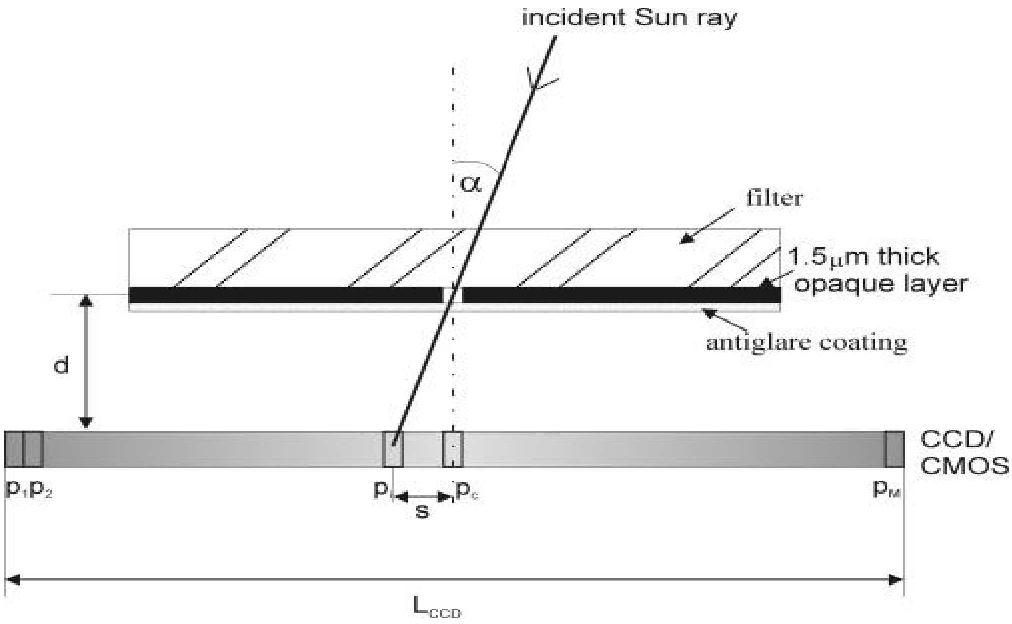
2. SENSOR DESCRIPTION

2.1 Principle of measurement and description of the optical part of the sensor

The principle of the measurement and construction of the DSS is schematically shown in Fig. 1. A thin opaque layer with a narrow slit is placed above the CMOS linear image sensor. Thus the Sun illuminates different pixels in dependence on the angle to main sensor axis. Anti-glare coating coats the opaque layer in which the slit is made to avoid unwanted reflections between filter and image sensor surface. The distance between the image sensor and the slit defines the field of view (FOV) of the DSS. To protect the image sensor against direct Sunbeams and radiation, and to fit the appropriate exposure of the image sensor a special attenuation-filter is used as a front window. There is a set of two identical mutually perpendicular linear image arrays with slits above them placed in one case. Thus we get two angles between Sun and sensor axis measured in two perpendicular planes that makes the determination of Sun vector possible.



$tg\ a = s/d; \quad s = k \times (p_i - p_c)$

here: $\mathbf{p_c}$ is pixel illuminated at $\alpha = 0$, $\mathbf{p_i}$ is pixel illuminated by the Sun at measured angle, and **k** is constant representing pixel spacing.

Fig. 1: Principle of the Digital Sun Sensor. The cross section of the sensor with simplified math is presented. In reality, it is also necessary to consider that the opaque layer may not be perfectly plan-parallel to CMOS surface, and that more pixels are illuminated by the Sun. The deviation of the Sun to an angle *b* in the perpendicular direction to CMOS array causes the increase of the distance *d* by a factor of 1/cos(*b*).

Since the FOV of a single pixel is very narrow, and the light intensity of the Sun is several orders higher than the intensity of the light reflected from the Earth the reflected light does not deteriorate the accuracy of measurement unlike in the case of analogue cosine law sensors, where of one photosensitive element has very large

FOV, and therefore it was sensitive also to the reflected light from the Earth. Thus, the digital sensor using a slit is applicable also for satellites on Low Earth Orbits.

2.2 Description of the electronics and data handling

All electronics is placed in a small case and provides the timing for the linear arrays, computation of Sun vector and data communication with the supervising computer or data collection system.

A block scheme of the sensor electronics is presented in Fig. 2. The analogue signal from both linear sensors is tied to the multi-channel AD converter and by means of Direct Memory Access (DMA) transferred in digital form to the SRAM memory. Both the AD converter and DMA controller are the inner parts of the main microprocessor. The auxiliary microprocessor provides the proper timing for image arrays, whereas the main microprocessor is responsible for data processing. According to the regime chosen a computed Sun vector (two mutually perpendicular angles), or signal levels of all pixels are communicated serially to a supervising data collection system or board computer. The latter regime is predominantly used in the case of testing the device.

An optional sub-board with DC/DC converter can be inserted to extend the supply voltage range.

The scheme of the electronics is shown in the Appendix 1.

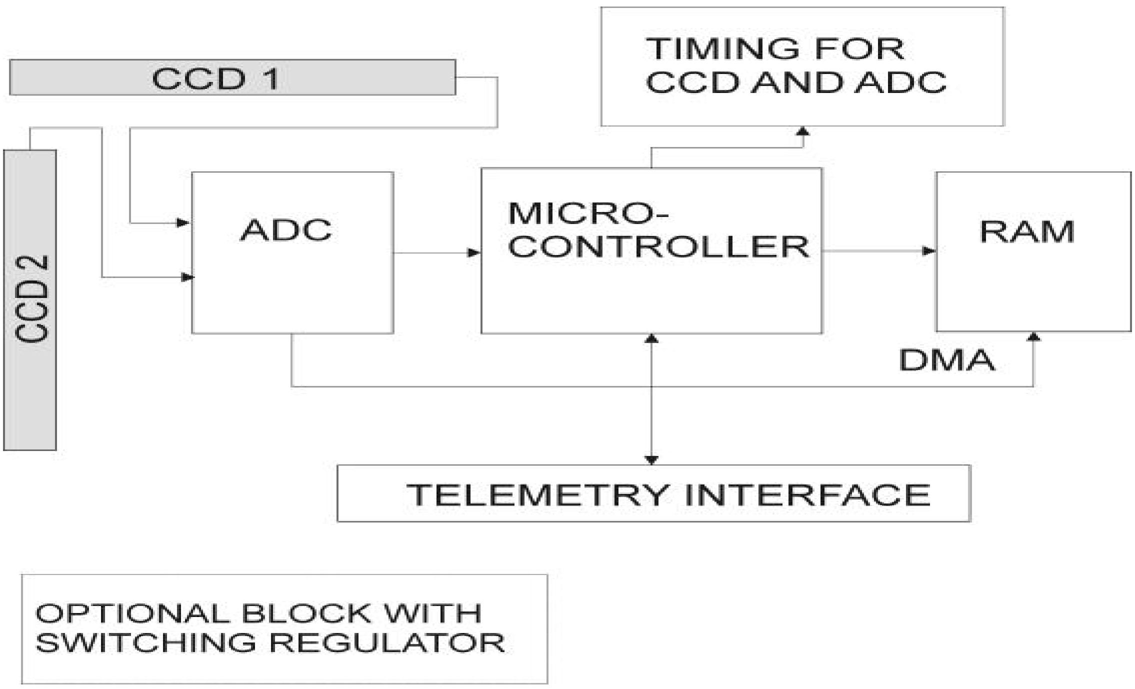


Fig. 2: Block schema of the electronics of DSS

2.3 Data format (*)

The DSS sends data only when it receives a command. There are the following commands and corresponding responses:

A) reading two angles p_{ia}, (p_{ib}) pixels respectively (see section 2.4)
Command: #'M', 02H
Response: EXP, 02H, 00H, 01H, SUNANGLE, TEMPERATURE, TDELAY
Where
EXP is a Byte reporting the preset exposure time T_{exp} [ms] =15+15*EXP
SUNANGLE consists of the following 4 Bytes:
STRED1H, STRED1L, STRED2H, STRED2L,
where STRED1H, STRED1L (STRED2H, STRED2L) defines the pixels p_{ib} , (p_{ia}) – see the section "Determining the angles", and STRED1H (STRED2H) means most significant Bytes.
TEMPERATURE consists of 2 Bytes: TEMPH, TEMPL,
where TEMPH means most significant Byte,
and temperature t in C° is defined as follows: t= -s*(TEMPH, TEMPL-600)-toff, where values of "s", and "toff" are delivered with the sensor.
TDELAY consists of 2 Bytes: TDH, TDL and defines the time elapsed (in ms) between the output data (response to command) and the last exposition (measurement)

B) reading all pixels of the CCD/CMOS sensors
Command: #'M', 01H
Response: EXP, 01H
EXP is a Byte reporting the preset exposure time T_{exp} [ms] =15+15*EXP
then
Command: 50H, 00H, 04H, 00H
Response: 04H, 00H, CCD12, TEMPERATURE, TDELAY
Where CCD12 consists of signal corresponding to individual pixels of both CCDs in the following order:
pixel(i)HighByteCCD1, pixel(i)LowByteCCD1, pixel(i)HighByteCCD2, pixel(i)LowByteCCD2,
where i runs from 1 to 1024 (dek) or 1 to 400(Hex)
TEMPERATURE consists of 2 Bytes: TEMPH, TEMPL (meaning is the same as in A)
TDELAY consists of 2 Bytes: TDH, TDL and defines the time elapsed (in ms) between the output data (response to command) and the last exposition (measurement)

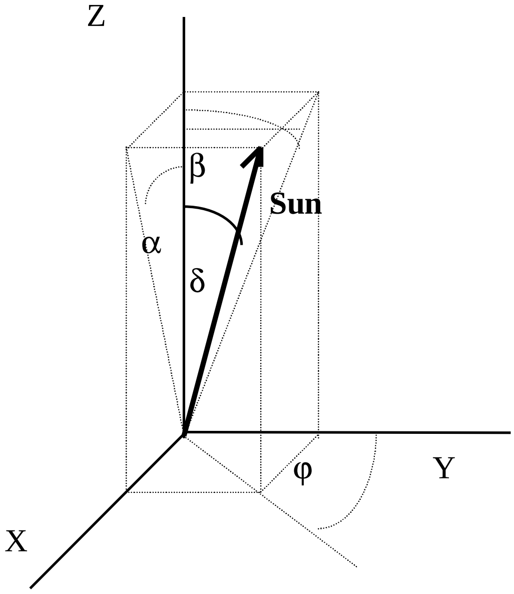
C) defining the exposure time
Command: #'M', 05H,
Response: EXP (old), 05H,
Command : XXH, EXP
Response: EXP(new), 05H,
where EXPis a Byte reporting the preset exposure time T_{exp} [ms] =15+15*EXP

Notes:
#'M' …means ASCI character 'M"
XXH …… means the Byte 'XX' in hexadecimal units
For example 01H … means the Byte '01' in hexadecimal format

If first character received are #'E', #'E' an error has occurred.
If the Sensor is not illuminated it gives the values "5" as the pixels p_{ib} , (p_{ia}) !!

2.4 Determining the angles

The Sun vector is determined by measuring 2 perpendicular angles α, β defined in the Figure 3.



$$tg^2 d = tg^2 a + tg^2 b \; ; \qquad (1)$$

$$tg\, j = tg\, a \;/ tg\, b$$

Fig 3.: Definition of the angles measured by DSS. XYZ are the axis of the DSS. The connector is placed in (-X) direction.

Calibrating coefficients, which are needed for the final determination of sun vector, are delivered for each piece of DSS separately. To determine the Sun vector 6 calibrating coefficients are needed (3 for each line sensor). Their meaning is obvious from the set of formulae (2), derived under the assumption that the "Sun moves" in the ZX plane (ZY respectively) :

$$\begin{aligned} p_{ia} &= p_{0a} + k_a \cdot tg(a - a_{OFF}) \\ p_{ib} &= p_{0b} + k_b \cdot tg(b - b_{OFF}) \end{aligned} \qquad (2)$$

p_{ia}, (p_{ib}) pixel in the center of illuminated area
p_{0a}, (p_{0b}) pixel in the center of illuminated area if optical axis is directed to Sun
($a,b=a_{OFF}$, b_{OFF})
k_a, (k_b) multiplying coefficient (sensitivity to the change of angle)
a, (b) angle to Sun in ZX (ZY) plane

a_{OFF}, (b_{OFF}) difference between mechanical and optical axis (non-collinearity of each line sensor with the opaque layer)

Since in the real operation of the sensor the Sun is not only in the ZX or ZY plane, consequently, the distance d between the effective part of the slit and CMOS line array increases by a factor inversely proportional to the cosine of the angle of deviation in the other plane. See also the Figure 1 and its caption for an illustrative explanation. Therefore, to calculate the angles a, b we have to use the set of equations (3)

$$\begin{aligned} p_{ia} &= p_{0a} + \frac{k_a}{\cos(b)} \cdot tg(a - a_{OFF}) \\ p_{ib} &= p_{0b} + \frac{k_b}{\cos(a)} \cdot tg(b - b_{OFF}) \end{aligned} \qquad (3)$$

This set of nonlinear equations can be solved, e.g. by an iteration process. First we assume the cosine to be 1, solving just an equation (2). Thus we get an estimate of a_1, (b_1). Next, we use (3) to calculate new estimates a_2, b_2. We repeat this process until new estimates a_{k+1}, b_{k+1} differ from the old ones a_k, b_k by a factor less than the accuracy of the sensor. Only several steps are needed. It is advantageous to start with the estimation of higher angle because its correction factor “1/cos” differs less from 1.