DTUsat II – An Asteroseismic CubeSat

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Abstract

We present a payload which will enable DTUsat II to map the core of stars by use of seismic techniques and produce unique scientific results. The payload consists of the Advanced Stellar Compass (ASC) developed at DTU and will make DTUsat II capable of observing brightness variations in bright stars and thus produce valuable observations that can not be obtained elsewhere.

Introduction

During the last 30 years we have through helioseismology, the study of oscillations in the Sun, learned more about the inside of the Sun than we know about the inside of the Earth. With DTUsat II we want to apply the same method to other stars and thereby determine important parameters such as age, mass, chemical composition and rotation for those stars.

We suggest to use the ASC to observe brightness variations below the percent level in a number of bright long period variable stars. The ACS is a star tracker used on larger satellites to determine the pointing with arcsecond precision by comparing CCD images of the sky with an onboard stellar catalogue. It consists of a small CCD camera and a small computer. Despite its size the camera is, however, also perfectly capable of performing photometry to the required precision for the science case presented here, and the existing software readily lends itself to such applications.

The satellite will observe each target star for up to 15 min. in each 100 min. orbit which will give a photometric precision of 0.1% and enable us to find pulsations in the targets with periods of the order of hours to days. Although such observations are scientifically very valuable they are also rare as ground based observations are severely limited by atmospheric scintillation and the rotation of the earth which will not allow a continous monitoring for several days. Space-based observations are the best alternative and the payload we present here will produce data of the same quality as have been obtained from over 20 years of ground-based observation for most of the targets. From such data an asteroseismic analysis may be undertaken to determine the structure of the target stars, and with this payload, DTUsat II will thus contribute unique knowledge about slowly pulsating stars to the emerging field of asteroseismology.

In the following we discuss possible science cases with the star tracker and the technical feasibily of implementing the ASC on DTUsat II.

Science with the star tracker

As DTUsat II is designed as a CubeSat the science case must be constructed bearing in mind that it can only set design parameters to a very limited extent. The science case must also be robust to changes in the satellite performance since it is uncertain for now. Below we therefore present a science case which – although ambitious – can be carried out with a minimum of pointing accuracy and within a range of photometric precision and satellite lifetimes.

For the case presented here the satellite is assumed to be in a scanning mode where it produces one data-point per star per orbit with a photometric precision of 0.1 to 0.5% – thus the satellite is not required to track targets on the sky but simply to scan the same field in each orbit.

The prime targets of DTUsat II are stars with periods longer than a few times the orbital period of the satellite. The main targets are γ Dor, SPB and β Cep stars with periods in the range 0.1 to 3 days. Valuable data will be obtained for a lot of other interesting stars however – including not only pulsating variable stars, but also eclipsing binary systems and exoplanets.

One key question which DTUsat II may answer is whether differential rotation, such as it is seen in the Sun, is also present in other stars. The Sun rotates on its axis just as the Earth does. However, unlike Earth which rotates as a solid body, the Sun rotates every 25 days at the equator and takes progressively longer to rotate at higher latitudes, up to 35 days at the poles. This differential rotation extends throughout the convective layer of the Sun and then vanishes immediately below it. But is the Sun the only star that has differential rotation?

In the only study of its kind Aerts et al. (2003) used 21 years of photometry of the β Cep star HD 129929 and found evidence of non-rigid rotation implying that the stellar core rotated four times faster than the surface of this star. If the same kind of rotation could be found in others stars, i.e. SPB stars, it would be one of the most important results for the study of stellar rotation for decades.

To find non-rigid rotation in SPB and β Cep stars one must have a high signal-to-noise ratio and continually sampled data to get the needed frequency resolution. We belive DTUsat II will meet both criteria, and to demonstrate this statement we have made a number of simulations of data obtained with DTUsat II for a SPB star (Fig. 1) spanning a range in satellite lifetime and photometry precision. In general the simulations have shown that the critical point for obtaining the needed frequency resolution is not the precision (which can be up to 0.5% and still provide the data with the needed quality), but rather a long time-base.

It should be stressed here that these are mission critia for a highly ambitious science mission. Valuable science can be obtained for e.g. eclipsing variables with a DTUsat II that 'only' provides one data-point per orbit, with a precision

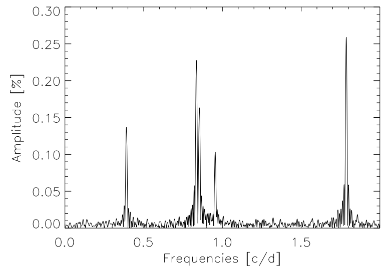

Figure 1: Simulation of an amplitude spectrum of a SPB star obtained with DTUsat II from a 100 day observation with a noise level of 0.1% per data point. Five frequencies are seen in the spectrum. Evidence of the high frequency resolution is seen for the two closely separated frequencies at 0.8 cycles per day (c/d). Such close frquencies also indicate differential rotation in the simulated star.

$\leq$1% for 14 days. Below we therefore discuss what results can be expected for three different time-bases and a precision per orbit of 0.1% (though this parameter is not critical):

- **14 days of continuous observations**. Valuable science can be obtained for a large number of eclipsing variables and multiperiodisity can be found in a number of γ Dor, SPB and β Cep stars.
- **50 days of continuous observations**. This will provide a unique dataset. We expect that the it will resolve possible differential rotation in a number of γ Dor, SPB and β Cep stars and significantly increase our understanding of the stellar interior. The data for i.e. SPB stars will be the best available.
- $>$**100 days of continuous observations**. We will then have a spectacular unique data set. The observations will resolve possible differential rotation in most of the observed γ Dor, SPB and β Cep stars. We expect that such a dataset will prove whether differential rotation is common in other stars or not and whether it is important in the stellar evolution.

Technical feasibility

The ASC (Jørgensen 2000) is a fully autonomous star tracker developed at The Department of Automation at DTU. The ASC consist of a Camera Head Unit (CHU) and a Data Processing Unit (DPU). In this design of the payload for DTUsat II we will only use the CHU and not the DPU. The processing of the data from the CHU will be done by the On Board Computer (OBC).

The basic requirement for the CHU is that it should be able to measure brightness variations to a relative precision of 0.1% in the flux. As we use a relatively large camera to measure bright stars we will have plenty of photons and do not expect photon noice to be a dominating noise source for these stars. To demonstrate the point we plot in Fig. 2 the expected relative RMS noise as a function of stellar magnitude. This estimate clearly shows that the precision

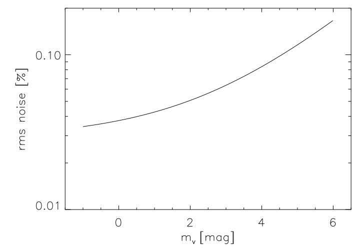

Figure 2: Estimated point-to-point scatter for the payload. The estimate assumes that the stars can be observed for 5 minutes each orbit, an exposure time of 1 sec., a sensitivity of the CHU of 10%, a white noise from the instrument of 40% of the photon noise and a maximum precision of each measurement of 0.5% (compared to the star tracker on WIRE where it is 0.035%).

is limited by the instrument rather than the number of photons. We therefore expect to be able to observe all stars brighter than $m_V = 6$. This corresponds to the stars visible to the human eye. There are about 10000 such stars in the sky of which about 1000 will be interesting targets and a further 200 are known γ Dor, SPB and β Cep stars.

The CHU has a volume of $50 \times 50 \times 45$ mm and a mass of 252 g and can therefore easily fit the specifications for a CubeSat in this respect. The CHU needs 350 mW when it is operating which is somewhat more than what is available for the payload. The solution to this is not to have the CHU operating during the entire orbit, e.g. only observe the northern hemisphere. The payload will not need to track objects on the sky. Instead it will scan a field of the sky each orbit, and the OBC will then perform astrometry and photometry on all the objects brighter than $m_v = 6$ in this field. One data point for each object for each orbit will be transmitted to the ground so each data point will be an average of many individual measurements.

Attitude Control System (ACS) requirements are then determined by the need to reproduce the pointing in each orbit within a few degrees and the need for the pointing to be stable over an exposure time such that stars will not blur too much.

The exposure time is expected to be one to two seconds so for the specifications of the CHU this translates into a high frequency pointing stability better than $3'$ sec^{-1}. Stars may be smeared out over a few pixels as the satellite scans the sky – depending on the size of the area on the sky to be scanned – but this can be handled during the image processing and will not be a problem. As jitter is not expected to reach a level above $1'$ sec^{-1} we thus believe the satellite can reach the required pointing stability on the short timescale. The CHU has a field of view (FOV) of $18.4° \times 13.4°$, so even pointing errors between orbits of $\sim 2°$ will still give a large effective FOV. This requirement is somewhat stricter than the current specifications for DTUsat II ($10°$ pointing), but as the payload will deliver attitude determination with arcsecond precision it should be possible to construct an ACS which is up to the task. Generally the payload can thus tolerate relatively large pointing errors.

The CHU can be placed on the front of the satellite (the side pointing towards the sun) with the aperture always pointing away from the sun. We expect to use the space between the back of the satellite and the CHU as a 5 cm baffel to reduce scattered light. The CHU should be in thermal contact with the back of the satellite in order to provide passive cooling.

The general requirements for the satellite and the specifications for a CubeSat are given in table 1. Here we have also given a number for the needed radio down-link. This number is based on the assumption that 1000 stars will be observed each orbit. If needed this number can easily be cut down to decrease the down-link budget.

Class	Payload requirements	CubeSat specifications
Power	350 mW (50% of orbit)	200-250 mW (average)
OBC	?	?
Radio	200 kbit per orbit	600 kbit per orbit
Volume	180 cm^3	200-250 cm^3
Mass	252 g	200-250 g
Attitude determination	$1''$	3°
Jitter	$3\,'sec^{-1}$	?
ACS	2°	10°
Lifespan	> 14 days	Months

Table 1: General requirements and specifications for DTUsat II. Note that the payload will provide attitude determination of $1''$ so this not a requirement to the CubeSat.

Points that need special attention when operating a CCD in order to obtain the required precision include radiation damage, temperature sensitivity, vignetting and intra-pixel sensitivity variations .

Radiation damage to the CCD can cause hot pixels with a higher dark current and lower the precision of the photometry performed with the CCD. However the software implemented in the ASC monitors hot pixels and the system will therefore reject measurements where a star is on a hot pixel. Furthermore no observations are planned over the South Atlantic Anomaly where the radiation is most intense so we do not expect radiation to be a significant problem.

The CHU can be operated at temperatures between -40°C and +20°C, but as the temperature increases the dark current will increase in the CCD. The satellite will have passive cooling through the back but during the construction a thermal analysis will be important to ensure that the dark current will not become a significant noise source.

Because of the relatively large FOV and the small lens of the ASC we expect point spread function variations over the FOV and vignetting. This is normal for wide-field observations and since we will perform aperture photometry on the images we can overcome such problems by using algorithms that take this into account when extracting the stellar brightness.

The last point we will discuss is the problems with sensitivity variations over the CCD from pixel-to-pixel and within a pixel. As we will defocus the PSF and as many measurements will go in to one data point we do not expect sensitivity variations within a pixel to be a problem. Variations from pixel-to-pixel (also known as flat field variations), will give rise to some noise, but as the star will be observed over many different pixels over an orbit, we expect to be able to remove most of this noise by proper modelling of the CCD sensitivity.

In general such concerns are alleviated by using a well known reliable camera such as the ASC which can furthermore be extensively tested before launch to ensure that we can account for the properties of the CCD in the data analysis.

On the people behind

This proposal has grown from an exam project for the course “Space Research” by the three authors. The project has therefore from the start been linked to this course given by lektor Hans Kjeldsen, and we intend to continue this connection as the course is repeated. As the project progresses there will be ample opportunity for students from the course to participate. Eventually students working on their bachelor and master degrees may become involved as well – and possibly carry some of the workload. Furthermore it should be noted that the astronomy group in Aarhus has been among the pioneers of asteroseismology and has great experience in both the observational and analytical aspects.

Summary

We have presented a payload which will let DTUsat contribute valuable data to the emerging field of asteroseismology and fill a niche not covered by any other observational program. It relies on the Advanced Stellar Compass which is familiar proven technology that should be easy to implement and operate and not likely to fail. The payload can achieve its main goals in many different scenarios depending on the orbit and satellite performance. The project has the potential to make unique science that will be recognized worldwide. It will rely on inter-disciplinary cooperation between engineers at DTU and astronomers at IFA, each among the world leading actors in their field.

References

[1] Aerts, C., Thoul, A., Daszyńska, J., Scuflaire, R., Waelkens, C., Dupret, M. A., Niemczura, E., & Noels, A. 2003, Science, 300, 1926

[2] Jørgensen, J. L. 2000, ESA SP-425: Spacecraft Guidance, Navigation and Control Systems, 103

Profiles

The idea to observe brightness variations in bright stars with a star tracker on a CubeSat was originally born at the 1st Danish Student Space Workshop organised by the Danish Astronautical Society in march 2004. Intensive design stydy was carried out during an exam project for the course Space Research by the three authors who at that time were all master's degree students in astronomy at IFA.

Christoffer Karoff
obtained his master's degree in febuary 2005 on the subject "Improving the Accuracy of Space-Based Photometry – Intra-Pixel Structure". The study included intensive measurements on a CCD similar to the one used in the ASC and a detailed analysis of noise in data from the WIRE satellite. After graduating Christoffer Karoff started on a PhD degree programme in astronomy with the title "Instrument Development and Data Analysis in Observational Asteroseismology". In his daily work Christoffer Karoff is deeply involved in the COROT mission (to be launched in august 2006) and analysis of data from state of the art instruments around the globe and from the WIRE satellite.

Morten Stejner Sand Pedersen
has been studying for his PhD on the subject "Compact Stars" since august 2004. In his studies Morten Stejner investigates the possibility that neutron stars – the degenerate remains of supernovae – are composed of a quark-gluon plasma known as strange quark matter rather than neutrons or other forms of hadronic matter. This involves detailed modelling of the relation between particle physics and surface properties of the stars. The aim of this work is to use neutron stars as astrophysical laboratories and find observable tests on the physics of super dense matter.

Henrik Robenhagen Jensen
obtained his master's degree in september 2005 on the subject "Analysis of the old open cluster NGC 2243 based on VLT observations – Determination of the radial velocity, membership, abundance and distance modulus". The study was based on data from the UVES and GIRAFFE spectrographs at the VLT in Chile. After graduation Henrik Robenhagen Jensen started in a training position as hospital physicist at Odense University Hospital.

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