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PLANETARY EXPLORATION WITH OPTICAL IMAGING SYSTEMS – REVIEW, WHAT IS THE BEST SENSOR FOR FUTURE MISSIONS

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I. ABSTRACT / INTRODUCTION

When we talk about planetary exploration missions most people think spontaneously about fascinating images from other planets or close-up pictures of small planetary bodies such as asteroids and comets. Such images come in most cases from VIS/NIR- imaging- systems, simply called ‘cameras’, which were typically built by institutes in collaboration with industry. Until now, they have nearly all been based on silicon CCD sensors, they have filter wheels and have often high power-consuming electronics.

The question is, what are the challenges for future missions and what can be done to improve performance and scientific output. The exploration of Mars is ongoing. NASA and ESA are planning future missions to the outer planets like to the icy Jovian moons. Exploration of asteroids and comets are in focus of several recent and future missions. Furthermore, the detection and characterization of exo-planets will keep us busy for next generations.

The paper is discussing the challenges and visions of imaging sensors for future planetary exploration missions. The focus of the talk is monolithic VIS/NIR- detectors.

II. PLANETARY EXPLORATION AND IMAGING

The subject of Planetary Exploration is to establish the origin and evolution of the planets, their moons, asteroids and comets in our Solar System. Techniques employed include remote sensing and in-situ investigations using instruments carried on spacecraft, astronomical observations from the ground, theoretical modeling and laboratory experiments.

Major progress in our knowledge of the Solar System was achieved over the last decades by planetary exploration missions to all of our planets and to several smaller bodies of the Solar System.

The scientific instruments for these missions perform detection, measurement and observational tasks, and specifically, scientific imaging instruments play arguably the most important roles in most of the missions. Scientific imagers in planetary missions are used for:

- The detection of objects (e.g. the small moons of Saturn, Jupiter)
- To study and to characterize planetary surfaces (including topography, dynamics and surface processes)
- Photogrammetric modelling
- The observation of atmosphere-surface interactions and climate-related processes
- Spectral mapping (e.g. for mineralogy studies of planetary surfaces and atmospheres)

III. MISSIONS - EXAMPLES – MARS

There are many examples of imaging systems that were developed and flown to explore our solar systems. Key objects are the planets, their satellites, asteroids and comets. These objects are imaged by fly-by missions, remote sensing by orbiting spacecrafts and recently by camera systems on landers and rover vehicles.

The most prominent example for past, present and future planetary exploration mission is Mars, the most explored planet in our solar system.

The first fly-by images were taken by Mariner 4 in 1965 with a Vidicon-camera which, however provided only poor spatial and radiometric resolution. The Viking 1 and 2 Vidicon cameras on the respective orbiters and landers in 1975 provided far superior results. The first spacecraft to orbit another planet was Mariner 9. Its Vidicon-camera system (wide and narrow angle camera) covered 100% of Mars’ surface. The images revealed former river beds and massive extinct volcanoes. After Viking 1&2, there was a series of failures.

The next successful lander mission was Mars Pathfinder (NASA, 1997) with a stereo camera (the Imager for Mars Pathfinder; IMP) onboard that was based on a 512x256 frame-transfer CCD from Loral-Fairchild (Smith et al., 1997).



Fig. 1. Mars-Express HRSC camera optics (top: stereo camera optics, bottom: Maksutov-Cassegrain optics of the SRC)

The first successful ESA-mission to Mars was Mars-Express, launched in 2003. Mars-Express has the High-resolution Stereo Camera (HRSC, Jaumann, Neukum et al., 2007) onboard which provides 3-D stereo and color data simultaneously from Mars with global coverage, see Fig. 2.

The HRSC Camera Head contains nine linear CCDs (THX 7808B- from Thomson, now e2v) that are mounted parallel to each other for operation in the so called pushbroom-mode. HRSC simultaneously provides high-resolution stereo, multicolour and multi-phase images of the Martian surface by delivering nine superimposed image swaths. Furthermore, the HRSC includes a Super Resolution Channel (SRC) that consists of a catadioptric Maksutov-Cassegrain telescope with nearly 1m focal length, an interline 1kx1k CCD array detector (the KODAK KAI10101 also used for Venus Monitoring Camera (VMC) and the associated sensor electronics, see Fig. 1. The SRC provides an image scale of 2.3m/px on-ground at a spacecraft altitude of 250 km (SRC-detector electronics, see Fig. 3) on Mars Express.

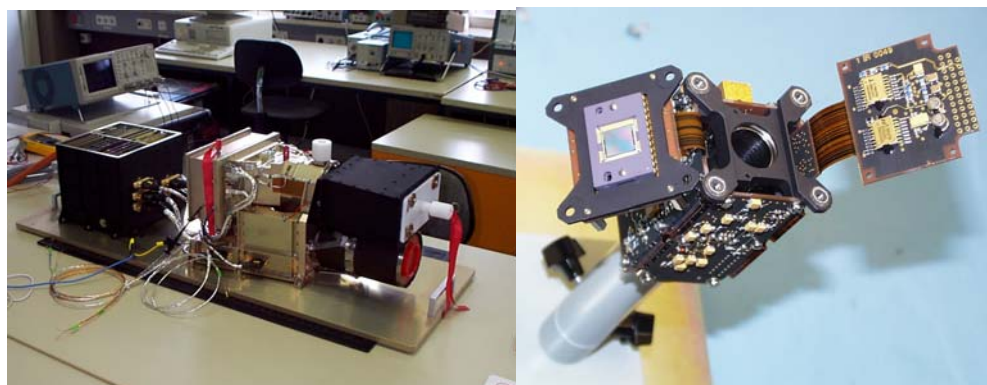


Fig. 2. - left: High Resolution Stereo Camera (HRSC) of Mars-Express (ESA) – image credit: DLR

Fig. 3. - right: Sensor electronics of the SRC – with the CCD KAI1010 from Kodak

IV. KEY REQUIREMENTS ON THE IMAGE SENSOR AND THE INSTRUMENT OPTICS

The requirements on the image sensor and the instrument optics depends mostly on the observational and the environmental conditions at which the instrument has to operate

Particularly, it is important what the observational conditions are:

- Detection or observation of star-like or areal objects
- Object brightness and contrast?
- Dwell-time?
- Spectral range and spectral bandwidth?

Generally, planetary imagers are much smaller devices than most space-based astronomical (and earth-observation) imaging instruments because planetary space-missions have demanding limitations on mass and power consumption. The environmental conditions, particularly in terms of temperature and radiation are in most cases harsher than for astronomical (and earth-observation-) space-telescopes. For instance, missions to the inner solar system (e.g. Venus, Mercury) have to cope with high temperatures and thermal gradients while missions to the outer planets, to the asteroid belt and to comets have to operate and to survive in very cold temperatures. An example of such very compact imager is Rosetta Lander Imaging System (ROLIS) that is part of the ESA-mission to the comet 67P/Churyumov-Gerasimenko, see Fig. 4.

The radiation environment, particularly at Jupiter and at the Jovian satellites is extremely harsh, reaching total ionizing doses $>1\text{Mrad}$.

The mass limitation for lander cameras is often below 1kg while the power consumption may not exceed few watts.

Furthermore, there is a strong limitation in data-volume that can be transmitted to ground because of the large distances between Earth and the planetary object under investigation. Therefore, large sensors (in terms of pixel-number) or sensor-mosaics like in astronomy-missions are exceptions.

Spectral sensitivity and noise are not always as important as in astronomy because many objects are sufficiently bright. However, dark objects like comets, asteroids and the outer planets require high radiometric sensitivity. This is also important when imaging through narrow spectral bandwidth-filters.

Flyby missions have often high ground velocity (v_g) resulting in short dwell times (T_{dwell}) that limits the exposure to few milliseconds or less. These short exposure times require high detector sensitivity in order to prevent large aperture optics resulting in high instrument mass.

The object contrast of atmosphereless planets and small bodies (e.g. asteroids) may reach $>80\text{dB}$ which make simultaneous observation of surface features in bright- and dark zones difficult, thereby requiring a large dynamic range of the detector or multiple exposures and image synthesis.

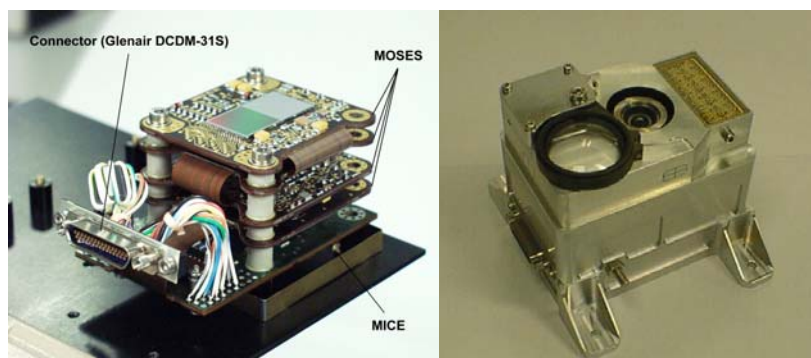


Fig. 4. ROLIS camera (right) and MOSES- detector electronics (left) – image credit: DLR

V. SELECTION GUIDELINE FOR INSTRUMENT OPTICS AND IMAGE SENSOR

In planetary science the image sensor (correctly called detector) is chosen as the basic-component of the instrument design, whereas the instrument optics is designed according to the specific instrument requirements and tuned according to the characteristics of the detector.

Generally, a reflective (catoptric-) design is chosen for high resolution systems with focal lengths larger than 0.5m and apertures above approx. 100mm because otherwise the instrument (-optics) becomes too heavy. It is also applied for systems where a wide spectral range, low stray-light or high radiation tolerance is required. A refractive (dioptric) optics is very convenient for compact wide angle cameras and cameras on landers and rover vehicles with short focal length (and apertures) where high energetic radiation and stray-light are no major issues.

An example for a compact and light weight imaging optics with low stray-light and high radiation hardness is the OSIRIS- camera, which currently provides high resolution images of the comet 67P/Churyumov-Gerasimenko. Another example is the JUICE-JANUS-camera that is designed to operate in the harsh Jovian environments, see Fig. 5. Both systems are based on an all reflective TMA-design concepts.

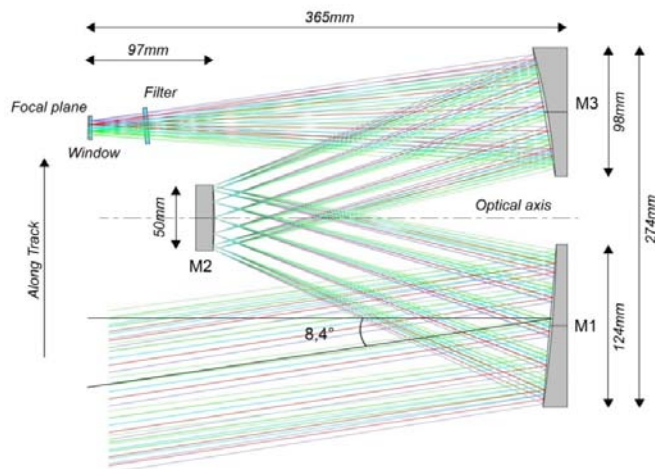


Fig. 5. Example- TMA optical layout of the JUICE-JANUS camera (credit: D. Greggio- INAF - Italy)

Generally, large aperture ratios (low f-number) can compensate the low quantum efficiency (QE) of a detector. However, this would result in high instrument mass at high resolutions, where large focal lengths are required. Therefore, nearly all modern (high- resolution-) planetary imagers are based on thinned, backside illuminated (BIL)- detectors and the dominating image sensor was and still is a BIL- silicon-CCD. At begin of the 1990ies the first active pixel sensor (APS) were developed which is based on the implementation of transistors (as active elements) into the pixel cells. Today, all APS sensors are based on the popular CMOS process of the semiconductor industry. The CMOS image sensor (CIS) is today the leading image sensor in most commercial applications. The question is, will it also replace the CCD in next science imagers for planetary exploration mission?

VI. CCD AND CMOS - COMPARISON

A. CCDs

The invention of CCDs by Boyle and Smith in 1969 resulted in a revolution in astronomy and space exploration. The first CCDs applied in planetary space mission were on the Vega (Soviet) and Giotto-missions (ESA) to comet Halley launched in 1984 and 1985 respectively.

It is a device that operates in the charge-voltage domain, where each pixel contains a discrete signal charge proportional to the incident light.

Today, the CCD is the dominant imaging device in planetary exploration missions. It offers many advantages.

1. It is a proven mature technology that is used in many space missions
2. Despite its sensitivity to high energy cosmic radiation it has sufficient radiation tolerance for most planetary missions
3. Design and processing is much more straightforward than CMOS resulting in shorter schedules for customized devices and lower costs
4. Excellent performance off-chip electronics EEE parts are available for signal processing (e.g. ADCs)
5. Very high QE also at UV and NIR spectral range (e.g. deep depletion and back-illuminated CCDs), see Fig. 6
6. TDI implementation (in charge domain- without noise summation) is straightforward
7. Many scientifically applicable devices readily available in different architectures and size (pixel size and pixel number)
8. Large dynamic range; very useful – in imaging of atmosphereless planetary objects
9. Electron multiplication available (impact ionization applied during charge transport) resulting effectively in very low readout-noise for photon-starved scenarios

Most of the sensor requirements listed in Table 1 can be covered by CCDs.

Table 1. Typical specification of a CCD image sensor for planetary exploration missions

Specification parameter	Specification	Comments, applicability
Spectral Range	400 - 1000nm	In most cases the NUV/VIS/NIR range is sufficient
Quantum efficiency	400nm: >0.1 600nm: >0.5 900nm: >0.1	Higher QE only required at asteroid/comet-, exo-planet search-, outer-planets-missions; at high resolution or fly-bys (with short dwell time) or at narrow-band filters
Architecture: -Linear array -TDI array -Area array	4k – 12k 2k-10k x (16...128) 1kx1k ...4kx4k	-Push-broom, medium resolution Fly-bys, high resolution mapping Lander cameras, mapping, detection
Pixel Size	Typically 5µm – 15µm	Related to FW Related optics (focal length)
Full Well (FW)	Typ. 100ke	Related to dynamic range
Dark signal	<<1nA/cm ²)	Important at low light levels and hot environments
Readout Noise	<10e- rms	-Important at low light level -Related to dynamic range
Radiation Hardness	≈30krad	-Mars, inner planets

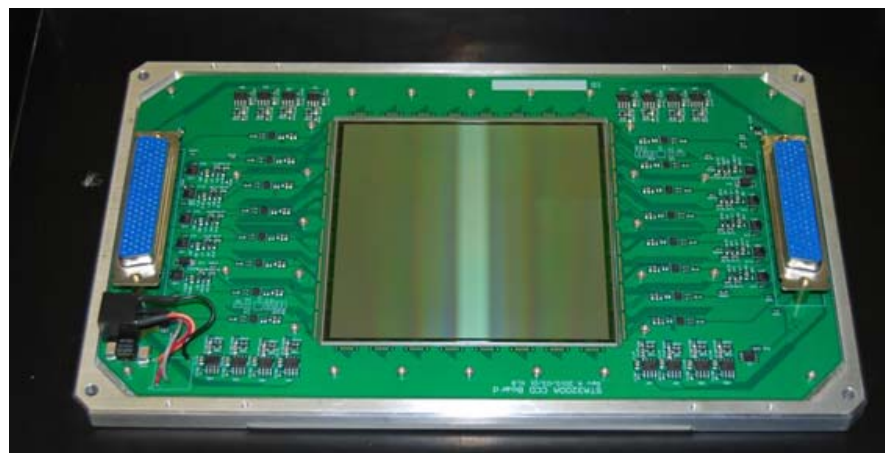


Fig. 6. STA3200 CCD (4kx4k, 24µm pixel, 90% QE at 1µm)- R. Bredthauer

B. CMOS Image Sensor (CIS)

CMOS- imaging sensors are based on CMOS- silicon technology originally developed for complex high integrated circuits of digital- and analog electronics. The general key-advantages are:

- Very small design rules allow very small pixels. 0.228µm rules are state of the art currently for CMOS; each pixel contains several transistors (recently typ. 3-5 MOSFETs);
- Very high level of integration allows implementation of CDS, global shutter, ADCs and further electronics for signal processing and control making possible “digital-only”-device;
- Low voltages, low power consumption
- Radiation: No significant CTE issue because of single (or few) clock transfers ; but CTE may be an issue at high radiation levels; can be improved with PMOS pixels
- Radiation: Possibility to implement radiation-hard- design rules; considerably less flat-band voltage shift because of ultrathin gate oxides (<5nm), however, these oxides can result in high increase in dark current compared to fully-pinned CCD
- True random x-y- addressing and windowing (x-y addressing to read pixels, rows, columns individually); while CCD reads serially

CMOS image sensors are based on parallel-readout architecture. Each pixel has its own amplifier and each column has its own readout (e.g. CDS, ADC) resulting in much lower bandwidth per amplifier and thus low noise at high readout frequencies. Therefore CMOS imager can be operated with very low noise at high frame rates.

CMOS imagers exhibit many advantages over CCDs. However, the question remains, is all that really so important for planetary imaging so that CIS will replace CCDs in near future?

In order to answer the question, the characteristics and advantages of both imaging devices have to be traded with the instrument requirements of planetary imagers.

VII. EVALUATION OF CCDs AND CMOS IMAGE SENSORS FOR PLANETARY IMAGING

Both types of image sensors (CCDs and CIS) are monolithic Si- sensors with very similar characteristics in respect to spectral range, quantum efficiency and dark current.

However, there are differences that may play a decisive role for future applications in planetary exploration missions.

CMOS image sensors have typically smaller pixels which is beneficial for high resolution systems because the focal length of the optics can be reduced. At the other hand small pixels have low full well capacity (FW) that would reduce the dynamic range (DR) of the device which is defined by :

$$DR = FW/N; N: \text{readout noise of the detector} \quad (1)$$

However, here is an important advantage of a CMOS image sensor, it has lower noise than CCDs at high readout rates (>1MSPs), which are required at high resolution remote sensing systems. CMOS image sensors can provide lower noise (N) than CCDs because of their inherent parallel readout architecture.

Today, CMOS devices can reach <5e rms at readout rates of >10MHz, as demonstrated for scientific CMOS-sensors - e.g. from sCMOS from BAE and SoloHi from SRI.

A. Spectral Range and Quantum Efficiency

There is no major difference between both devices except that CCDs usually have higher QE in the NIR spectral range because of the deeper depletion of the photosensitive field region (thick silicon). As an example, the deep depletion CCD STA3200 can achieve 90% QE at 1 μ m, see Fig. 6. CMOS devices have typically thin epitaxial layers of 8-20 μ m. Furthermore, there are only few CMOS sensors readily available as backside thinned devices while front-illuminated CMOS sensors suffer from the limited 'fill factor' and they have low QE- similar to front-illuminated CCDs. Therefore some manufacturers (e.g. e2v) are now putting their CMOS sensors through the same back-illuminated process as CCDs so in future QE may not be a deciding parameter in the near UV.

B. Architectures

CCDs are readily available as linear arrays, TDI arrays and as area arrays in many different sizes while CMOS imaging sensors are only available as area arrays and (few) linear devices. TDI can also be implemented in CMOS devices either as CMOSCCDs or as digital TDI. However, this design results in higher complexity of the image device or of the external electronics. CMOSCCD would greatly reduce the complexity of the camera-instrument electronics.

C. Dark Signal

In general CCDs exhibit a lower dark current. However, there is no major difference between CCD- and CMOS in the un-irradiated condition. Both devices are pinned. However, evidence from device irradiations has shown some dark current generation from un-pinned regions can occur. Typically, the transfer gate limits dark current for CMOS unless special processing and operation are utilized (as e.g. was done on SOLOHI).

D. Radiation

Radiation damage caused by high energetic particles and photons is one of the most important issues in planetary imaging with silicon (CCD and CMOS-) detectors.

Most critical are degradations which may result in total loss of the device. This may happen e.g. after latch-up in a CMOS device as known from microprocessors or memory devices in space. Other degradations change

the performance characteristics of the detector and may have an impact on the signal-to-noise ratio of the instrument.

Generally, CMOS image sensor can be regarded as less critical in a harsh radiation environment. However, a true direct comparison of performance between CCD and CMOS, particularly under extreme radiation conditions has not yet been performed.

E. Costs

It is general accepted that for the CCD, the cost of customization is within financial envelope of small-medium missions. In the case of CMOS imagers, however, the production of a custom device is much more expensive due to the 10x higher effort required for design and manufacturing, and therefore this becomes a prohibitive option for many applications, which have therefore to rely on 'off the shelf' devices.

VIII. FUTURE MISSIONS

There are numerous future missions in the planning phase for exploration of our solar system with unmanned space-crafts that will be equipped with scientific imaging instruments.

First, there are no doubts that the exploration of Mars will continue with landers, rovers and remote sensing imaging instruments. If Mars was (or still is) a habitable planet, the detection of liquid water or life traces is of high scientific interest for our understanding of habitability. However, these places, if they exist at all, are probably hidden below the surface, in caves or other protected places. Therefore, autonomous robotic vehicles with low power consumption but high sensitive imaging instruments are required to perform the search and detection tasks. The radiation environment on Mars does not require radiation-hard detector technologies. Therefore, CCDs can be easily applied there. However, the request for low power and compact imaging devices will push for application of CMOS imagers.

The small bodies of our solar system, the asteroids and comets are also scientifically very interesting. Our goal is to land on asteroids and comets and to bring samples back to Earth for detailed analyses in our well-equipped ground based laboratories. Approach and landing on a small and dark body is not an easy task. It requires high sensitive but low power imaging instruments with sufficiently high frame rate for object detection, navigation, surface- approach and sample acquisition.

Then, the exploration of the large (potentially habitable) moons in our solar system, which could contain liquid water below their ice-crust (e.g. Europa and Ganymede at Jupiter) are also of key-scientific interest. The close distance of the Jovian moons to the strong magnetic field of Jupiter results in an extreme high radiation load to the instruments. Therefore, imaging sensors have to be sufficiently radiation hard to operate and to survive at these harsh environmental conditions. Here, again, radiation-hard CMOS sensors are generally better suited than CCDs. Two examples of recent developments of radiation-hard CMOS-sensors are shown in.

It is the 4Mpix SoloHi sensor developed from SRI for the Solar Orbiter (NASA-NRL-ESA; to be launched in 2016) mission and the 3Mpix CIS115 sensor currently developed by e2v. The rad-hard SoloHi CMOS sensor has already TRL6- technology level from NASA. Both sensors, see Fig. 7, would be well suited for future Jovian missions (e.g. JUICE- ESA) because of their performance see also and high radiation tolerance.

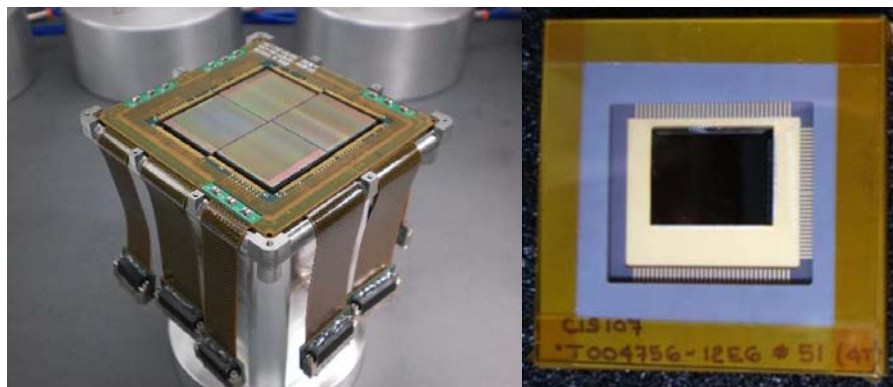


Fig. 7. - left: SoloHi Flight CMOS sensor (4x4Mpix, 10um, 5T) from SRI and right: CIS107 CMOS sensor (precursor of CIS115, 3Mpix, 7um, 5T) from e2v

IX. CCD OR CMOS

CCDs were and are the most dominant image sensors because of their excellent electro-optical performance, wide availability, heritage and cost. However, many of the future missions require either small, low power imaging devices that can be used for landing or sample acquisition missions or they require image sensors that can survive harsh radiation environments without major performance degradation.

As an example, DLR has designed and built lander cameras for future Mars and asteroid missions that are equipped with first generation 1kx1k CMOS image sensors.

A problem is that there are only few scientifically applicable CMOS image sensors readily available and the development of customized devices is very time-consuming and often a schedule driver. Most of the existing CMOS- devices don't yet use the full technological potential of the CMOS technology and have not met the required scientific performance or radiation hardness. Furthermore, the design and development of a new scientific customized CMOS- devices (like CMOS- ASICs) is very expensive and not without development risk. Therefore, we are still at the beginning of a transition between CCD to CMOS image sensors in planetary space experiments; the trend however seems clear, more missions will start to adopt CMOS imagers.

However, in many other scientific applications in planetary exploration CCDs will probably continue to stay for long time such as detection of exo-planets and other applications that are closely related to astronomy, where high electro-optical performance in terms of electro-optical sensitivity and large dynamic range are required.

Generally, it can be summarized that CMOS imagers exhibit many advantages over CCDs. However, depending on the instrument requirements in planetary exploration, CCDs may be satisfactory. Usually power, mass and radiation environment are the ultimately deciding factors which technology is the best.

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