CONSIDERATIONS ON THE USE OF *CCD* AND *CMOS* SENSORS IN GEODESY

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Abstract: *The unprecedented development of digital photographic techniques imposed the development of innovative technologies in photographic and video cameras which were later adopted by different engineering specializations. Among these innovations adopted by manufacturers of surveying instruments can be mentioned: autofocus systems, sensors for capturing the light (initially as CCD and later as CMOS sensors), techniques for video monitoring (by processing images captured at preset intervals), etc. In this article, the authors present some of the technologies implemented in geodetic instruments based on CCD or CMOS sensors, aspects that distinguishes the two types of sensors, trends in the development of these sensors and the latest surveying applications that use them.*

Keywords: *total stations, CCD sensors, CMOS sensors, video monitoring, electronic reading*

1. INTRODUCTION

It is hard to believe that from the invention of *CCD* (Charge-Coupled Device) devices in 1969 by Willard Boyle and George Smith, one would have suspected the vast areas of applicability from present and especially the possibilities opened by this discovery for the future more or less distant. The strong impact of this device (*CCD* and technologies inspired by it) on technologies imposed in 2009 granting to inventors the Nobel Prize for Physics (shared with Charles Kuen Kao) by The Nobel Foundation for "The Invention of year for semiconductor imaging circuit - the *CCD* sensor". [1]

CCD applications began in force with the first digital camera, invented by engineer Steven Sasson of Kodak in 1975. In 1976, the recognition satellite *KH-11 Kennan* was equipped with *CCD* devices for images acquisition.

Technological revolution continued by the adoption of these devices in astronomy, where they simply revolutionized the observations technique. In present the geodetic astronomy use extensively *CCD* image acquisition techniques for taking observations in its positioning techniques [3,4].

Although somewhat erroneously perceived and viewed as a rival to the *CCD* sensor, the *CMOS* sensor is nothing more than a good alternative, sharing the same principles. It is obvious to anyone who deepens this problem that *CMOS* (Complementary Metal–Oxide–Semiconductor) sensor could not exist without the idea that formed the foundations of the *CCD* sensor and that the two sensors are very similar in construction and principles (the main differences being the practical implementation of these principles).

The digital revolution in image acquisition continued with the gradual replacement of the photo and video cameras equipped with film by digital instruments equipped with *CCD* or *CMOS* sensors. Currently, anyone can see the existing photo and video progress and also the obvious correlation between the performance of these devices with the quality of the image sensor, whether the sensor is *CCD* or *CMOS*.

The modern geodesy realized the potential of this technology in taking observations and the manufacturers of the geodetic equipment reacted accordingly with these needs by developing systems that have integrated *CCD* or *CMOS* sensors for images acquisitions or for various technical tasks. Even without specific geodesy instruments, the geodetic researchers have adopted and adapted other technologies for their needs. The photo-video techniques allowed monitoring of important objectives by taking images at predetermined intervals drawing conclusions about the changing in their structure or in their own positions in time (by time series) and space.

2. *CCD* AND *CMOS* SENSORS

A. *CCD Sensors*

Beyond its electronic aspects, the *CCD* is simply an array of photocells. They convert photons of light (falling on photodiodes of the sensor) in electrons, generating electric signal which is stored in digital form for image reconstruction (formed on the sensor) in a computer or minicomputer. During the exposure of the sensor to the light, the objects (based on their color) will generate in the exposed areas large or small amounts of electricity correlated with the intensity of light that reaches (during exposure), each element of the array (represented by the photodiodes). If the image sensor is continuously evaluated, video monitoring results. It is worth mentioning that a video is nothing but a very quick succession of still images, conventional measured and defined as "frames per seconds", abbreviated *fps*. From this point of view, the image sensor plays the same role in the static images, as in the video images.

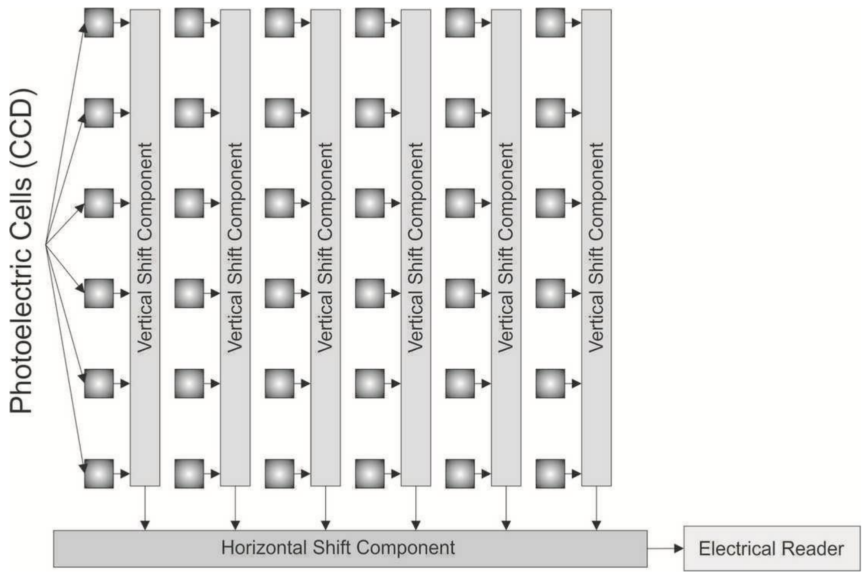

Fig. 1: The serial algorithm for the collection of the electrical values in Interline *CCD*

A *CCD* sensor with 12MP (Mega Pixels) resolution for example, has about 12 millions of photodiodes. For each snapshot, the computer of the instrument equipped with this sensor should read and determine approx. 12 millions of electric charges. These determinations are made in a serial way for the *CCD* sensors with a so called „interline interface”: each photo-diode transmits its load to the computer first vertically and then horizontally. Based on these values, the computer reconstructs the image (Fig. 1).

To avoid the loss of light, each cell in the matrix of the sensor is coated with micro lens specifically designed to capture light from neighboring areas (Fig. 2) [4]. This arrangement applies to the *CMOS* sensors in the same way.

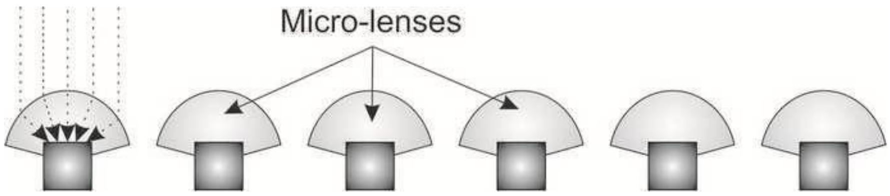

Fig. 2 each cell from the sensor is equipped with micro lens to cover inter-cell spaces

The main disadvantage of this type of image sensor (*CCD*) is the method of electric charges transmission to the processing unit. The serial transmission is time-consuming, especially for videos. Currently, *CCD* sensors with interline transfer may not exceed 25 fps barrier, being in this respect inferior to the *CMOS* sensors. However, *CCD* sensors are suitable for instant exposure to light (with so called Global Shutter), allowing to the video equipment to reduce some unwanted effects, especially in recording subjects with high speed movement. However, the *CCD* developed the so called the smear effect, the effect of vertical columns of light that appear in the image. For the *CMOS* sensors, this effect is virtually nonexistent.

It is worth noting that, till the development of the backlit *CMOS* sensor named *BSI* (Back Side Illuminated) *CMOS*, the *CCD* sensors were considered to be the most suitable for taking pictures in low light conditions. For *CCD* sensors, the main source of noise is the electrical transport to the processing unit. By their construction principles, the *CMOS* sensors eliminates the disadvantage of the electrical information transportation and thus do not add this type of noise in the image. With *BSI* technology development, *BSI CMOS* sensors are currently considered the most suitable in taking pictures in low light conditions.

CCD sensors are about 10 times more sensitive to light than *CMOS* sensors. *CCD* sensors are at the same time (at present) more expensive and electrical information transmission technology of the diode to the processing unit is power consuming. This makes the instruments with *CCD* more power consuming than those with *CMOS* sensors.

The electrical signal carried serially, line by line in *CCD* interline devices is at first analog and therefore require analog-to-digital conversion, hence and the additional loss of time while accumulating extra noise.

B. *CMOS* sensors

The *CMOS* sensors differ from *CCD* sensors only by the transportation modality of electric charges to the processing unit. In terms of principles, the *CMOS* sensors share the same technology as the *CCD* sensors. They uses the same photoelectric effect whereby photons are converted into electrons, the electric charge being directly proportional to the intensity of light falling on the photodiode (which represents the basic cell of the image sensor array).

The main difference between the two sensors is that in the *CMOS* case for each photodiodes is associated an electronic component that accumulate directly the electrical information. This information is then sent electronically and independently through electronic circuits (metal wires) to the processing unit (where the reconstruction of the image is made). Since each photodiode transmit immediately their information to the processing unit makes the *CMOS* sensor to be considered the best for video films with more *fps*. The *CMOS* cameras reach often 200 *fps* and even 2000 *fps*. These remarkable speeds in recording images are possible thanks to a trick done in the image collection process: each image it is not taken simultaneously but gradually, with the so-called *Rolling Shutter* [5]. Practically, every picture is taken line by line (somewhat sequentially) from the top to the bottom. As soon as the bottom of the sensor was exposed the above part is exposed again and the process is repeated as often as needed. Through this sequential and continuous image recording can be obtained in a second of time this impressive number of frames, number limited only by the speed of the *Rolling Shutter*.

It is worth mentioning that this rapid recording of frame has some side effects, especially for objects moving at very high speeds (propellers aircraft, fan blades, items taken from the train or plane, etc..): a) the effect of *skew* that makes the vertical objects taken at high speed to appear distorted and inclined in the direction of the movement, b) the *wobble* effect that makes objects moving at high speeds to appear duplicated and distorted (with stretchy and rubbery appearance), c) *partial exposure* effect that makes certain portions of the image to be displayed differently illuminated in relation with others (especially for long exposures to strong light sources - such *flash light*).

CMOS sensors came to the top with a reversal in the structure of its metal wire, meaning that the photodiodes are placed with their back near the light, avoiding blind spots of micro-lenses. These types of sensors are named Back Side Illuminated (*BSI*) *CMOS* sensors. Figure 3 inspired from the Sony website [2], presents this reversal that was not constructively possible until recently.

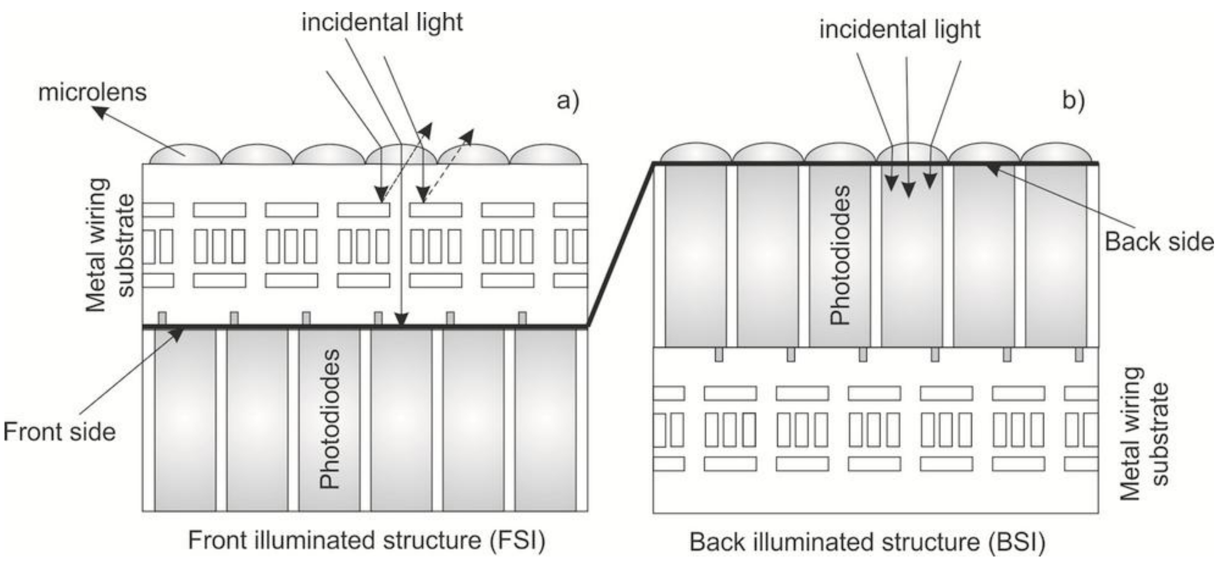

Fig 3 BSI vs. FSI sensor

In Fig. 3, can be seen how the reverse of the *photodiodes substrate* with the *metal wiring* substrate, a higher proportion of light reaches directly the photodiode in the *BSI CMOS* case, unlike in the *FSI* (Front Side Illuminated) case, where most of the light is lost in the metal wiring.

By this artifice, *BSI CMOS* sensors are twice more sensitive to light and also have a significant noise reduction in low light conditions, compared with the *FSI CMOS* sensors [2].

If at the foregoing advantage is added the low production costs (even ordinary

electronics factories can build such sensors), low power consumption and prospects of development, can be easily understand why this type of sensor came to the top in present.

To have a complete picture must be noted that in the *BSI CMOS* sensors case, the images taken in good lighting conditions, because of the direct illumination of the photodiodes, can appear the disadvantage of so called *crosstalk* between pixels (this can cause pixels to bleed into each other), which makes losses in the image contrast (these images can get the unwanted wash-out appearance).

C. *CCD* vs. *CMOS* sensors

The *CMOS* vs. *CCD* debate is a trap mainly used for purely commercial purposes in advertising campaigns. With all these advantages and disadvantages of each type of sensor, sensor superiority over another is strictly a matter of context and content (the direction chosen), each discovery allowing one or the other to dominate a particular aspect in the process of images acquisition. We mention again that these sensors are fundamentally the same; the two types of sensors (*CCD* and *CMOS*) can be regarded as brothers rather than enemies.

3. USING THE *CCD* AND *CMOS* IN GEODETIC APPLICATIONS

A. The quality of the images depends directly by the pixel size

In digital photography, the aim is the printed photos on large papers (posters). If the photo is aimed for viewing on computer, then a similar resolution to those of modern monitors would be sufficient. Thus, a resolution of 1280x800 px (about 1MP) should be sufficient. Even for large monitors with higher resolutions, 2MP resolution of the *CCD* or *CMOS* sensor would be sufficient.

The actual megapixels competition of the compact cameras has a predominant commercial role, because the quality of printed photos is given mainly by the *quality* and the *size* of the physical sensor. A large sensor (in physical size) with the same number of megapixels with a smaller sensor will generate a higher quality image simply because *each pixel will be bigger*. A large pixel will generate more electricity without noise, corresponding to a greater amount of light received. The end result will be a cleaner, brighter and higher quality image even in low light conditions (as internal noise is also low). For compact cameras where the sensor is small (1/2.3", which corresponds to sizes: 6.16mm width and 4.62mm height and thus an area of approx. $28mm^2$), a relatively high resolution (12 megapixels) would translate into a very small pixel size: approx. 2.3 μm^2. The amount of light that can be perceived by such small cell is quite limited, it must be amplified digitally, and the noise that will be found in the final image will be significant. Printing large size of these files (such as *A2* paper) will highlight technical imperfections. That is why clutter a large number of pixels in a so small area is a non-sense, the image is ultimately weaker in the case of cameras with more megapixels than those with fewer megapixels (at sensors of the same size).

For comparison, consider one of the largest currently existing sensors (found in 35mm Full Frame format): 36 mm. widths and 24mm. height with an area of $864 mm^2$. At 12MP resolution of such a large sensor, will results a pixel size of 72 μm^2. This pixel is about 30 times larger than that of a compact camera! It is easy to understand that in such a cell of this size, the quality and quantity of light received is substantially higher. In this case there is no need of a digitally amplification and therefore the noise is considerably reduced. A print at *A2* paper will generate a quality poster, pleasant to look at.

The above considerations highlight an important aspect: the most important element in choosing an image sensor, in addition to its *quality*, is the *pixel size*.

B. *CCD* or *CMOS* geodetic applications

In geodetic applications, the main objective is certainly not printing but even for these applications are valid principles listed above: the *quality* of the sensor and *pixel size*. In most applications (some of them listed below), a sensor with a big size pixel (and - in some applications eg. Photogrammetry - with high resolution), will help considerably in obtaining of good results.

a) **Digital Levels (geometric leveling).** Each reading in these instruments is derived from images taken from rods by a *CCD* or *CMOS* sensor. The counting of divisions is done electronically. Besides the obvious advantages compared to conventional reading (human), this method presents several drawbacks: difficult measurements in low light conditions (counting division is made difficult on an image with blur and noise, autofocus is done slowly or is impossible). It is preferred that these levels to have quality *CCD* or *CMOS* sensors (autofocus and high quality pictures of the rods). In addition, the whole system depends on the quality of the rods. Scratches or missing areas on rods can block entire measurement process [6].

b) **Electronic compensator for total stations**. Most electronic total station incorporates an electronic compensator mono-axial or bi-axial. In most cases, due to its simplicity, these compensators are based on liquid vials. Reference fluid provides a physical reference close to perfection, and thus the inclinations of the total stations can be obtained in relation to the reference surface [6].
Readings of deviations from the reference surface is often achieved with the aid of *CCD* or *CMOS* sensors whether if they are linear (see Figure 4) or as a matrix (Fig. 4b).

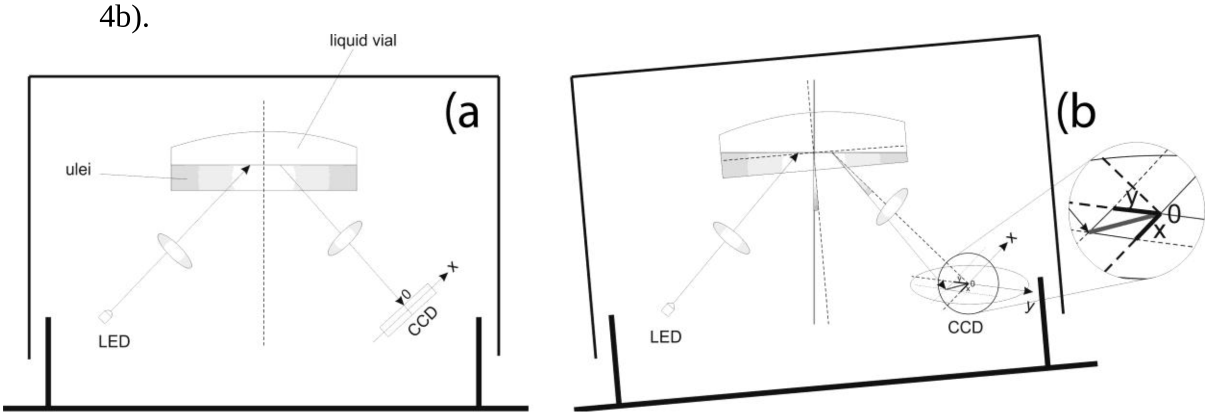

Fig. 4 a) Mono-axial electronic compensator (using linear CCD or CMOS sensor) b) Bi-axial electronic compensator (using CCD or CMOS matrix sensor)

c) **Prism tracking in the motorized total stations systems.** In these systems, *CCD* or *CMOS* sensors are integrated by superimposing over optical field of a matrix of pixels (placed in the focal plane of the lens – Fig. 5a). The movements of the prism are monitored in a local coordinates system, each pixel with maximum brightness corresponding to the instantaneous position of the prism. When the position of the prism is changing, the system calculates a displacement vector *e*, the motorized total station is moving in the direction of the vector *e* cancellation (Figure 5b) [6].

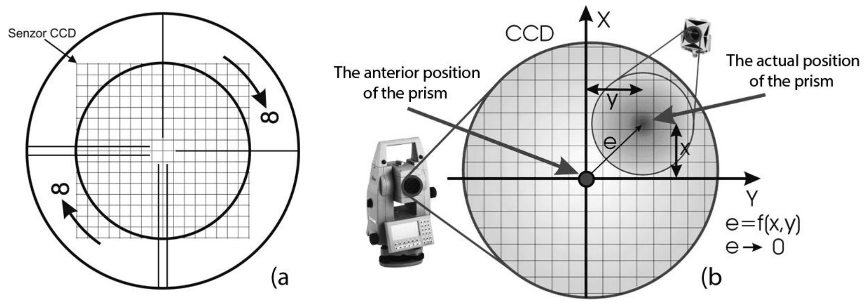

Fig 6 a) *CCD* (CMOS) sensor superimposed on the optical field, b) The displacement vector *e*. By its cancellation, the total station track continuously the prism

d) **Video Total Stations.** On the same principle presented in the previous paragraph, these video total stations associate a *CCD* or *CMOS* sensor with optical field. In these total stations, the user chooses a point on the video image and the total station will identify the corresponding point in the field and then measure its geodetic elements (angles, distances, coordinates). In the stakeout processes, on the video image, the total station will visually indicate the discrepancies between measured and projected positions.

e) **Electronic autocollimators**. Autocollimators allow obtaining with high accuracy (up to thousandths of arc seconds) of the inclination angles relative to the line of collimation. If total station is equipped with an autocollimator, the readings will be made using the total station angle device. In the electronic autocollimators case, the inclination angles are determined on a *CCD* or *CMOS* sensor. Each measured pixel correspond some shift in the direction of tilt. From the right triangle formed the inclination angle can be obtain trigonometrically. In these systems, the accuracy of the reading is obtained either by interpolation (performed on medium resolution sensors), or by choosing a higher resolution sensor [7].

f) **Video monitoring.** The relative position of two objects (the telescope equipped with *CCD* or *CMOS* sensor and target sight) can be monitored by video. Relative readings between the center of the target and the intersection of the crosshairs of the telescope can be quantified by electronic *CCD* or *CMOS* readings. The problem in such systems is the propagation medium that acts as a bending factor for each angle direction that is monitored.

g) **Terrestrial and aerial photogrammetry.** As in the classical photo-video image acquisitions the photogrammetry made the transition from analog to digital (albeit more slowly than in traditional photography), speculating the clear advantages of *CCD* and *CMOS* sensors. If in the past, small sensor resolutions obliged the specialists to a laborious process: taking analog images, which are then digitized by scanning at high resolutions. In the present, the high resolution and large size sensors [3] led almost in totality to the digital age. In terrestrial photogrammetry, the transition from analog to digital has enabled the development of the 3D Modeling Software with impressive accuracy (in direct correlation with the quality of the photo equipment and implicitly with the quality and size of the *CCD* or *CMOS* sensors).

4. CONCLUSIONS

The *CCD* or *CMOS* revolutionized the image acquisition technologies and influenced directly the geodetic measurements. Whether these sensors are used directly in the measurement process (geometric leveling with digital levels, video total stations, video monitoring, photogrammetry) or are used as precision reading devices (electronic compensator in total stations, electronic autocollimators) or auxiliary electronic devices (prism tracking), these sensors have made important contributions in precision, optimization and efficiency in taking geodetic measurements.

It is expected that this progress will continue, given the proportional interest of camera equipment manufacturers to improve *CCD* and *CMOS* sensors. Mobile phones are already equipped with such performance sensors and the photos are technically outstanding. Under these conditions, camera equipment manufacturers are forced to come up with improvements, and as has happened in the past, the engineering domains (geodesy also) will benefit by these technical discoveries.

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