

## Development of the Pico Star Tracker ST-200 – Design Challenges and Road Ahead

Tom Segert  
 Berlin Space Technologies GmbH  
 Marchstr. 12 / Sekr. F6 / 10587 Berlin / Germany ; +49 30 22192562  
 Segert@Berlin-Space-Tech.com

Steven Engelen (1;2), Matthias Buhl (3) and Bert Monna (2)  
 (1) Delft University of Technology, Chair of Space Systems Engineering  
 (2) SYSPA B.V." ; (3) Berlin Space Technologies GmbH

### ABSTRACT

The Pico Star Tracker ST-200 under development by Berlin Space Technologies GmbH (BST) is specifically designed keeping the limitations of CubeSats in mind. It comes in a compact 29x29x37mm<sup>3</sup> package. It weights 74g and has a power consumption of 220mW average (620mW peak). The ST-200 offers a set of standard interfaces (I<sup>2</sup>C, SPI, RS485, RS232) and accepts input voltages of 3.3 to 5V. It can detect stars with a limiting magnitude of 6 and has an accuracy of 30 arc seconds (~0.01°). Using its internal star catalogue ST-200 calculates the satellite attitude from lost in space solution and delivers the Euler angles or quaternion with an update rate of 5 Hz in tracking mode. The ST-200 is based on 20 years of star tracker development in Berlin including TUBSAT missions and multiple international customers. It is the successor of the Micro Star Tracker ST-100 developed by BST. For the electronics miniaturization as well as the implementation of new strategies for star tracker with ultra low power and low mass BST cooperates with Syspa B.V. of the Netherlands.

### INTRODUCTION

Satellite missions need a solid fundament to build on. The attitude control system is a cornerstone for every sophisticated mission. While CubeSats have shown more and more capacities over the last years, high performance star sensor systems are still missing. BST is an expert in small satellite technology and builds on 20 years of star tracker development in Berlin. For the required extreme miniaturization of the star tracker electronics BST cooperates with Syspa B.V. in the Netherlands.

#### *Heritage: 20 Years of Star Tracker Development in Berlin*

Berlin – notably the Technische Universität Berlin (TUB) – is a pioneer in star trackers for small satellites. Already TUBSAT-A the first university satellite of TUB launched in 1991 contained a star sensor.

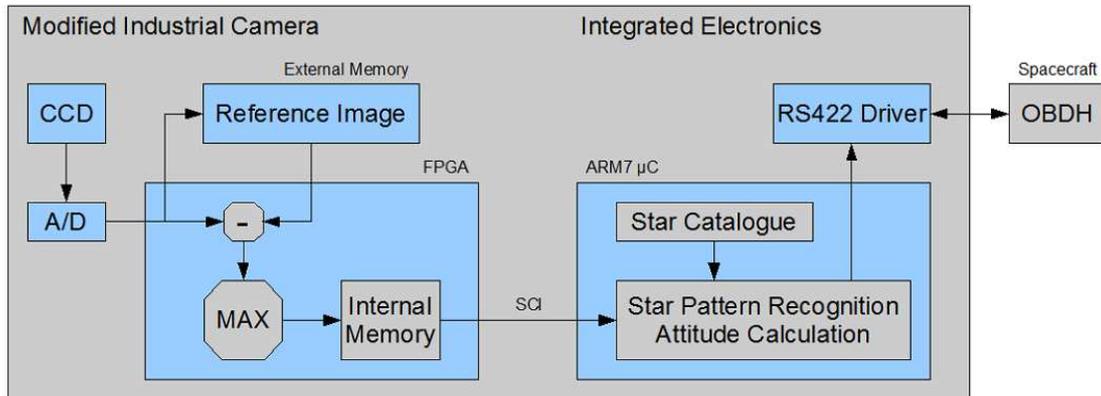
At TUB three generation of star sensor systems have been developed. The first generation relied on star identification on ground thus was limited to a star gyro function. This was done due to the lack of computational power in the micro processors used for TUBSAT-A. A second version of this first generation star sensor was flown on TUBSAT-B in 1994.

Autonomous star identification was integrated on TUBSAT-N and MAROC-TUBSAT for the second generation of TUB star sensors in 1998. The third generation was using the main instrument as a lens to accomplish arc second precision and was flown on DLR-TUBSAT in 1999.



**Figure 1: Second Generation Star Sensor**

Based on these developments at TU Berlin a number of commercial products have been developed. Especially the second generation was notably successful.



**Figure 2: Block Diagram of ST-100 for Micro Satellites**

***Star Sensor Systems developed by BST***

As a spin-off, BST builds on the extensive star sensor heritage developed at TU Berlin. The ST-100 is based on the 4 star trackers that were delivered for the twin satellite Mission LAPAN-A2/ORARI. The ST-100 uses a modified industrial camera as optical head. Integrating of the star extraction algorithms into the COTS camera allowed fast development time and compact design. A detailed block diagram is shown in Figure 2. The ST-100 shown in Figure 3 is the basis of the ST-200 pico tracker currently under development by BST.



**Figure 3: ST-100 Star Sensor for LAPAN-A2 and LAPAN-ORARI**

**1. TECHNOLOGICAL APPROACH**

The ST-200 is a miniaturized version of the ST-100 star tracker. While electronics, optics and mechanics have been modified to fit the needs of a CubeSat mission the proven star extraction and identification algorithms stayed the same.

***Design Requirements***

The ST-200 is tailored for 1U (and larger) CubeSat missions. Therefore a number of technical requirements were set up:

- Mass < 80 g
- Power consumption < 250 mW (average)
- Pointing accuracy: 0.01 degree
- Update better than 5 Hz
- Full lost in Space capability
- Design Life 1 year (typical CubeSat mission)

In addition a number of non technical requirements were kept in mind:

- Short development time (<12 month)
  - o Utilize existing ST-100 algorithms
  - o Cooperate with partners for miniaturization of the electronics
- CubeSat affordable (low cost)

## COMPARISON OF ST-100 TO ST-200

The ST-200 as it can be seen in Figure 4 is significantly smaller than the ST-100. In Table 1 both star trackers are compared.



**Figure 4: ST-200 Electronics**

With the electronics and optics finished ST-200 enters the final development phase.

**Table 1 Comparison of ST-100 and ST-200**

	ST-100	ST-200	Improvement
Mass	740g	74g	90%
Power Consumption	3W peak	0.7 W peak	77%
Price	low	lowest	50%
Accuracy	30"/200"	30"/200"	
Design Life	3 years	1 year	
Sensor	CCD	CMOS	
Processor	ARM 7, FPGA	ARM9	
Number of PCB	4	2	50%
PCB Footprint	50x50mm	35x35mm	50%
Interfaces	RS422	RS485 SPI, I <sup>2</sup> C	
Full Design Qualification	YES	YES	
Acceptance Test for each FM unit	Yes	On Request	
Electronics Integration	Moderate	High	
Lens	COTS	Custom	
External Baffle	YES	On Request	
Availability	High	Moderate	
Market Readiness	2009	2011	

## REQUIRED MODIFICATIONS

Starting point for the miniaturisation was the in depth analysis of the existing design. While perfectly suitable for a micro satellite the ST-100 is not quite useful for CubeSats due to its large mass and volume as well as high power consumption.

The following main drivers for mass were identified

- 5mm AL-Shielding
- Large high performance COTS lens
- Complex Electronics (4 boards)

The following main drivers for volume were identified

- Complex Electronics (4 boards)
- Large high performance COTS lens
- Large Baffle

The main drives for power consumption was identified:

- FPGA for image processing

In the following section the required modifications from ST-100 to ST-200 will be described.

### *Electronics Miniaturization*

In order to avoid the high power FPGA of the ST-100 a high performance ARM-9 was used. A CMOS sensor instead of a CCD decreased the required number of PCB. In addition a demanding multi layer design allowed reduction of the footprint from 50x50mm to 35x35mm. Integration of a set of common interfaces increases the interoperability of the ST-200. The design of the miniaturized electronics was done by Syspa B.V.

### *Opto Mechanics*

The ST-100 utilizes high performance COTS lens that weights more than 200g. Smaller lenses exist however often with less than desired image quality. Therefore BST uses a modified board lens for the ST-200. Secondly the AL shielding was reduced from 5mm to 2mm. This lowers the unit mass but increases radiation issues. Therefore the ST-200 has a reduced design life when compared with ST-100. Also reduced was the size of the baffle. Using a CMOS sensor with enhanced radiometric performance eases the reduction in availability.

**Software** The ST-200 used a customized Star Catalogue. It was tailored on the detection capabilities of ST-200. The star detection and identification algorithms could stay unchanged. The software was adapted from the ARM-7 of ST-100 to the ARM-9 architecture of ST-200.

## IMAGE PROCESSING AND STAR DETECTION ALGORITHMS

There are number of challenges to overcome when designing a star sensor:

- Hotspot detection and elimination
- Star extraction
- Star pattern identification
- Tracking mode

### *Radiation Correction*

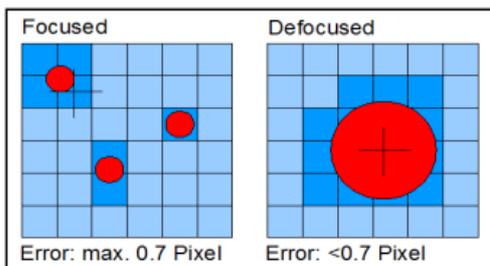
There are two major approaches for the elimination of hotspots:

- Black List (Reference List with hot spots)
- Dark field correction (reference image subtraction)

The advantage of the widely used black list approach is that it is fast. The disadvantage is that most of the hot pixels are not completely dead. The approach chosen by BST is to work with a difference image. TUB missions have proven that approach using commercial CCD sensors (not radiation hardened). The basis of this approach is to save a standard sensor image as reference image and subtract it from all of the following images. Star extraction is done on the resulting difference images. The reference image is updated regularly. The disadvantage is that the noise is increased by a factor of  $\sqrt{2}$ .

### *Star Extraction and Accuracy*

Most star sensors use a defocused optic and cloud extraction to extract stars. By calculating the brightness centre and determining all pixels belonging to the star the star position can be determined with sub pixel accuracy. There are two main disadvantages: a high computational power requirement and a low SNR as the star is spread over many pixels. This can be seen in Figure 5.



**Figure 5: Star Extraction Concepts**

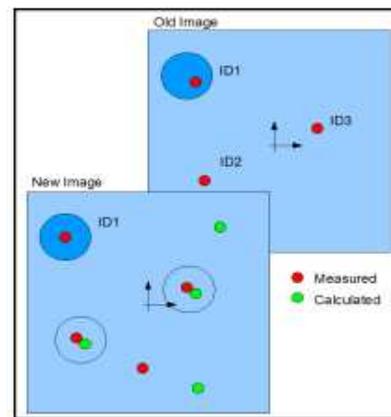
Due to high development effort (cost) and computational requirements (power draw) this approach is not well suited for the low resource availability (power, mass, cost) mission concept of a CubeSat. Therefore BST has to use the proven panorama approach developed by TUB. Basis is that in each sensor row only the brightest pixel is counted and written in a table. This significantly speeds up the star extraction process as it allows reducing the required computational power by a factor of 1000.

### *Star Pattern Identification*

The initial star pattern recognition (or star identification) from a lost in space situation is based on standard techniques. The angular distances of stars in the image are compared with angular distances of the catalogued stars to identify the objects in the image. This algorithm is very robust, allowing for other objects than stars (e.g. planets or satellites) to be present without failing.

### *Tracking Mode*

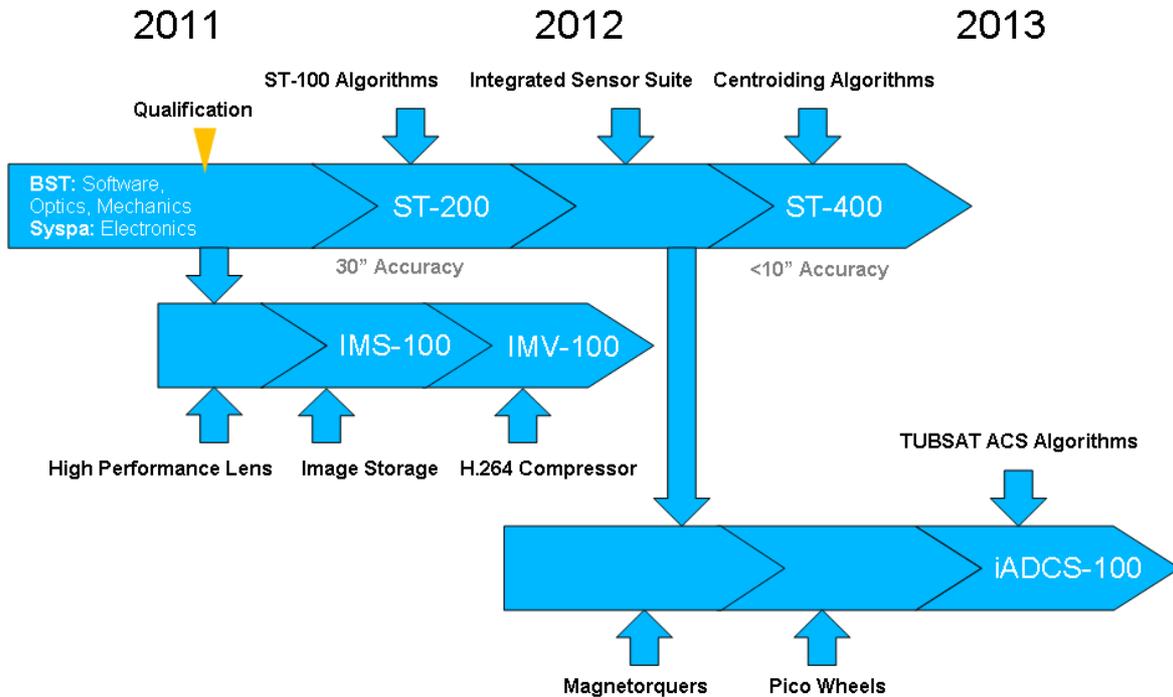
After the attitude is found, the star sensor switches into tracking mode. This tracking mode allows fast update rates of up to 5 Hz on the ST-200. These algorithms were developed by BST. Basis of the tracking mode is to take a star in the new image and identify the corresponding star in the old image (here ID1) within a given search radius.



**Figure 6: Tracking Mode**

Once this star has been identified star all of its neighbours can be taken from the catalogue. The star positions of these neighbours are calculated from the catalogue with the previous attitude information. Now all stars are referenced between the old and the new image using a suitable distance criterion.

**ROADMAP ON FURTHER DEVELOPMENTS BASED ON ST-200**



**Figure 7: Development Roadmap for Pico and Nano satellites ADCS solutions from BST**

The roadmap described in Figure 7 is tailored to present and future small satellites based on the low cost CubeSat approach. A number of upgraded solutions will be available:

- CubeSat Camera Solution (IMV)
- High Performance Star Tracker (ST-400)
- Integrated ADCS solution (iADCS)

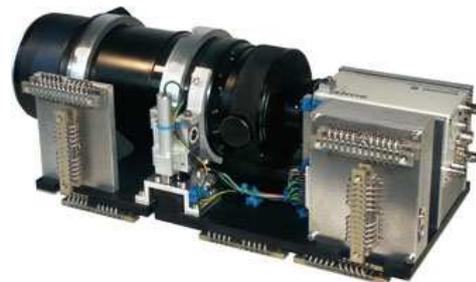
**Improved Star Trackers for enhance nano satellites**

Besides the classical Cubesat missions focussed on unit based design a number of enhanced nano satellites in the 20-30kg are under development by a number of manufacturers. The basic idea is to build capable and versatile platforms based on the CubeSat derived components. These new class of highly capable space craft will need enhanced star sensor performance, too. Therefore BST and Syspa jointly develop the ST-400.

The ST-400 is a high performance version of the ST-200. Upgraded custom lenses as improved algorithms as well as data fusion with additional sensors allow higher performance the resolution to <10 arc sec.

**IMS-100 and IMV-100 Imaging Solutions**

The second branch of development is the imaging solutions IMS-100 and IMV-100. These units are based on the core of the ST-200 but lacking its image processing (star extraction) capabilities. Further differences are the utilisation of a color sensor (instead of monochrome of the ST-200). Data storage, JPEG Image compression (IMS-100) or H.264 compression (IMV-100) will be added via daughter board. High performance rugged lenses allow IMS-100 and IMV-100 to achieve up to 25 m GSD.

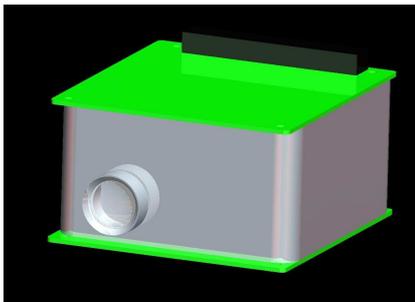


**Figure 8: Video compression daughter board for IMV-100 is derived from HRVI-6HD series**

BST utilized its extensive knowledge for satellite real time video payloads such as the HRVI-6HD for implementing the required image processing and compression. The IMV-100 will allow CubeSats the same real time experience as its larger LEOS micro satellite platform (albeit with lower resolutions). Imaging modes with up to 1080p will be possible with IMV-100 depending on available downlink.

***Integrated ADCS solution***

The iADCS-100 is the answer for CubeSat developers that need a high performance ADCS for their mission but want to avoid the hefty development required and risk associated with such a development. The iADCS-100 of BST offers a full solution with integrated reaction wheels, magnet torquers, full sensor suite and complete ACS algorithms for autonomous operation in a ½ U package.



**Figure 9: Composed outside view of iADCS-100**

The iADCS is designed as an autonomous ADCS solution in full compliance to the CubeSat standard as it resembles a stack of four PC-104 boards. It will offer a number of operation modes such as Nadir pointing, as well as autonomous target acquisition and tracking. The design goals of BST and Syspa are set as follows:

- Target power consumption:
  - o Nominal power draw: < 900 mW
  - o Peak power draw: < 1500 mW
- Target volume:
  - o Integrated volume: < 100 x 100 x 50 mm (L x W x H)
  - o OEM versions available for dense system integration

As the iADCS is the third branch of the BST development roadmap and requires a number of components yet to be finished expected marked readiness is foreseen for 2013.

**CONCLUSION AND OUTLOOK**

The ST-200 under development by BST and Syspa is a sophisticated star tracker for CubeSat missions. It is based on 20 years of star tracker development in Berlin. The ST-200 is the first step on the roadmap towards an integrated ACDS solution for CubeSats.

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