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Earth's thermal radiation sensors for attitude determination systems of small satellites

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Abstract. Satellite attitude determination is a complex process with expensive hardware and software and it could consume the most of resources (volume, mass, electric power), especially of small satellites as CubeSats. Thermal radiation infrared detectors could be one of useful sensors for attitude determination systems in such small satellites. Nowadays, these sensors are widely used in contact-less thermometers and thermo-cameras resulting in a low-cost technology. On low Earth orbits the infrared thermal sensors can be utilized for coarse attitude determination against a relative warm and close Earth's globe.
Key words: attitude determination system – thermopile sensor – far infrared radiation – nanosatellite – picosatellite – CubeSat

1. Introduction

Current state-of-the-art of the satellite attitude determination systems (ADS) is in scope of high precision technologies for space telescopes and high resolution observing cameras, which need the accurate and long-term stable pointing. It covers the cooperation of star trackers, earth horizon detectors, Sun detectors, accelerometers, gyroscopes and magnetometers. Typical ADS equipment is illustrated in (Christe et al., 2016) for NASA sounding rockets experiments.

Small satellites like CubeSat (Mehrparvar et al., 2014) commonly dont require the precise attitude determination system, because small dimensions do not allow realizing high directional antennas or telescopes. Required precision of CubeSats attitude determination is mainly given by coarse pointing of wide angle cameras or simple antennas toward the Earth. For these purposes the typical solutions with camera star trackers, Earth horizon detectors, Sun sensors or magnetometers are not suitable and effective due to high mass, volume and power supply requirements. Moreover, such technologies have many technical shortages when trying to apply them in CubeSats.

For example, magnetometers are influenced by supply currents of inner electronics systems of small satellites without deployable booms (Sheinker & Moldwin, 2016). Low cost MEMS accelerometers and gyroscopes suffers by offsets affecting the measurement precision. Overcome this issue of MEMS is relative complicated as shown in (Greenheck et al., 2014). Star trackers designed from commercial cameras can be damaged from direct Sun light irradiation and should be protected by mechanical shutter (Prokhorov et al., 2013). Two axis Sun sensors have be used in small satellites, but they are able to work only in sunlit, not in eclipse.

In the last years several papers deal with the design of Earth horizon detector for small satellites with using modern MEMS thermopile sensors with integrated optics, e.g. (Sáez et al., 2016), (Nguyen, 2014), (Kuwahara et al., 2016). The main focus is commonly put on the getting of high accuracy of nadir vector determination by signal processing from four mutually inclined narrow beam thermopile detectors.

In this paper the idea of usage low cost and low power far infrared sensors for the coarse attitude determination of small satellites is presented. Far infrared sensors are currently in massive usage in the area of contact-less thermometers, air conditioning control, human presence detection systems and thermal imaging cameras. These sensors can be used in small satellites on low Earth orbits (LEO) for distinguishing of relatively warm and close Earth globe and cold free space. A far infrared sensor was also proposed by our team for avoiding false trigger on VZLUSAT-1 during X-ray telescope experiments (Baca et al., 2016).

2. Far infrared sensors in ADS of small satellites

For several decades the thermal sensors were mainly based on photonic principle due to high sensitivity and fast response time, but with the necessity of cryogenic cooling. This makes them impractical for small satellites. In the last decade the thermopile principle gains popularity due to the technological progress in micro electro-mechanical systems (MEMS). This technology allows lightweight and cheap pixel based uncooled sensors with sufficient sensitivity and response time even for thermal imaging cameras.

2.1. Principle of thermopile sensors

Thermopile sensors use thin and thermally insulated layer with far infrared absorber which is capable to fast reach the equilibrium temperature with the mean temperature of objects in the sensor's field of view. The second layer (called reference) has the ambient temperature of own sensor. Between these two layers the serial interconnections of two different electric conductors are wired. If the connections of two different conductors are alternatively joined to absorber layer and reference layer, the output voltage will depend on the temperature difference between absorber and reference layers.

Current MEMS devices can realize in small area high number of serially connected two different conductors for higher sensitivity and thin insulated absorber for fast reaching of equilibrium temperature. This allows the production of thermopile pixel array in small footprint with integrated far infrared optics and filter coating for visible spectrum blocking. Cheap and low power consuming arrays with limited pixel number are currently available on the market and new types with higher resolution are continuously announced to the near future.

2.2. Sensors considered for small satellites

The simple ADS system can be based on a single element thermopile sensor with analog output as well as on the thermopile sensors array with digital output. Table 1 shows the selection of several currently or in near future available sensors with basic properties. These sensors are dedicated for usage in common environments. Their exposition to the rocket launch vibration, fast thermal cycling on the low Earth's orbit, fast transition from atmospheric air pressure to vacuum and to the space radiation environment could limit their lifetime and proper functionality in space. It is impossible to test these sensors by concurrent effects of all space influences in the ground facilities, only particular influences can be separately analyzed on dedicated testbeds. For this reason we decided to test thermopile sensors in real space missions, as is described in section 4.

Table 1. Considered thermopile sensors with basic properties

Type	Resolution	Nominal FOV	Consumption	Interface
TPS230	1x1	82°	not applicable	analog
MLX90615	1x1	100°	4 mW	digital or PWM
AMG88	8x8	60°	15 mW	digital
MLX90640	32x24	110° x 75°	33 mW	digital

2.3. Arrangement of sensors for coarse ADS

The conventional thermopile based ADS uses four slightly inclined narrow beam sensors placed on one satellite wall for precise attitude determination, requiring the Earth partly in the field of view. In contrary, our proposed system for coarse attitude determination uses highly inclined wide beam sensors to create all-sky sensing system, enabling robust attitude determination regardless the actual Earth position. The simplest form of coarse attitude determination system uses the six single element thermopile sensors (e.g. analog TPS230 or digital MLX90615). If one sensor is placed per one satellite wall and walls are perpendicular to each other, they create omni-directional contact-less temperature sensing system. Each sensor measure a far infrared radiation from the objects inside its field of view, weighted by its relative directional sensitivity.

Satellite's fixed body coordinate system uses azimuth and elevation for description of the Earth center position and sensor's directional characteristics. Azimuth plane is counted in the direction of X, Y, -X, -Y of CubeSat walls (Mehrparvar et al., 2014) with initial point in the center of wall X. Elevation

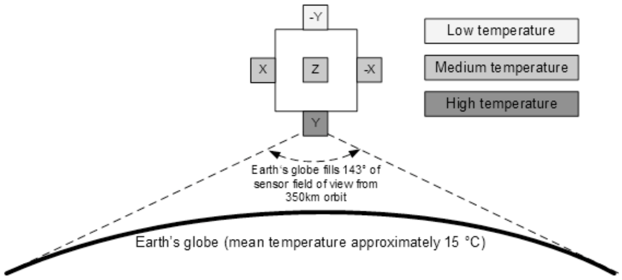

Figure 1. Placement of sensors for coarse attitude determination system.

plane is counted positively toward the Z wall and negatively toward the -Z wall. CubeSats commonly use orbit altitudes from 350 km up to 700 km. The Earth globe fills approximately 143° from the theoretical 180° sensor's field of view for 350 km orbit altitude and 130° for 700 km orbit altitude. Placement of sensors and geometry of Earth in the field of view is illustrated in figure 1 and 2.

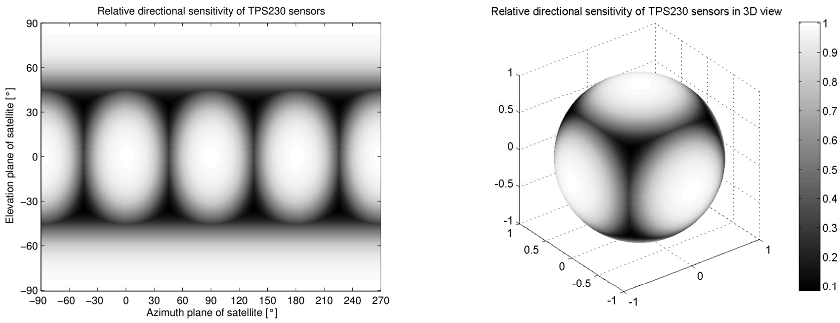

Figure 2. Omni-derectional sensing system with six sensors, their placement and relative directional characteristics in satellite fixed body coordinate system.

2.4. Calculation of temperature in the sensor's field of view

Measured temperature of the objects in the sensor's field of view is given by incoming far infrared power weighted by sensor's relative directional sensitivity. Measured temperature depends on relative position of the Earth projected into sensor's directional characteristic, because the Earth do not fill full sensor's field of view. Matlab simulations were performed to calculate weighted temperatures in the field of view of all sensors based on the actual Earth position. In simulations the satellite orbit altitude equal to 350 km and mean Earth surface temperature equal to 15 °C was considered.

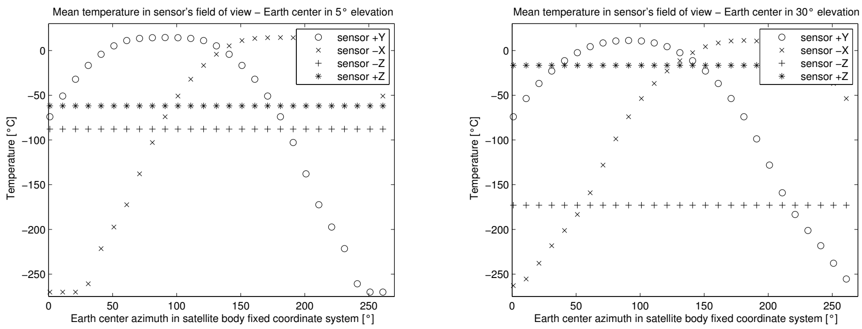

Figure 3. Theoretical temperature visible in TPS230 sensor's field of view dependencies on the actual Earth center position in the satellite body fixed coordinate system.

In figure 3 the weighted temperatures in the field of view of four neighbor sensors are plotted for arbitrary azimuth and two elevations of the Earth center. If the Earth center is in the center of sensor's directional characteristic, the sensor will see weighted temperature 14.6 °C. This is almost equal to considered temperature of the Earth surface, because the cold free space irradiates the sensor only in edge with small relative sensitivity. As the Earth center moves from the center of sensor's directonal characteristic, the temperature decreases.

2.5. Principle of Coarse attitude estimation

Complexity of attitude determination algorithm can be scaled according to the purpose of use. For example, if the satellite is equipped by small planar antenna on each wall, their switching to radio-transceiver could be controlled only by the sensor finding with the highest measured temperature. In this case, ADS distinguishes 6 possible attitudes with approximately 55 ° of maximal estimation error from true nadir vector. This maximal estimation error occurs if the three sensors measure almost the same temperature (irradiated equally by the Earth).

More accurate estimation of nadir vector (with approximately maximal error 27.4 °) could be done by selecting of tree sensors with the highest measured temperatures and their comparison. In this case, ADS distinguishes 26 possible attitudes (6 from the directions of sensor's directional characteristic centers, 12 from the directions of two directional characteristics midpoint, 8 from the directions of three directional characteristics midpoint). Distinguished attitudes are marked in omni-directional sensing characteristic in figure 4.

We also proposed more advance nadir vector estimation based on look-up tables with calculated temperatures of all sensors for arbitrary position of the Earth center. The set of six actually measured temperatures is correlated with set of six calculated temperatures for all possible positions of the Earth center with resolution 1 ° in azimuth and elevation direction. Position with the highest

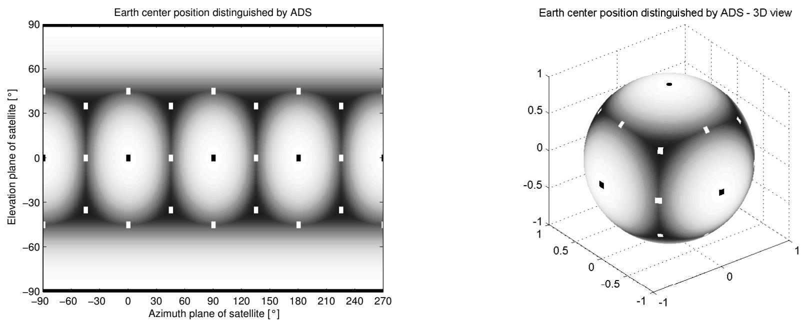

Figure 4. Earth center position distinguished by ADS - black marked positions by selection only the highest measured temperature, white marked positions added by selection and comparison of the three highest temperatures.

Table 2. Simulated accuracy of nadir vector determination for different conditions of temperature measurement error and with application of low temperature threshold.

Temp. threshold	Std. dev of temp. measur.	Mean nadir accuracy (std. dev.)
-100 °C	0.5 °C	8.8° (6.1°)
-80 °C	0.5 °C	13.2° (6.2°)
-60 °C	0.5 °C	16.6° (7.4°)
-40 °C	0.5 °C	17.6° (8.2°)
-100 °C	1 °C	8.9° (5.4°)
-80 °C	1 °C	13.2° (6.3°)
-60 °C	1 °C	16.7° (7.4°)
-40 °C	1 °C	17.9° (8.2°)

correlation between two sets of temperatures is new nadir vector estimation. This method was statistically tested with adding the random error to temperature measurement and with adding the threshold on the lowest measurable temperatures. Results are in table 2.

The key factor for attitude accuracy is the lowest measurable temperature by sensors. Far infrared absorber try to reach the equilibrium temperature with the objects in its field of view. However, especially for low temperatures it is also affected by parasitic thermal radiation of sensor's ambient temperature. This ambient thermal radiation is non-ideally insulated from infrared absorber and it limits the minimal measurable temperature. Figure 5 shows the theoretical angle range of the Earth measurability by one sensor without low temperature limit and with simulated limit equal to -60 °C.

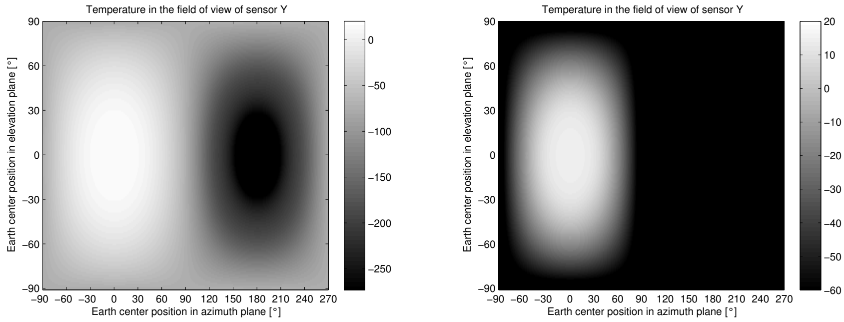

Figure 5. Low temperature threshold of sensors influences the range of angles in which the Earth surface temperature is detectable.

3. Current test plan

ADS system based on thermopile sensors cannot be tested in ground laboratory facilities, because it is not possible to reach in vacuum chamber the same thermal conditions in the sensor's field of view as in space. Sensors placed in vacuum chamber have to be exposed to equivalent thermal radiation of Earth, to cosmic low temperature thermal radiation and to sun spectrum generator for parasitic heating of sensors cover layer at the same time. This is technically almost unrealizable. Therefore the sensor test during the real space mission is irreplaceable for proper sensor verification.

A simple test of the ADS using TPS230 thermopile sensors, ultraviolet EPD365 sensors and visible wavelength BPW21 sensors was originally planned on our PilsenCube university satellite. Unfortunately the satellite was not completed. However, the EPD365 and TPS230 sensors were redesigned for VZLUSAT-1 for triggering Sun imaging via lobster eye roentgen optics. VZLUSAT-1 on-board computer system allows periodic measurement of sensors outputs, so the measured time line from TPS230 sensor could be downloaded, off-line processed and verified by conventional ADS system (magnetometer, gyroscopes) used in this satellite. VZLUSAT-1 should be launched in May 2017.

The second test of thermopile sensor is planned at the end of 2017. During this test the AMG88 thermopile array will be launched by the sounding rocket to several minutes into space as a secondary payload. Test should demonstrate the ability of the Earth globe shape detection in thermal image of AMG88 sensor. If these two tests of the thermopile sensors will succeed, the MLX90640 sensors will be used for the full functional test of ADS in our future PilsenCube II project, derived and redesigned from our unfinished first generation of satellite.

4. Conclusions

Far infrared thermopile sensors are promising the low cost, low power, low volume and low weight technology for coarse attitude determination in small satellites and could be usable in the both sunlit and eclipse conditions. However, these sensors are dedicated for operation in normal ground conditions and their ability to survive and work properly in hard space conditions have to be verified. For example the inner signal processing could be sensitive to space radiation affecting the sensor lifetime. Also sensor optics is covered by blocking filter for visible and near infrared spectrum. In cosmic vacuum this filter layer could be heated more than in atmospheric pressure and it has non-ideal transparency in far infrared wavelength. It could cause partly measuring of this layer temperature instead of the temperature of free space in the sensor field of view. Outgassing of sensors during launch and operation in vacuum with the change of sensor's thermal characteristic could also affects its proper functionality. Therefore we are planning several basic tests of this technology in space for near future. If the results will be promising, the MLX90640 thermopile array with higher resolution will be assembled to PilsenCube II satellite to perform function test of attitude determination system.

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