Phase B

SwissCube Science Mission Definition and Payload System Engineering

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1 INTRODUCTION

This document refreshes the targeted science mission of the SwissCube satellite and describes the actual state of the payload design. It is important to note, that the science mission has significantly changed since end of phase A.

In the first phase, the fundamental reason for the mission was to gain a better understanding of atmospheric physics during the day, principally the intensity of selected oxygen lines, their dependence on latitude, longitude, altitude, solar events and time. Furthermore, a demonstration of the ability of a 1kg satellite to perform a scientifically useful Earth observation mission was targeted [R1].

During phase B, the science mission has been focused on a more technological objective. A model of the airglow in function of intensity, latitude and solar local time has been established in order to demonstrate the feasibility of using airglow as basis for a low cost Earth Sensor (ES). An observation of the airglow with SwissCube will allow validating this model, or at least bringing additional information to the model.

1.1 Abbreviated terms

ADCS	Attitude Determination and Control System
CDMS	Command and Data Management System
CCD	Charge Coupled Device
CMOS	Complementary Metal Oxide Semiconductor
DCR	Dark Count Rate
ES	Earth Sensor
FF	Fill-Factor
FOV	Field Of View
PDP	Photon Detection Probability
SPAD	Single Photon Avalanche Diode

2 MISSION OBJECTIVES

The payload mission is to perform space-based observations of the airglow occurring in the upper atmosphere at approximately 100 km altitude. The motivation for these observations is to demonstrate the feasibility of using airglow as basis for an Earth Sensor (ES).

A number of studies exist on the temporal and latitudinal variability in the oxygen emissions in the 50–120 km region of the mesosphere and lower thermosphere. They provide a wide database on the airglow emission rates for different altitudes, local times and latitudes. An airglow model based on these observations has been developed and allows testing the Earth Sensor concept. Nevertheless, an observation of the airglow with a highly sensitive detector (like a SPAD or a similar sensor) would provide a more realistic characterization of the concept and confirm its feasibility. The following observations would be of particular interest:

1. The minimum, maximum and mean airglow emissions at limb depending on altitude
2. The minimum, maximum and mean airglow emission at zenith and hence information about background radiation due to scattered sun- or moonlight
3. Mean tidal variations, with a particular attention on emission near the solar terminator
4. Aurora effects around the poles

The orbit of the satellite SwissCube is expected to be sunsynchronous and does not guarantee a pass close to the solar terminator [R3]. Furthermore, we can not count on the fact that the satellite will observe an aurora. Hence, the scientific mission of SwissCube will be focused on limb and zenith measurements of the airglow during both daytime and eclipses. Nevertheless, the zone near the solar terminator or aurora effects will be observed if possible.

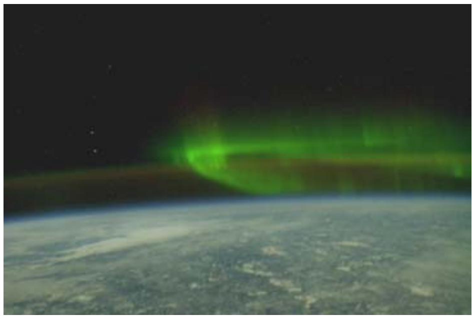

Figure 1: Nightglow and aurora borealis.

2.1 Design requirements

The science objectives described in the previous section lead to several requirements on the project. A summary of the most important ones is given in this section. For further details, please refer to [R4].

2.1.1 Function of the payload

The payload of the SwissCube satellite may be a technology demonstrator of a novel ES. If accepted, it shall satisfy the following conditions:

- The payload observes the same wavelength as the ES (762 nm), with a resolution of at least 10 nm.
- The payload has at least the same spatial resolution ([0.3]°) and the same FOV ([20]°) as the ES.
- If possible, airglow emissions are observed with a CMOS SPAD detector-array.
- The payload survives, with a permanent damage or later performance degradation of less than [20]%, having its boresight directly sun pointing for a period of at least 10 hours.
- The payload is able to perform the science mission with the sun no closer than [30] ° from the sensor boresight.

2.1.2 Science mission: duration, observation area and coverage

Variations in airglow emission intensities are expected to strongly depend on altitude, latitude and local time. Hence, these are the driving parameters and determine the frequency of measurements.

In a first time, airglow emissions shall be observed at different regions and under different angles of observation. These measurements will provide first idea of expected minimum, maximum and mean intensities of airglow emissions during both day and night. Furthermore, it will allow analyzing background radiation due to scattered sun- or moonlight. The first observation phase shall last 3 month. During this period, 20 images of the airglow shall be taken. These images can represent the following observations:

- 5 images of dayglow measured at limb between 50 and 120 km
- 5 images of dayglow measured at zenith
- 5 images of nightglow measured at limb between 50 and 120 km
- 5 images of nightglow measured at zenith

In a second time only observations of airglow emissions at limb between 50 and 120 km shall be carried out. Since they constitute the basis for a new low-cost Earth Sensor, their variation in intensity has to be studied more carefully. Hence, the variation of emission intensity depending on latitude can be observed over a longer period. The duration of this second phase will be determined by the life time of the satellite.

Following observations can to be carried out:

- Dayglow at a latitude above 85° N
- Dayglow at a latitude between 40° N and 50° N
- Dayglow at a latitude between 5° S and 5° N
- Dayglow at a latitude between 40° S and 50° S
- Dayglow at a latitude above 85° S
- Nightglow at a latitude above 85° N
- Nightglow at a latitude between 40° N and 50° N
- Nightglow at a latitude between 5° S and 5° N
- Nightglow at a latitude between 40° S and 50° S
- Nightglow at a latitude above 85° S

The atmosphere at a specific latitude can be measured at the same local time of measurements within 45 days. An observation of oxygen emissions over one year would allow analyzing seasonal variations.

2.1.3 Science data product

The science data products shall include the measurements of the airglow intensity, the location and the local solar time of the area of observation. For a good evaluation of the airglow model, the local solar time and the location of the observed area during measurement shall be known with an accuracy of [± 30] min, respectively [± 5]° in latitude.

The payload shall be able to detect at least airglow emission at limb at any local solar time with a SNR of 3 to provide significant observations. A measurement of the whole range of airglow intensity without saturation would be advantageous. This would require a detector, which is able to measure between [6'000] and [$12 \cdot 10^6$] incident photons/pixel/s.

2.2 Derived requirements

2.2.1 Attitude and orbital position determination

The requirements on the targeted accuracy of the local solar time and the location of the observed area presented in the sub-section 2.1.3, lead to specifications on the attitude determination of the space system. A detailed analysis still has to be done to define the required precision for the satellite attitude and its orbital position (right ascension of ascending node, argument of perigee and true anomaly).

2.2.2 Attitude control – pointing stability

The space system shall have a pointing stability of less than [3] °/s in any direction in order to keep the requirements on the stability of the satellite as low as for the Earth Sensor application.

2.2.3 Compression of scientific data

If the science data are compressed, the compression shall be robust and not decrease the image quality more than for the ES application. Hence, the compression shall be loss less and able to handle single bit errors. Furthermore, the data of one image shall not depend on previous images.

2.2.4 Data transmission

Assuming that one image can be transferred to the ground station per access, the space system shall have enough memory aboard the satellite to be able to get the scientific measurements as described in sub-section 2.1.2 without perturbation even if it looses the contact with the ground station during [20] days. If this requirement is respected, all images aboard the satellite can be transferred to the ground station between two successive scientific observations.

3 DESIGN ASSUMPTIONS AND APPROACH

Several constraints and assumptions had to be made to define the requirements described in chapter 2 and to draw the first baseline design of the payload. To simplify the lecture of this report, they are repeated it the sections where they are used for calculations. Nevertheless they are summarized below.

[A1] The altitude of the satellite ranges between 400 km and 1000 km. The scientific instrument has to be able to operate efficiently for any satellite altitude within this range.

[A2] The average contact time period between the satellite and a ground station is 10 minutes per day, whereof 5 minutes can be used for the transmission of scientific data. Therefore, one image may be transferred to the ground station per day.

[A3] A compressed image has a size of 50 kbits whereas an uncompressed image needs 230 kbits at maximum.

[A4] The image stability must remain below 100 % .

[A5] The SNR of the scientific measurements shall be at least 3.

4 PAYLOAD

The function of the payload is to image airglow emissions as specified by the science mission requirements described in chapter 0. Furthermore, it shall satisfy its level 4 requirements which are presented in the following section.

4.1 Design requirements

This section summarizes the requirements on the payload, which have not been described in the sections 2.1 and 2.2 or those which have to be defined more in detail.

4.1.1 Requirements on volume, mass and power consumption

Since there will not be enough place to attach all the required electronic components of the payload subsystem to the optical system, the payload's electronics shall consist of a headboard, including the detector and attached to the optical system, and a mainboard on a second PCB, housing the power supply, and other components required to successfully operate the detector and communicate with the CDMS subsystem. The space which has been attributed to the payload has a volume of [30 (length) x 30 (height) x 70 (depth)] mm^3 for the optical system and the headboard, and a volume of [70 (length) x 30 (height) x 20 (depth)] mm^3 for the mainboard. The total mass of the payload shall be less than [60] g.

The payload shall be turned on only if science observations have to be carried out and consume at maximum [450] mW (peak power) during [10] s within 4 days.

4.1.2 Environment

The payload shall take measurements at night and day. Therefore, it shall be able to operate within a temperature range of -40° to 70° C. The non-operational temperature of the science instrument shall be -50° to 90° C to guarantee that the instrument tolerates the temperature variation during manufacturing and testing processes. Further environmental requirements are described in [R5].

4.1.3 Detector control

The payload shall be able to communicate with the CDMS subsystem or the ground station at all times, when turned on. It shall operate the detector according to the parameters provided by the CDMS microcontroller, which include the integration time, the binning factor, the Dark Count Rate (DCR) suppression factor. A successful procedure for taking an image shall be executed as described in subsection 4.2.1.2.

In order to minimize failure propagation, a failure of the payload subsystem shall not endanger any element interfacing with it.

4.2 Technical description of the payload

The payload consists of two main elements:

- a detector and its corresponding electronic circuit, which detect incoming photons and generate a digital output proportional to the local light intensity. The electronic circuit provides the required power and control signals for the detector and interfaces with the CDMS or the ground station.
- an optical system used to magnify and image a selected line of the airglow on the detector

4.2.1 Detector and control electronics

4.2.1.1 Detector

The payload of the SwissCube satellite is a technology demonstrator of the ES currently developed at LMTS-EPFL. Since this ES instrument will be based on a SPAD-array, it would be best to use this same detector for the prototype in order to provide a more realistic characterization of the ES concept and confirm its feasibility. However, it might be difficult to adapt such a novel solution to the low-power and low-mass specifications of the SwissCube project and the control electronics might not be ready in time to be launched with SwissCube. Therefore, a backup solution, like the use of commercial CMOS-detectors or CCDs, has been studied and designed in parallel in order to assure that a scientific instrument will be ready in time for the launch in 2008. The backup detector shall be as similar as a SPAD-array as possible to provide comparable observations of the airglow. Table 1 evaluates the two types of detectors which might be used as backup. For each characteristic, the detector which is closer to the performance of a SPAD-array gets a positive weight.

Characteristic	Weight	CCD	CMOS
Pixel size	1	+	
Array size	3		+
FF · PDP	3		+
Dark Current	3		+
Responsivity	3	+	
Dynamic Range	3		+
Uniformity	2		+
Shuttering	3		+
Speed	1		+
Antiblooming	1		+
Biasing and clocking	2		+
Total		+4	+21

Table 1: Evaluation of the backup solution for the scientific instrument.

The evaluation of the two backup options shows clearly that the performances of a CMOS detector are closer to those of a SPAD-array. Thus, it is this type of sensor which will be used if SPADs can not be integrated into the payload of SwissCube.

The most interesting options are the KODAK KAC-9619 and the MICRON MT9V032. Both detectors are highly sensitive CMOS detectors, with similar power requirements and a similar size as a SPAD-array, if a Binning of 4 x 4 pixels is applied. However, the Dark Count Rate (DCR), the Fill-Factor (FF) and the Photon Detection Probability (PDP) are significantly higher for the CMOS sensors. Nevertheless, they will be able to detect similar photon fluxes as a SPAD-array.

The characteristics of the three detectors are summarized in Table 2. The photon flux has been calculated for the worst case, hence for a telescope aperture of 8 mm and a FOV of 0.156°/pixel for a pixel pitch of 30 µm (giving a total FOV of 20° for a SPAD-array with 128 x 128 pixels). Since the MICRON MT9V032 is smaller and cheaper than the KODAK KAC-9619 and has nevertheless a similar performance, it is the most interesting option.

Performance	**Unit**	**MT9V032**	**KAC -9619**	**SPAD**
Array size	pixels	188 x 120 †	162 x 122 †	128 x 128
Pixel pitch	µm	24 x 24†	30 x 30†	30 x 30
Total FOV	°	23.5 x 15	25.3 x 19	20 x 20
Dynamic range	dB	100	110	140
Fill-factor	%	20	47	15
Photon Detection Probability	%	45	27	5
Dark Counts (25°)	Hz	4000	3500	25
Power consumption	mW	320	170	?
Required integration time	s	< 0.2	< 0.2	< 0.2
Detector performances at night for limb measurements				
Minimum photon flux *	photons pixel^{-1} s^{-1}	340 †	760 †	50
Mean photon flux *	photons pixel^{-1} s^{-1}	860 †	2 k †	100
Maximum photon flux *	photons pixel^{-1} s^{-1}	3 k †	6 k †	340
Detector performances at day for limb measurements				
Minimum photon flux *	photons pixel^{-1} s^{-1}	70 k †	150 k †	9 k
Mean photon flux *	photons pixel^{-1} s^{-1}	170 k †	380 k †	22 k
Maximum photon flux *	photons pixel^{-1} s^{-1}	310 k †	680 k †	40 k

† including Binning of 4 x 4 pixels

* including FF and PDP

Table 2: Characterization of the two detectors.

4.2.1.2 Electronic circuit

The electronic circuit consists of two PCBs: a headboard measuring [30 (length) x 30 (height) x 20 (depth)] mm^3, which is attached to the optical system and bears the detector; and a mainboard, measuring [70 (length) x 30 (height) x 20 (depth)] mm^3 and housing the power supply and other components required to successfully operate the detector and communicate with the CDMS subsystem.

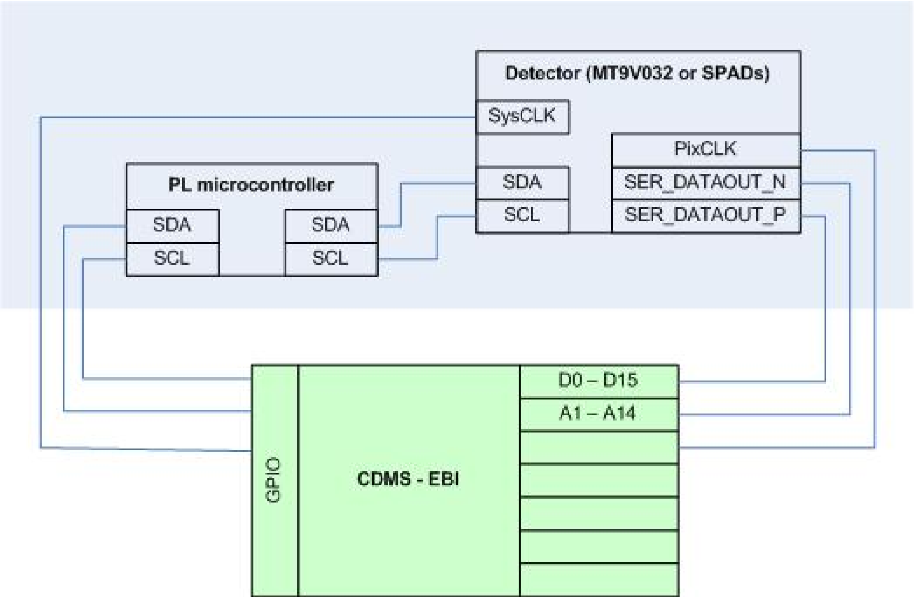

Figure 2: Software interface between CDMS and Payload.

The block diagram of the electronic circuit is shown in Figure 2. The microcontroller is only used to interface the detector with the CDMS and does not read or compress the science data. Nevertheless, it is required to guarantee a standard software interface between CDMS and the payload, no matter which detector type will be used on the final satellite and to allow a direct communication between the ground station and the payload subsystem.

The read-out of both detectors[1] needs a high frequency (> 13 MHz) and can not be done with a small microcontroller. Thus, we will use the microcontroller of the CDMS to read the science data, compress it if necessary and store it aboard the satellite until transfer to the ground station.

A successful procedure to take an image consists of the following steps:

- CDMS sends a message to EPS to turn on the payload subsystem
- EPS turns on the payload subsystem and sends an acknowledgement to CDMS
- CDMS sends a command to the payload microcontroller to initialize the detector

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[1] SPAD-array or CMOS detector.

- Payload microcontroller initializes the detector according to the received parameters (integration time, binning factor, DCR suppression factor, …) and sends an acknowledgement to CDMS for successful initialization of the detector
- CDMS sends a command to the payload microcontroller to capture an image
- Payload microcontroller triggers the image capturing, formats the scientific data in a 10 bit format and sends a message to CDMS to start the lecture of the science data
- CDMS reads the science data, compresses it if necessary and stores it in a memory until transfer to the ground station
- CDMS sends a message to EPS to turn off the payload subsystem
- EPS turns off the payload subsystem and sends an acknowledgement to CDMS

Recovery plans have to be elaborated for all possible failure scenarios during this procedure.

The required size of the memory depends on the chosen detector array and the compression of the data. There are basically two configurations:

  - A CMOS detector of 752 x 480 pixels with 10bits/pixel which will be compressed during lecture by Binning of 4 x 4 pixels. Thus the image has a size of 226 kbits.
  - A SPAD-array of 128 x 128 pixels with 10bits/pixel giving an uncompressed image of 164 kbits.

Thus, the required memory for scientific data will not exceed 1.2 Mbits, even without compression.

4.2.2 Optical system

The optical system shall provide a total Field of View of at least [20] ° and a minimum resolution of [0.3] °/pixel. The targeted detector pixel pitch is 30 µm and requires a focal length of about [6] mm. In order to relax the complexity of the optical system (and to minimize the dimensions of the optical system), the aperture has to be as small as possible. However, a larger aperture would be preferred, since a higher photon flux would increase the SNR and provide more reliable measurements. A good compromise between the complexity of the optical system and a maximum aperture is reached for an aperture of 8 mm.

The detailed design of the optical system has not been done, yet. Preliminary analyses show however, that the use of several lenses is required.

5 RECOMMENDATIONS

5.1 Baseline Design / Analysis recommendations

At the time of writing, the payload configuration is characterized by:

- a measuring of the O_2(0-0) A-band emission at 762 nm at night and day at limb and zenith
- an optical system which comprises several lenses with an aperture of Ø 8 mm and a focal length of 6 mm
- a SPAD-array of 128 x 128 pixels **or** a CMOS detector with 188 x 120 binned pixels
- a total FOV of 20° x 20° and a FOV of 0.15°/pixel for the SPAD-array **or** a total FOV of 23.5° x 15° and a FOV of 0.125°/pixel for the CMOS detector

5.2 Future tasks

During the next semester, the payload design shall be specified more in detail: The optical system and the mechanical structure of the instrument will be studied, implemented and tested. The control electronic of the CMOS detector will be adapted to the science mission and the power, mass and volume specifications of the satellite. In parallel, the control electronics of the SPAD detectors will be modified in order to fit the requirements of the SwissCube satellite.

At the end of [June], the whole instrument based on the CMOS detector will be assembled and ready for a detailed testing. The control electronics and the SPAD-array might be integrated in the SwissCube payload by end of [August], if its power consumption, mass and volume could be reduced.

6 CONCLUSION

The science objectives and the consequential requirements for SwissCube have significantly changed since end of phase A. Instead of the scientific motivation to gain a better understanding of the atmospheric physics, a more technological objective is targeted: The payload mission is to perform observations of the airglow in order to validate the airglow model which has been established and confirm the feasibility of using airglow as basis for a low-cost Earth Sensor (ES).

The main challenge of the payload subsystem is the design of the optical system, which requires a small focal length, a big aperture and a big FOV. An intensive study has to be done in order to find an adapted solution, which satisfies the requirements on the optical performances with respect to the mass and volume constraints.

Another challenge is the adaptation of the SPAD-array to the SwissCube satellite. The actual control electronics which is needed to operate the SPAD-array is very power hungry and has to be reduced. Furthermore, an adaptation of the interface to the SwissCube standard is required. If the SPAD-array can not be adapted to the specifications of SwissCube during the next semester, the backup CMOS sensor has to be integrated in the payload.

7 REFERENCES

7.1 Normative references

[N1]

7.2 Informative references

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