development Canada. The startracker will consume a maximum of 0.5 W, and have a maximum mass of 500 g.

BRITE will use nanosatellite sized reaction wheels for attitude control. These reaction wheels are built by Dynacon Inc. and will give each BRITE satellite attitude stability of +/- 0.5 arcminutes in the pitch and yaw axis and +/- 2.5 arcminutes in the roll axis over a 15 minute observation. Vacuum core magnetic coils on all three axis will be used for momentum dumping.

With the startracker and reaction wheels, BRITE will have attitude control accuracy to 1.5 arcminutes. For a 3048 pixel row size in a 24° FOV, this means that a star image will not move more than 5 pixels during the entire observation window. This is an unprecedented level of attitude control and determination for a nanosatellite.

Communications

Each BRITE satellite will be capable of full duplex communications with the ground during its mission. The satellites will use UHF for uploading commands and software from Earth, and an S-band transmitter for transmitting back down to Earth. The BRITE constellation will use four groundstations on Earth: one at SFL in Toronto, Canada, one at the University of British Columbia, one at the University of Vienna and one at the Graz University of Technology.

Thermal

To minimize cost and complexity, the GNB is designed to use only passive thermal control over a broad range of orbits. Thermal analysis for the BRITE satellites has shown that these passive thermal control techniques will be sufficient to keep the photometer below the required 20 °C. This strict temperature requirement is necessary to minimize imager noise due to dark current, which is highly dependent on temperature.

Computers

Each BRITE satellite will have three processor boards. The main On Board Computer (OBC) handles power and communication while a second computer handles the attitude determination and control of the BRITE satellite. A third computer, the Science OBC, controls the photometer and handles the photometric data. Communications between the boards occurs through a serial peripheral interface. Each processor board is based around an ARM7 processor and will have 256 KB of code memory and 2 MB of hardware Error Detection And Correction (EDAC) memory to store program variables and data. Long term storage of data will be in 256 MB of flash memory.

PHOTOMETER DESIGN

Telescope Design Requirements

The overall photometer on each BRITE satellite will be comprised of specially built optics coupled with a CMOS imaging detector. Table 3 outlines the design requirements for the photometer instrument.

Table 3: Photometer Instrument Requirements

Photometer Requirement	Minimum Requirement
Point spread function	5-7 pixels
Intensity spread	99% within 12 pixel diameter
Vignetting	none
Image distortion	none, telecentric
Maximum size	6x6x18 cm
Power consumption	< 0.5 Watt
SNR	3000 per 1000 s exposure
Memory	Sufficient for one full frame exposure (28 MB min)
Absolute time accuracy	0.01%
Mass	< 500 g

Optics Design

The stringent design requirements of the optics for the BRITE photometer make it extremely difficult to use off the shelf solutions. Low-cost commercial lens systems often exhibit strong vignetting and position-dependent image distortion, which are contrary to the primary mission requirements restricting vignetting and distortion. Secondly, BRITE has requirements for the point spread function (PSF) which is attained by a lens system that is not sharply focused, contrary to almost all commercial lens systems.

The solution for the BRITE-Constellation is to use a custom optical design that is telecentric, eliminates vignetting, and provides the necessary PSF. The first optics design iteration used a double-gauss lens system with a central aperture-stop. This first design satisfied all of the design requirements, but would require a large baffle to limit stray light to acceptable levels. This baffle would have to be external to the satellite bus and would greatly increase the complexity of the satellite and satellite launch system. As a result, the double-gauss lens system was abandoned.

The second design iteration takes into account the fact that the BRITE photometer does not have to be sharply focused. The lens system must be designed to accommodate both the wide field-of-view and the unfilled pixels of the CMOS detector. This allows the image of each star to be smeared across a number of pixels to minimize the pixel-to-pixel variation in the imager. Analysis has shown that a full width at half maximum (FWHM) of 5-7 pixels is sufficient to overcome any error in the photometric measurements due to less than 100% fill factor of the imager pixels. This is important since a CMOS imager, which typically has a lower fill factor than a CCD imager, will be used for BRITE.

The slightly out of focus approach to the optics allows for a different design using an external aperture stop (Figure 3). The external aperture stop design still satisfies all of the mission requirements as well as being much better suited to suppressing stray light. While a complete stray light analysis still has to be completed, preliminary analysis indicate that a baffle short enough to fit completely inside the satellite bus can be used, greatly reducing the complexity of integrating the photometer to the satellite.

The optical system has a focal length of 70 mm and an overall length of 100 mm. The external stop aperture will be 30 mm in diameter with a FOV of 24°, giving the optics an effective focal ratio of 2.33. The image size on the focal plane will be a circle with diameter 29.8 mm. The optics are being designed to have maximum intensity transmission between 380 and 850 nm with each pair of BRITE satellites using either a blue or red nearly square box filter. Analysis shows that filters with bandpasses of 380 to 565 nm and 565 to 850 nm will give nearly similar photon counts for an average star using the two different filters.

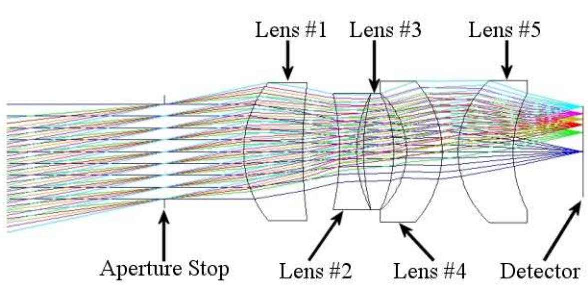

Figure 3: Optics Design

Another mission requirement is that each BRITE satellite should be as identical to the others as possible in order to reduce non-recurring engineering costs. This is in keeping with standard nanosatellite design philosophy. Unfortunately, optimization of the optics is required to deal with the two different filters. This means that there will be two slightly different optical designs, each one optimized for either the red or blue box filter.

Electronics Design

Traditionally CCD imagers have been used for science and space applications. CCD imagers are a proven technology, can have close to 100% fill factor, and exhibit low dark current. Unfortunately, CCD imagers require a lot of power, typically 2 Watt or more. For a spacecraft platform that only produces 5 Watts nominally, even 2 Watts for the imager is excessive. Additionally, science-grade CCD imagers are quite expensive.

The high power consumption, more complex electronics and high cost make CCD imagers unsuitable for a nanosatellite platform. For these reasons, CMOS imagers were looked to as an alternative for the BRITE imager. While CMOS imagers have not traditionally been used for science, this has started to change.[3]

The current design of the photometer uses the IBIS4-14000 (IBIS) from Cypress Technologies (formally FillFactory). Table 4 outlines some of the relevant specifications of the IBIS imager. The IBIS imager is a 13.9 megapixel CMOS imager that has the best combination of price, availability, and technical specifications for our mission. The IBIS has a 35 mm film frame size (35x24 mm) with square pixels of 8x8 μm. This pixel size together with the optics described previously, give the photometer a resolution of 23.6 arcseconds per pixel. The relationship of the IBIS size (35 x 24 mm) to the image size produced by the optics (29.8 mm diameter) means that the image will fit on the long side of the imager but will be slightly clipped on the imager's shorter axis.

Table 4: IBIS4-14000 CMOS Imager Characteristics

Characteristic	Typical Value
Imager size	35x24 mm
# of pixels	4560x3048
Pixel size	8x8 μm
Peak quantum efficiency	45%
Full well charge	65000 e^-
Dark current (at 20□C?)	223 e^-/s
Power consumption	< 176 mW

The photometer will use a custom set of electronics to operate the IBIS imager. The electronics will include four A/D converters to convert the IBIS analog pixel values, and 32 MB of memory to temporarily hold a full frame image. The imager and memory timing and signals will be controlled using a Complex

Programmable Logic Device (CPLD).

The photometer will use four 14-bit A/D converters operating at 3 MHz. With a row overhead of 42 μs/row required by the IBIS, this means that an entire image can be written to the photometer's 32 MB of RAM in 1.3 s. The photometer will be capable of taking sequential images with exposure times between 1 and 1000 s, with the only lag due to reading and storing pixel data in between images.

Communication with the Science OBC will be handled by the CPLD within the photometer and data transferred through a 16-bit data bus. The Science OBC will be responsible for dictating when images will be taken and for retrieving each image from the read out electronics. To reduce the amount of time required to retrieve each image, the Science OBC will be able to request only selected regions (subrasters) of interest from each image from the readout electronics. This alone will reduce the amount of data transferred and stored from the photometer by a factor of almost 1,000. To further reduce the amount of data, the Science OBC will also be responsible for coadding images of each region of interest over an entire observation window. Thus only one image for each region of interest will be saved per 15 minute observation window. Finally, the Science OBC will also be responsible for loss-less compression of the images for eventual download to Earth.

SFL is currently in the process of building and testing a prototype of the control electronics for the photometer. Future testing will be done using the photometer electronics with a ground-based telescope to analyze signal to noise characteristics of the electronics with actual photometric data.

Photometer Housing

The housing of the photometer is contained in three separate sections (figure 4). The rightmost section holds the header board, upon which the CMOS imager is attached. The imager is on a printed circuit board that is separate from the rest of the photometer electronics in order to be able to mount it directly onto the photometer-optics housing without requiring a lot of extra space.

The optical cell holds the lenses. It was necessary to split the optical cells into two separate parts due to the configuration of the lenses (see Figure 3). The lenses will be mounted elastomerically using a space rated epoxy.

The third section of the photometer housing is the baffle. The baffle also holds the filter at the external pupil stop location. One advantage to this configuration is that the filter protects the lenses within the optics housing from debris. The shape of the baffle section will be finalized once the stray light analysis has been completed.

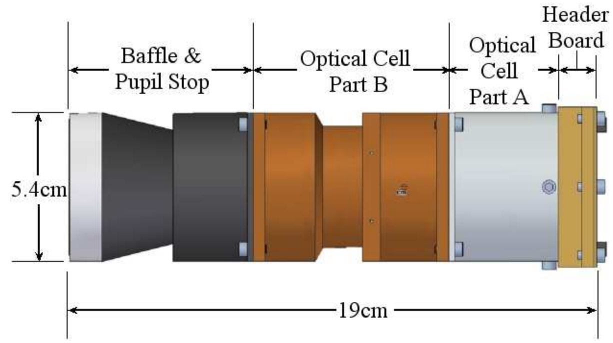

Figure 4: Photometer Housing

The photometer housing is being designed to be light tight; it would be far more difficult to ensure that the entire satellite is light tight. The problem with making the photometer light tight is that it conflicts with the venting requirements of the satellite bus. Mission requirements for the generic nanosatellite bus dictate that all components must be able to vent gases to prevent pressure-induced failures on orbit unless specifically designed to operate under pressure. One option being pursued at the moment is to add vents along the optical path around the edges of the lens in the optics section. This would allow for venting of the photometer housing once it leaves the Earth's atmosphere, while still minimizing stray light to the detector.

The photometer housing will be kept thermally isolated from the rest of the satellite as much as possible. This thermal isolation will aid in keeping the photometer temperature stable through eclipses as well as prevent distortion of the image due to deflections caused by temperature gradients in the photometer housing. Lowering the average temperature of the satellite bus using passive thermal coatings will keep the instrument temperature below the required 20 °C.

One major issue that has come up during the design of the photometer is sun stare. It would be extremely problematic should a door or some sort of cover over the optics be required to prevent damage to the imager in a sun stare condition. Thermal analysis of the imager in conjunction with the optics, however, has shown that the temperature of the imager never rises above 54 °C, even in a steady state condition. This temperature is within the maximum allowable range for the imager, which means that no external covering is required over the photometer aperture.

CONCLUSION

There are many unsolved questions concerning the evolution of stars and their role in the creation of heavy elements in the universe. The mathematical models that are used today to model the evolution of luminous stars, the source of most of the heavy elements in the universe, are limited due to lack of data to constrain parameters within those models. The BRITE-Constellation of four nanosatellites will help to provide those data using precise differential photometry on the brightest stars seen from Earth. Each BRITE satellite's photometer will provide measurements of coherent stellar variability precise to 20 parts per million using a CMOS imager and custom built optics. The BRITE-Constellation will be at the forefront of nanosatellite technology, providing scientific data that will do much to advance the knowledge of the evolution of luminous stars and the life-cycle of matter in the Universe.

ACKNOWLEDGMENTS

The authors thank the Canadian Space Agency for its financial support of two concept studies. Acknowledgment is also given to the Ontario Centres of Excellence Inc. (ETech Division) for their support of the development of enabling nanosatellite technologies. NCD and AFJM are grateful to NSERC, Canada for general financial support. The authors also thank the University of Vienna, the Graz University of Technology, and FFG/ALR for financing and leading the development of two BRITE satellites. Peter Ceravolo (Ceravolo Optics Ltd) is acknowledged for the optics design.

In addition, the following organizations have made valuable donations to the CanX program: AeroAntenna Technology Inc. – Agilent Technologies – Altera – Alstom – Altium – Analytical Graphics Inc. – Ansoft – ARC International – ATI – Autodesk – @lliance Technologies – Cadence – CMC Electronics – EDS – E. Jordan Brookes – Emcore – Encad – Honeywell – Micrografx – National Instruments – Natural Resources Canada – NovAtel Inc. – Raymond EMC – Rogers Corporation – Stanford University – Texas Instruments – The MathWorks – Wind River.

REFERENCES

1. Moffat, A.F.J, and W.W. Weiss, Principal Investigators, "BRIght Target Explorer (BRITE) Constellation: Luminous Stars as Cosmic Engines. Volume 1: Technical and Managerial Proposal," Submitted to the Science Branch of the Canadian Space Agency, Mar. 2006.

2. Rankin, D., D. D. Kekez, R. E. Zee, F. M. Pranajaya, D. G. Foisy and A. M. Beattie, "The CanX-2 Nanosatellite: Expanding The Science Abilities of Nanosatellites," Proceedings of the 55th International Astronautical Congress, Vancouver, Canada, Oct. 2004.

3. Bigas, M., E. Cabruja, J. Forest, and J. Salvi, "Review of CMOS image sensors," Microelectronics Journal, vol. 37, p 433-451, 2006.