

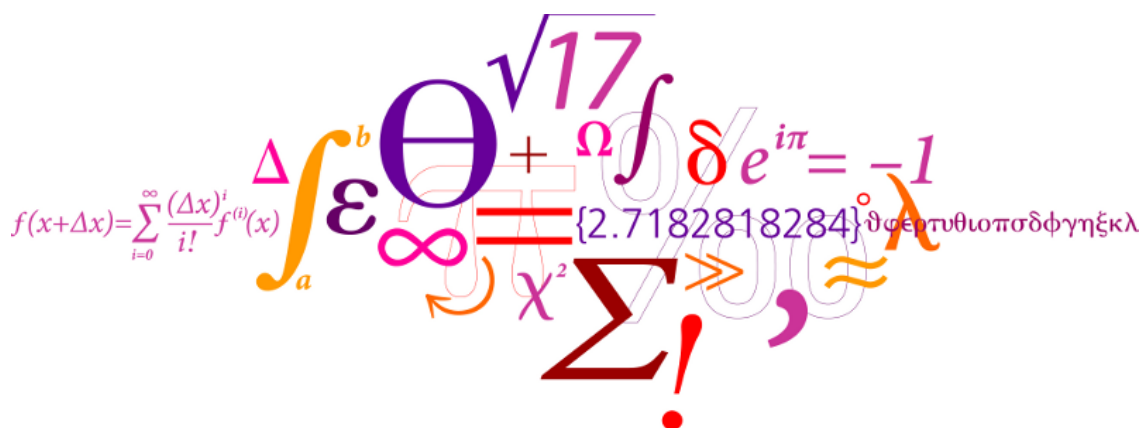
MICROCOMPUTER

PROJECT REPORT

by

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Contents

Introduction au projet	1
1 Problem formulation and delimitation	2
1.1 Problem formulation	2
1.2 Problem delimitation	3
2 Theory Section	5
2.1 Mars Features	5
2.1.1 Atmosphere of Mars	5
2.1.2 climate of Mars	7
2.1.3 Albedo	7
2.2 Artificial Light Source	7
2.2.1 Design of the Light Source	8
2.2.2 Validation of the Light Source	9
3 Development	11
3.1 Scene Analysis	11
3.1.1 CCD	11
3.1.2 Field of View	11
3.1.3 Focal Length	12
3.1.4 Aperture	13
3.1.5 Irradiance	14
3.1.6 Target's Radiance	16
3.1.7 Target's Irradiance	16
3.1.8 Light Source Irradiance	17
3.1.9 Signal/Noise Ratio	18
3.1.9.1 First case	19
3.1.9.2 Second case	20
3.1.9.3 Third case	21
A LED Properties	22

B CCD Properties

23

Introduction

Part 1

Problem formulation and delimitation

1.1 Problem formulation

In this report, we assume that we would like to send a rover on Mars, capable of communicating with Earth. Self-powered by solar panels, it will land at latitude 50° where it could get enough sunlight to recharge its lithium batteries. It is provided with an arm whose hand is replaced with a camera (see figure 1.1). The latter will be used by scientists to observe relevant rocks to study. In order to accomplish this mission, once a stone is designed, the camera must be able to keep it in focus, despite the wind, the movement of the robot or any other perturbation. This implies a real time image analysis to be able to rectify the position of the camera. As a robust method is needed to maintain the stone in front of the arm, the identification of patterns should be completed by carrying out a 3D map of the surface. A luminous source should then be added to the rover to be projected on the surface containing the rock and detected by the camera.

This luminous source must be powerful enough to outshine the sunlight during the day, notwithstanding that the energy needed to make it work has to be negligible compared to the amount provided to the rover. Moreover, the characteristics of the camera need to be perfectly adapted to Mars, as once the rover has landed on the red planet, it would be impossible to adjust it.

Will it be feasible to design such an embedded system, composed of a camera, a luminous source and algorithms, capable of keeping a rock in focus thanks to a 3D map, for an application on Mars soil?

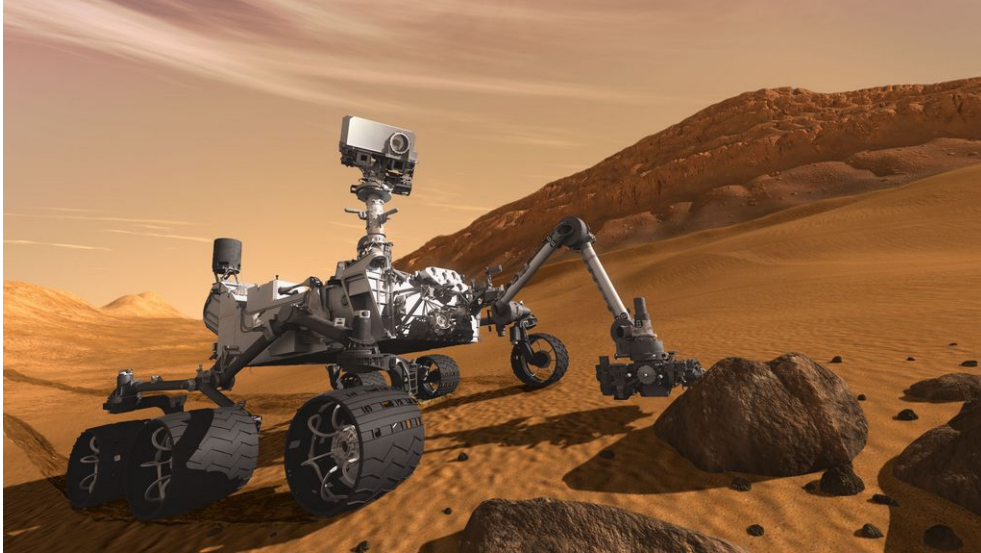


Figure 1.1: Curiosity Rover with an embedded camera on a arm [5]

1.2 Problem delimitation

In order to design the rover's camera which will be used to study rocks and to implement a robust algorithm to carry out a 3D map of the rock's surface, different characteristics of Mars and of the target need to be specified. However, as all of them cannot be taken into account, some simplifications and choices will be assumed.

Mars delimitation

Plenty of missions on Mars have been realized and a great deal of data has already been gathered. Nevertheless, even if some of them will be used to designed our system, others will be simplified or even ignored. The first simplification concern the atmosphere of Mars. Indeed, even if its composition is now well know, it will be assumed that the dirt on the surface Mars plus the different layers of the atmosphere absorb, or scatter, 10% of the solar energy. Moreover, the influence on the image acquisition that the dirt between the target and the camera could have will not be taken into account. The second reduction cover the temperature. Indeed, even if it can reach -143°C during winter, 27°C during summer and have around 60°C variations between daytime and nighttime[6], we will assume that the CCD sensor works well all the time.

Target delimitation

Regarding the target, that is to say the part of the rock being studied, it is supposed to :

- be vertical;

- not exceed 2*2 meters
- have an area between 0.1 and 1 square meters;
- have a relief less than meters.

Camera delimitation

Then, regarding the camera which is designed during this study, it is presumed to :

- be between one and two meters far from the target;
- be right in front of the target, that is to say that the angle between the normal of the target's surface and the focal axis of the camera is 0° ;
- be able to capture the image of a target of 2 meters height maximum.

The different characteristics of target and the camera are represented figure 1.2

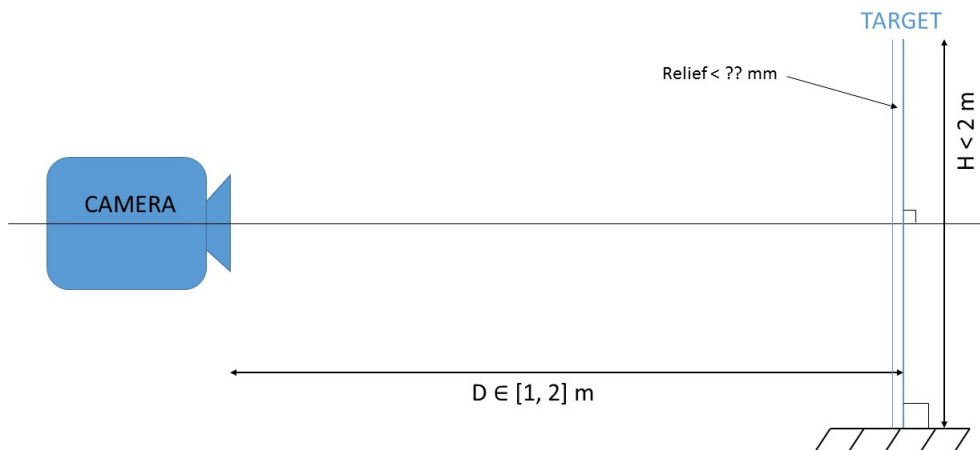


Figure 1.2: Schema of the scene

Part 2

Theory Section

2.1 Mars Features

Mars, the fourth planet from the Sun (1.3814 to 1.6660 AU) is the second smallest planet of the the Solar System (its radius is 3389.5 km). Known as the “Red Planet” because of the amount of iron oxide on its surface, it has an orbital period of 668.6 sols (Mars’ solar day), that is to say 687 days, with an average day length of 24h37m.

2.1.1 Atmosphere of Mars

Because of its thin atmosphere, Mars has surface features which present analogies with both Moon, through the impact craters, and Earth, with volcanoes, deserts, polar ice caps. It is mainly composed of carbon dioxide CO_2 (96,0 % \pm 0,7 %), argon Ar (1,93 % \pm 0,01 %) and oxygen O_2 (0,145 % \pm 0,009 %). As the gravity of Mars is low, the height of the atmosphere is 11 km, more than one and a half times higher than the Earth’s one (7 km). Moreover, due to this low gravity, the wind can disrupt a rover easier than on Earth and a large amount of suspended dust is perpetually present at the surface.

Regarding the dust, of which the particles have a mean diameter of $1,5\mu\text{m}$, is continually injected into the atmosphere by wind or dust devils (a 12 km high one can be seen 12 Figure 2.1). Such eddies are far from anecdotal because they bring dust to significant volumes of the atmosphere. Even if the amount of dust is never very massive, it can be lifted by winds slower than 2 m/s and maintained indefinitely by wind of only $0,8\text{ m/s}$.

Moreover, regarding the wind on Mars, in low altitudes, the Hadley circulation¹ dominate and is almost the same process which, on Earth, generate the Trade winds. In high altitudes, a battery of areas of high and low pressure,

¹movement on a planetary level of the layers of gases surrounding the planet



Figure 2.1: Dust Devil. Mars Reconnaissance Orbiter, made by HiRISE on Feb. 16, 2012

named baroclinic pressure waves², dominates the weather. The Mars wind lift a large amount of dust and can even trigger huge dust storms which can affect the whole atmosphere (see Figure 2.2). Cyclonic storms can also appear on Mars. Indeed, cyclones similar to the ones of Earth tend to create during summer in the northern hemisphere but only in high latitudes.



Figure 2.2: Two views of Mars with spatial telescope Hubble before and after the big dust storm in 2001

²In meteorology a baroclinic atmosphere is one for which the density depends on both the temperature and the pressure

2.1.2 climate of Mars

Because of its distance to the Sun bigger than the one of Earth, Mars receives less solar energy 3.1.5. Additionally, as its atmosphere is thinner, there is only a negligible greenhouse effect, and hence the average temperature is around -63°C on the surface of Mars with wide variations between daylight and night.

Then, the obliquity of Mars is close to the one of Earth (respectively $25,19^{\circ}$ and $23,44^{\circ}$) but the eccentricity of Mars is bigger (0,09332 against 0,01671 for Earth) which means that, if Mars has similar seasons to Earth, they have different intensity and duration during the martian year. Thus, the northern hemisphere has seasons less pronounced than the southern hemisphere because its aphelion is at the end of spring and its perihelion at the end of autumn. Thus, there are short and soft winters and long and fresh summers in the northern hemisphere. On the opposite, the southern hemisphere has very pronounced seasons with long and cold winters and short and warmer summers than in the northern hemisphere. That is why there are higher temperature differences in the south.

2.1.3 Albedo

Mars surface is covered by sand and volcanic rocks. The first purpose of this project is to allow scientists to examine these rocks through the camera. To achieve it, it is needed to know their characteristics, especially their albedo. As a reminder, the albedo is the fraction of incident light which is reflected from a surface. We can assume that the power reflection of Martian rocks is the same than on Earth. Then, to cover a wide range of rocks, the albedos of a black and of a white stone would be considered. Charcoal, as a dark rock, is a powerful absorber of the sun radiation, with an albedo around 0.05. On the contrary, chalks are poor absorbers and their albedo reach 0.45 according to [3]. In the following parts of the report, it will be taken for granted that Martian rocks have an albedo between 5 and 45%.

2.2 Artificial Light Source

In order to carry out a 3D mapping of the target, the system needs a light source to project points which will be used by the 3D mapping algorithm. In this section, the source of light will be designed.

2.2.1 Design of the Light Source

First of all, the green has been chosen as color of the light source. Indeed, in order to detect easily the points projected on the target, a distinctive color should be used. As we can see figure 2.3, the CCD selected for the camera has the best quantum efficiency for a wavelength around 510 nm , which means that the green is the color that is the best recorded by the camera. Secondly, as the surface on Mars is mainly orange, red and brown, this color should stand out.

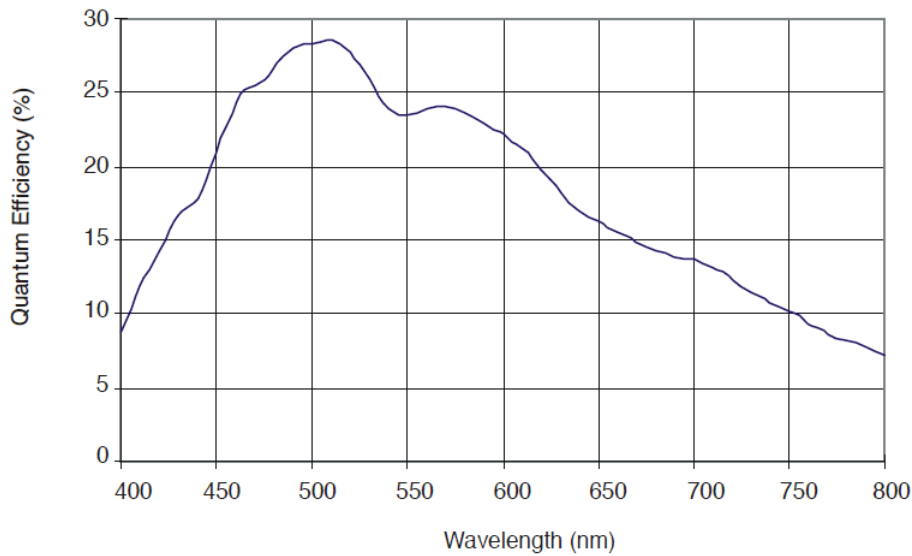


Figure 2.3: Quantum efficiency versus wavelength of the CCD

Then, as only 300 mW are available to aliment the light source and a lot of lightning energy is needed to outshine the sunlight, a LED has been chosen. Indeed, LEDs have great energy performances. The properties of the chosen LED can be seen in Annex A. Note that the use of a laser have been studied, but the energy cost would have been too expensive. Moreover, even if we cannot obtained a coherent light, as a laser do, with a LED, it is still feasible to obtain a monochromatic and directional light. Thus, we will assume that the LED can bring enough light (proof in part on Signal Noise Ratio2.2.2). Then, as the 3D mapping algorithm needs a grid of points, the LED cannot be used in its present condition. Moreover, lot of light would be lost without an optic system. Thus, a system has been designed to concentrate the luminous beams of the LED and to transform the continuous light into a grid of point. The system uses a lens and a grid (Figure 2.4).

As the LED has a diffusion angle of 30° (Annex A), the lens needs to be close enough to collect all the light beams of the LED to avoid losses of energy. In order

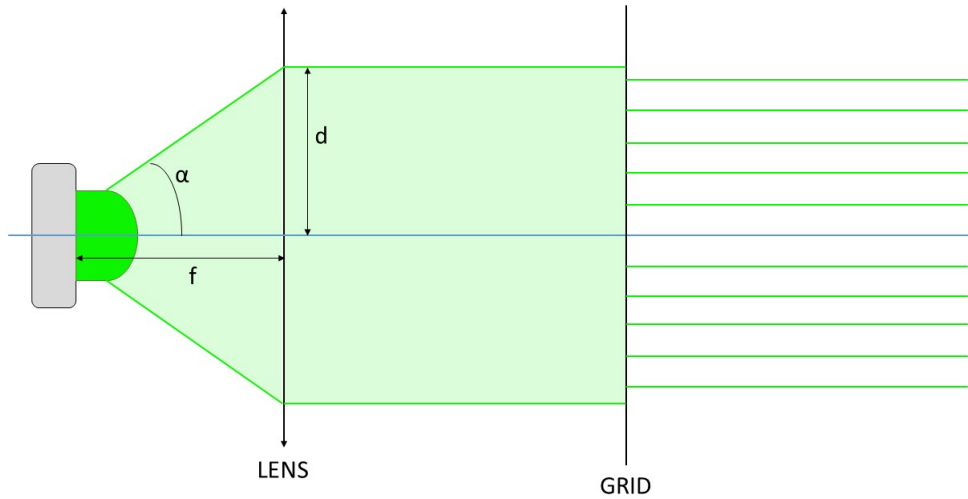


Figure 2.4: schema of the LED system

to capture as much light as possible, the diameter of the lens should follow (2.1).

$$d = f \tan \alpha \quad (2.1)$$

with

$$\alpha = \frac{30}{2} = 15^\circ, \text{ the half of the diffusion angle.}$$

f , the focal length of the lens

Moreover, it should be pointed that there is a loss of energy because of the lens and the grid. We will assume that the energy loss coefficient of the lens LFL_{led} (Loss Factor Lens Led) is 0.5 and the one of the grid LFG_{led} (Loss Factor Grid Led) is 0.3.

2.2.2 Validation of the Light Source

In order to verify whether our light source has enough power or not to outshine the sunlight, the Signal/Noise ratio (SNR) has to be calculated (see part Signal/Noise ratio 3.1.9.3). Knowing that 100 is a really great SNR, as the SNR of images recorded with this system is [32, 348], it can be concluded that the LED can be chosen as light source. Indeed, even if 32 is a low ratio, it is only when all the different poor conditions happen in the same time and it does not happen frequently. Moreover, 100 to 347 are really high ratios that permit to have the 3D

algorithm working well. Thus, the design of the light source is validated.

Part 3

Development

3.1 Scene Analysis

In order to design the camera and find its characteristics, a scene analysis have to be carried out. Our study is based on the MER (Mars Exploration Rover) cameras properties [4]. To begin with, we choose an image sensor.

3.1.1 CCD

The Charge Coupled Device (CCD) is commonly more sensitive to light than its counterpart, the CMOS (Complementary Metal Oxide Semiconductor). Moreover, in the near infrared CCD appears to have a better response. Since Mars has a reddish color, it seems more accurate to select the CCD detector.

As scientists will need to discern the details of rocks, the resolution should be around the megapixel. Taking into account the cost, which will increase with the resolution, and the time of computation for an image with too many pixels, 1024×1024 seems to be an acceptable compromise.

Finally, the last element to consider is the pixel size. A trade-off have to be found between having a higher resolution (smaller pixels) and more sensitivity (larger pixels). All the camera of the MER mission were conceived with a pixel size of $12 \times 12 \mu m$ for a resolution of 1024×1024 . It was decided to comply with that value.

For the next parts of this report, we will use the data sheet of the FTT1010M CCD image sensor as a basis for our calculations which will require CCD details.

3.1.2 Field of View

According to the book [1], the Field of View (FoV) “is the angle of the cone of directions encompassed by the scene that is being images”. This solid angle is

needed to compute the focal length the camera should have.

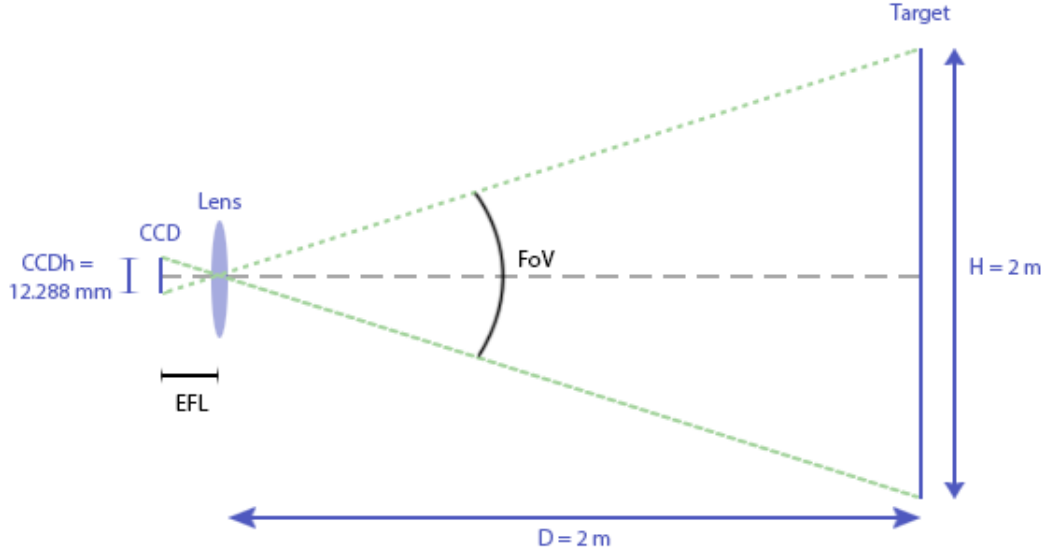


Figure 3.1: Field of View and Effective Focal Length

A simple relationship between the distance lens-target, the size of the target and the FoV can be deduced from the detailed diagram 3.1:

$$\tan\left(\frac{FoV}{2}\right) = \frac{1}{2} \times \frac{H}{D}$$

We derive and get

$$\frac{FoV}{2} = \text{atan}\left(\frac{1}{2} \times \frac{H}{D}\right)$$

Numerically, with our problem delimitation, the Field of View is equal to $26.6^\circ \times 26.6^\circ$.

3.1.3 Focal Length

Thanks to the previous diagram, the Effective Focal Length (EFL) can also be determined:

$$EFL = \frac{1}{2} \times \frac{CCDh}{\tan\left(\frac{FoV}{2}\right)} = 12.29 \text{ mm}$$

where $CCDh$ is the image section of the CCD according to the data sheet.

In order to get the real focal length, we choose $rf = 1 \text{ m}$ for the distance of

focus of the camera.

$$f = \frac{1}{\frac{1}{rf} + \frac{1}{EFL}} = 12.14 \text{ mm}$$

3.1.4 Aperture

To determine the diameter of the aperture, several criteria have to be accounted for. If the diameter is too small, the sharpness of the image will decrease due to the diffraction effect. In fact, at large aperture, the diffracted light is negligible compared to the total amount of light entering the system. On the other hand, we should also consider the Depth of Field (FoV). We need to insure that it is big enough to allow us to see the whole target on the image. The relationship between the DoF and the diameter is inversely proportional. That means that if we increase the diameter, we will lessen it. The Circle of Confusion (CoC), linked to the DoF is also a factor to take into consideration for the choice of the diameter. According to Wikipedia [7] It corresponds to “an optical spot caused by a cone of light rays from a lens not coming to a perfect focus when imaging a point source”. The smaller the CoC is, which corresponds to a better focus, the bigger is the DoF, and also the smaller is the diameter.

As the behaviour of the depth of field and of the circle of confusion runs counter to the diffraction one, a trade-off has to be found.

These formula are used to calculate the Diameter of Confusion (DoC) and the diffraction spot:

$$DoC = Dsr \cdot \frac{|r - rf|}{r} \cdot \frac{f}{rf - f}$$

where Dsr is the diameter of the aperture

$$DiffractionSpot = 2 \cdot EFL \cdot \tan(1.22 \cdot \frac{\lambda}{Dsr})$$

where λ is a wavelength of the sunlight

In the delimitations, it is assumed that the wavelengths of the sunlight belong to [400 800] nm. To settle on a diameter, the diameter of confusion and the diffraction spot were computed for diameters varying from 1 mm to 5 mm and wavelengths from 400 nm to 800 nm. The results are shown graphically in figure 3.2. As the diameter of confusion cannot be bigger than the height of a pixel, the line corresponding to 12 μm was also added to the graphic. In order to have the best trade-off, that is to say all the curves under 12 μm , we have chosen a effective

lens entrance aperture D_{sr} equal to 1.9 mm , corresponding to $DoC = 0.0117 \text{ mm}$.

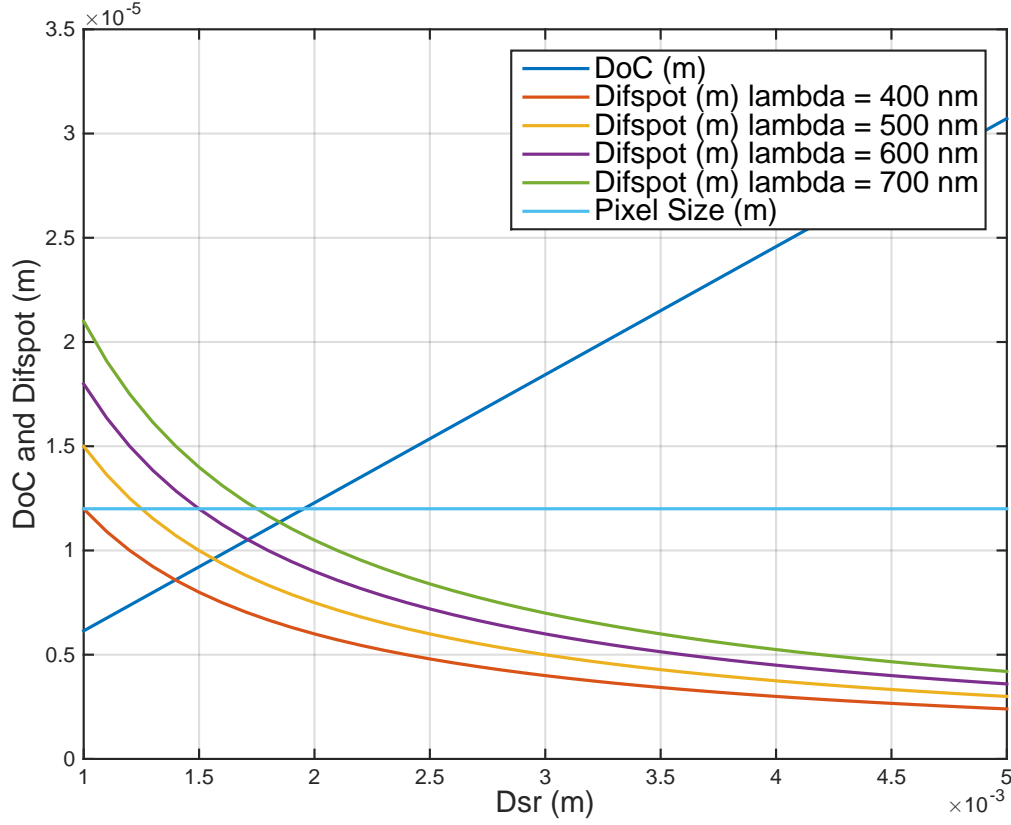


Figure 3.2: Diameter of confusion and diffraction spots as a function of the diameter

The circle of confusion can be deduced:

$$CoC = DoC \cdot m \quad \text{where } m = \frac{EFL}{rf}$$

and then:

$$DoF = \frac{2 \frac{f}{D_{sr}} CoC (m + 1)}{m^2 - \left(\frac{CoC}{D_{sr}}\right)^2} = 12.29 \text{ mm}$$

That means that the roughness of the rock analysed cannot be more than $\frac{DoF}{2} = 6.14 \text{ mm}$ since we could not see the whole rock if not, and the 3D map will then be flawed.

3.1.5 Irradiance

First of all, the irradiance F of the light from the sun falling at the top of the

atmosphere of Mars can be calculated as following : Conservation of energy :

$$4\pi R_{\odot}^2 F_{\odot} = 4\pi R^2 F \quad (3.1)$$

with

$R_{\odot} = 6,956.10^8 \text{ m}$: solar radius

$F_{\odot} = 6,45.10^7 \text{ W.m}^{-2}$: energy flow of the surface of the sun

$R \in [2.06644, 2.49228].10^{11} \text{ m}$: distance Mars-Sun (Aphelion and Perihelion)

$$F = F_{\odot} \left(\frac{R_{\odot}}{R} \right)^2 \in [502, 730] \text{ W/m}^2 \quad (3.2)$$

In this report, we will consider that the rover is working on a specific date and we will chose the one when R corresponds to the semi-major axis. In this case $R = 2,27936.10^{11} \text{ km}$ and

$$F = 589 \text{ W/m}^2 \quad (3.3)$$

Moreover, we can assume that a part of the irradiance is absorbed by the atmosphere. Knowing that the atmosphere of Earth absorbs and scatters to space around 30% of the incident irradiance of the Sun[8], and knowing that the atmosphere of Mars is thinner than the one of the Earth (150 times less dense), we will postulate that 10% of the incident irradiance is absorbed. Thus, using (3.3) the actual irradiance F_a of the light from the sun falling on the surface of Mars is

$$F_a = \frac{90}{100} F = \frac{90 * 589}{100} = 530 \text{ W/m}^2 \quad (3.4)$$

However, this irradiance is the one of surface exposed perpendicular to the sun's beams. As Mars is a sphere, the projection need to be considered. Knowing that the weather is better into the northern hemisphere of Mars (2.1.2) and the fact that a latitude between 30 and 70 degrees is favored for a landing[2], we will assume that the rover has a latitude of 50° . This latitude corresponds to an angle of 40° between the surface of Mars and the sun's beams. Moreover, suppose that the rover stop working when this angle is inferior to 10° . Thus, the irradiance F_{50} at a latitude of 50° is

$$F_{50} = F_a \sin(\text{angleBeams}) \in [92, 341] \text{ W/m}^2 \quad (3.5)$$

with $angleBeams = [10, 90 - latitude] = [10, 40]^\circ$.

3.1.6 Target's Radiance

Considering the trajectory of the Sun into the sky of Mars and knowing that the rock target is more or less vertical to the surface of Mars, the angle θ between the target's normal and the sun's beam is considered to be included in $[10, 50]^\circ$. In addition, in the optimal case (when all the optimal conditions are provided to have the maximal radiance), the BRDF of the surface of the target is assumed to be 90% Lambertian and 10% Glossy while in the worst case the BRDF will be only Lambertian. In this way, the radiance of the target R_T is

$$R_T = \begin{cases} \frac{F_{50}\alpha}{\pi} \cos \theta & \text{optimal case} \\ F_{50}\alpha(\frac{9}{10\pi} \cos \theta + \frac{1}{10}) & \text{worst case} \end{cases} \quad (3.6)$$

with

$\alpha \in [0.05, 0.45]$, the albedo of the target

$\theta \in [10, 50]^\circ$, the angle between the target's normal and the sun's beam

Thus,

$$R_T \in [1.44, 58.58] \text{ W/m}^2 \quad (3.7)$$

3.1.7 Target's Irradiance

Now, the irradiance of the target I_T can be calculated with

$$I_T = R_T \frac{\pi}{4} \left(\frac{Dsr}{EFL} \right)^2 \cos(\alpha_{CT})^4 \quad (3.8)$$

with

α_{CT} the angle between the normal of the target and the axis of the camera

Dsr the effective lens entrance aperture

EFL the focal length

However, knowing that the camera is supposed to be right in front of the target, we have

$$\alpha_{CT} = 0$$

And according to (3.8), (3.7), 3.1.4 and 3.1.3, we have

$$I_T \in [0.0271, 1.1000] \text{ W/m}^2 \quad (3.9)$$

Finally, the luminous power from the target to the camera per pixel W_{lum} is

$$W_{lum} = I_T P_s \quad (3.10)$$

with

$$P_s = 12.10^{-6} \times 12.10^{-6} \text{ m}^2, \text{ the pixel size of the CCD}$$

According to (3.9)

$$W_{lum} \in [3.900, 158.40].10^{-10} \text{ W/pixel} \quad (3.11)$$

3.1.8 Light Source Irradiance

Now, the luminous power of the light toward the CCD from the light source reflected by the target W_{LED} needs to be determined. First, the luminous power of each point W_{dot} projected by the source is

$$W_{dot} = \frac{LFLLed.LFGLed.P_{LED}}{N_{point}} = 4,4960.10^{-04} \text{ W} \quad (3.12)$$

with

$N_{points} = 10 \times 10 = 100$ points, the number of points projected on the target

$$P_{LED} = \frac{C_{LED}\Omega}{L_e} = 0.2997 \text{ W}, \text{ the power of the LED}$$

$C_{LED} = 84 \text{ cd}$, the power of the LED in candella (Annex A)

$\Omega = 2\pi(1 - \cos \alpha) = 0.2141 \text{ sr}$, the solid angle of the LED (Annex A)

$L_e = 60$, the luminous efficiency of the LED

Then, the irradiance of a light point E_{point} is

$$E_{point} = \frac{W_{dot}}{A_{point}} = 71.5558 \text{ W/m}^2 \quad (3.13)$$

with $A_{point} = 6,2832.10^{-6} \text{ m}^2$, the surface of a point.

Finally, W_{LED} can be calculated following the same steps as in the previous part 3.1.7 except the fact that we have to consider an angle $\theta_{Led} = 10^\circ$ between the light source and the normal of the target. Thus, the luminous power per pixel received by the CCD from the source light is $W_{LED} = [3.033, 33.271].10^{-12} \text{ W/pixe}$

3.1.9 Signal/Noise Ratio

Three different cases will be studied. In the first one, we examine the case of a target illuminated by the sun without the use of laser, the second one considers the use of lasers by night and the last one, which is the case that we need to consider for our rover, study the use of lasers by daylight. In order to calculate the Signal/Noise ratio, the different noises need to be determined. Three will be taken into account: the readout noise, the dark current noise and the noise from the sun light.

The three different cases have the readout and the dark current noise in common which are given by the datasheet of the CCD B.

$$\delta_{readout} = \frac{RMS}{N_{pixel}} \quad (3.14)$$

$$= 2,3842.10^{-05} \text{ el/pixel} \quad (3.15)$$

$$\delta_{dark} = \left(2,55.10^{15} N_{dc0} T_s (P_s.10^2)^2 T^{\frac{2}{3}} e^{-\frac{E_g}{2kT}} \right)^{\frac{1}{2}} \quad (3.16)$$

$$= 0.0067 \text{ el/pixel} \quad (3.17)$$

with

$RMS = 25 \text{ el}$, the RMS readout noise B

$N_{pixel} = 1024 \times 1024 \text{ pixels}$, the number of pixel of the CCDB

$N_{dc0} = 30 \text{ pA/cm}^2$, the dark current level at 20°C B

$T_s = 0.1 \text{ s}$, the shutter time

$P_s = 12.10^{-6} \text{ m}$, the pixel size B

$T = 197 \text{ K}$, the temperature

$$E_g = 1.1557 - \frac{7.10^{-4}T^2}{1108 + T}$$

$k = 8,62.10^{-5} \text{ eV/K}$, the Boltzmann's constant

3.1.9.1 First case

In this case, the signal that needs to be considered is the sun light reflected by the target. Therefore, the readout and the dark current noises are the only two which need to be considered and the noise is

$$N = \sqrt{\delta_{readout}^2 + \delta_{dark}^2} = 0.0067 \text{ el/pixel} \quad (3.18)$$

Then, the number of photons per shutter time N_p corresponding o the radiance of the target is

$$N_p = \frac{1}{\lambda_{max} - \lambda_{min}} \int_{\lambda_{min}}^{\lambda_{max}} \frac{W_{lum}ts}{\frac{h.c}{\lambda}} d\lambda \in [1.177, 47.810].10^6 \text{ photons/pixel} \quad (3.19)$$

with

$ts = 0.1 \text{ s}$, shutter time

$h = 6,6263.10^{-34} \text{ J.s}$, Planck's constant

$c = 3.10^8 \text{ m/s}$, velocity of light

$\lambda \in [400, 800] \text{ nm}$, wavelength of the sunlight

The number of photons per pixel going to the lens N_{CCD} is

$$N_{CCD} = \frac{\pi \left(\frac{D_{sr}}{2}\right)^2}{2\pi(r)^2} N_p \in [0.1328, 5.3936] \text{ photons/pixel} \quad (3.20)$$

with $r = 2 \text{ m}$, the distance between the camera and the target

The number of photons per pixel to the lens registered by the CCD Nen_{CCD} is

$$Nen_{CCD} = N_{CCD} \int_{\lambda_{min}}^{\lambda_{max}} CCDqe(\lambda).alphaLens(\lambda) d\lambda \in [0.0208, 0.8457] \text{ photons/pixel} \quad (3.21)$$

with

$CCDqe$, the quantum efficiency of the CCD 2.3

$alphaLens$, the pass band efficiency of the lens

Finally, according to (3.18) and (3.21) we obtain the Signal/Noise ratio

$$\frac{S}{N} = \frac{Nen_{CCD}}{N} = [3.1, 126.8] \quad (3.22)$$

Knowing that, 100 is a really great Signal/Noise ratio, we can conclude that the system could record images of satisfactory or high quality the most of the time. However, if the different poor conditions accumulate, the quality of the image will greatly decrease.

3.1.9.2 Second case

In this case, the signal that needs to be considered is the light of the pseudo laser reflected by the target. Therefore, the noise is still the same as in the first case. Proceeding in the same way as into the first case 3.1.9.1 but considering only the wavelength of the LED(520.10^{-9} m), the number of photons per pixel from the artificial light source going toward the CCD is $Nen_{LED} = [2.4556, 26.9410] \text{ photon/pixel}$.

And the Signal/Noise ratio is given by

$$\frac{S}{N} = \frac{Nen_{LED}}{N} = [368, 4040] \quad (3.23)$$

It can be deduced from this SNR that the system light source plus camera would work perfectly by night. Indeed, the minimum of this ratio is 368 which is larger than 100, an excellent ratio. Working by night would be the best scenario but the day work needs to be considered.

3.1.9.3 Third case

In this case, the current case, it will be determined if the artificial light source is powerful enough to outshine the sunlight. Thus, the sunlight is now considered as a noise, the shot noise.

$$N = \sqrt{\delta_{readout}^2 + \delta_{dark}^2 + \delta_{shot}^2} = [0.0219, 0.8457] \text{ el / pixel} \quad \text{with } \delta_{shot} = nen_{CCD} \quad (3.24)$$

As the signal and the noise are ranges because of the different conditions possible, the SNR should be

$$SNR = \left[\frac{S_{min}}{N_{max}}, \frac{S_{max}}{N_{min}} \right] \quad \text{with } S = Nen_{LED}$$

However, it can be noticed that one parameter, the albedo α , is varying for both lights, the sun and the artificial light source. Indeed, if the target has an albedo α_{min} , this albedo needs to be considered in both calculation of the Nen_{CCD} and Nen_{LED} . Therefore, the calculation of the SNR needs to take into account this correlation and we have

$$SNR = [32, 348] \quad (3.25)$$

It can be concluded that the artificial light system is powerful enough to outshine the sunlight. Moreover, the quality of the image of the points should have an excellent quality, which would permit the 3D mapping algorithm to work perfectly. Also, even if the worst conditions are gathered (minimum albedo, sunset), the SNR is still equal to 32, which is acceptable.

Appendix A

LED Properties

Caractéristiques

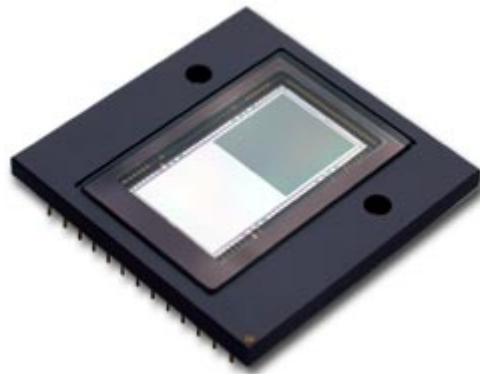
• Couleur	Vert
• Température de couleur	525nm
• Intensité Lumineuse	84000mcd
• Ampérage Requis	20mA
• Angle de Diffusion	30°
• Consommation	220mW
• Tension d'alimentation	9.3 - 10.5V
• Durée de vie estimée	80 000 Heures

Figure A.1: LED Datasheet

Appendix B

CCD Properties

DATA SHEET



FTT1010M

1M Frame Transfer CCD Image Sensor

Product specification

2007, April 17

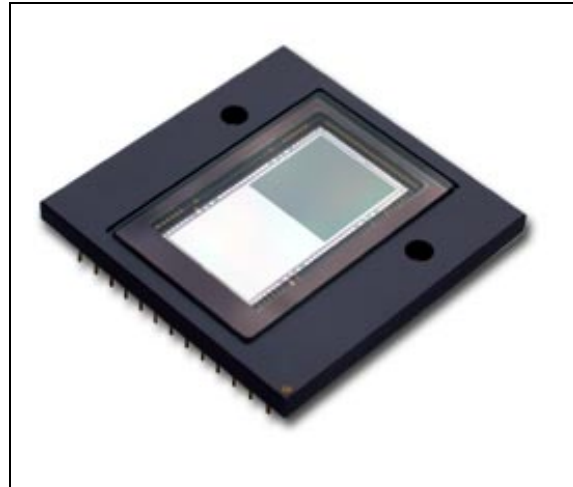
DALSA
Professional Imaging



1M Frame Transfer CCD Image Sensor

FTT1010M

- 1-inch optical format
- 1M active pixels (1024H x 1024V)
- Progressive scan
- Excellent antiblooming
- Variable electronic shuttering
- Square pixel structure
- H and V binning
- 100% fill factor
- High dynamic range (>72dB)
- High sensitivity
- Low dark current and fixed pattern noise
- Low readout noise
- Data rate up to 2 x 40 MHz
- Mirrored and split readout
- RoHS compliant



Description

The FTT1010M is a monochrome progressive-scan frame-transfer image sensor offering 1K x 1K pixels at 30 frames per second through a single output buffer. The combination of high speed and a high linear dynamic range (>12 true bits at room temperature without cooling) makes this device the perfect solution for high-end real time medical X-ray, scientific and industrial applications. A second output can either be used for mirrored images, or can be read out simultaneously with other output to double the frame rate. The device structure is shown in figure 1.

Device structure

Optical size:	12.288 mm (H) x 12.288 mm (V)
Chip size:	14.572 mm (H) x 26.508 mm (V)
Pixel size:	12 μ m x 12 μ m
Active pixels:	1024 (H) x 1024 (V)
Total no. of pixels:	1072 (H) x 1030 (V)
Optical black pixels:	Left: 20 Right: 20
Timing pixels:	Left: 4 Right: 4
Dummy register pixels:	Left: 7 Right: 7
Optical black lines:	Bottom: 6 Top: 6

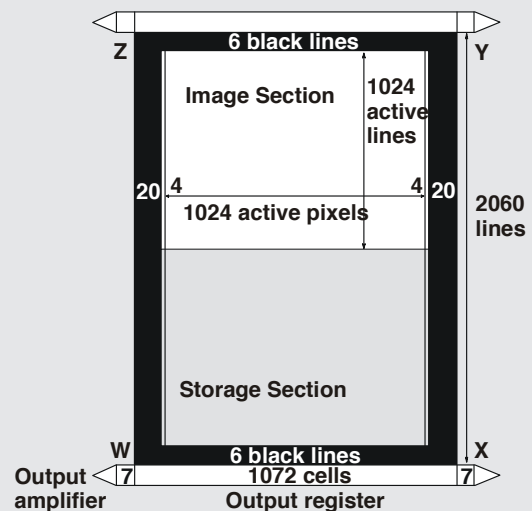


Figure 1 – Device Structure

1M Frame Transfer CCD Image Sensor

FTT1010M

Architecture of the FTT1010M

The FTT1010M consists of a shielded storage section and an open image section. Both sections are electronically the same and have the same cell structure with the same properties. The only difference between two sections is the optical light shield.

The optical centres of all pixels in the image section form a square grid. The charge is generated and integrated in this section. Output registers are located below the storage section. The output amplifiers Y and Z are not used in Frame Transfer mode and should be connected as not-used amplifiers.

After the integration time, the charge collected in the image section is shifted to the storage section. The charge is read out line by line through the lower output register.

The left and the right half of each output register can be controlled independently. This enables either single or multiple readout.

During vertical transport, the C3 gates separate the pixels in the register. The letters W, X, Y, and Z are used to define the four quadrants of the sensor. The central C3 gates of both registers are part of the W and Z quadrants of the sensor.

Both upper and lower registers can be used for vertical binning. Both registers also have a summing gate at each end that can be used for horizontal binning. Figure 2 shows the detailed internal structure.

IMAGE SECTION	
Image diagonal (active video only)	17.38 mm
Aspect ratio	1:1
Active image width x height	12.288 x 12.288 mm ²
Pixel width x height	12 x 12 μm^2
Fill factor	100%
Image clock pins	A1, A2, A3, A4
Capacity of each clock phase	2.5nF per pin
Number of active lines	1024
Number of black reference lines	6
Total number of lines	1030
Number of active pixels per line	1024
Number of overscan (timing) pixels per line	8 (2x4)
Number of black reference pixels per line	40 (2x20)
Total number of pixels per line	1072
STORAGE SECTION	
Storage width x height	12.864 x 12.360 mm ²
Cell width x height	12 x 12 μm^2
Storage clock phases	B1, B2, B3, B4
Capacity of each clock phase	2.5nF per pin
Number of cells per line	1072
Number of lines	1030
OUTPUT REGISTERS	
Output buffers (three-stage source follower)	4 (one on each corner)
Number of registers	2 (one above, one below)
Number of dummy cells per register	14 (2x7)
Number of register cells per register	1072
Output register horizontal transport clock pins	C1, C2, C3
Capacity of each C-clock phase	60pF per pin
Overlap capacity between neighbouring C-clocks	20pF
Output register Summing Gates	4 pins (SG)
Capacity of each SG	15pF
Reset Gate clock phases	4 pins (RG)
Capacity of each RG	15pF

1M Frame Transfer CCD Image Sensor

FTT1010M

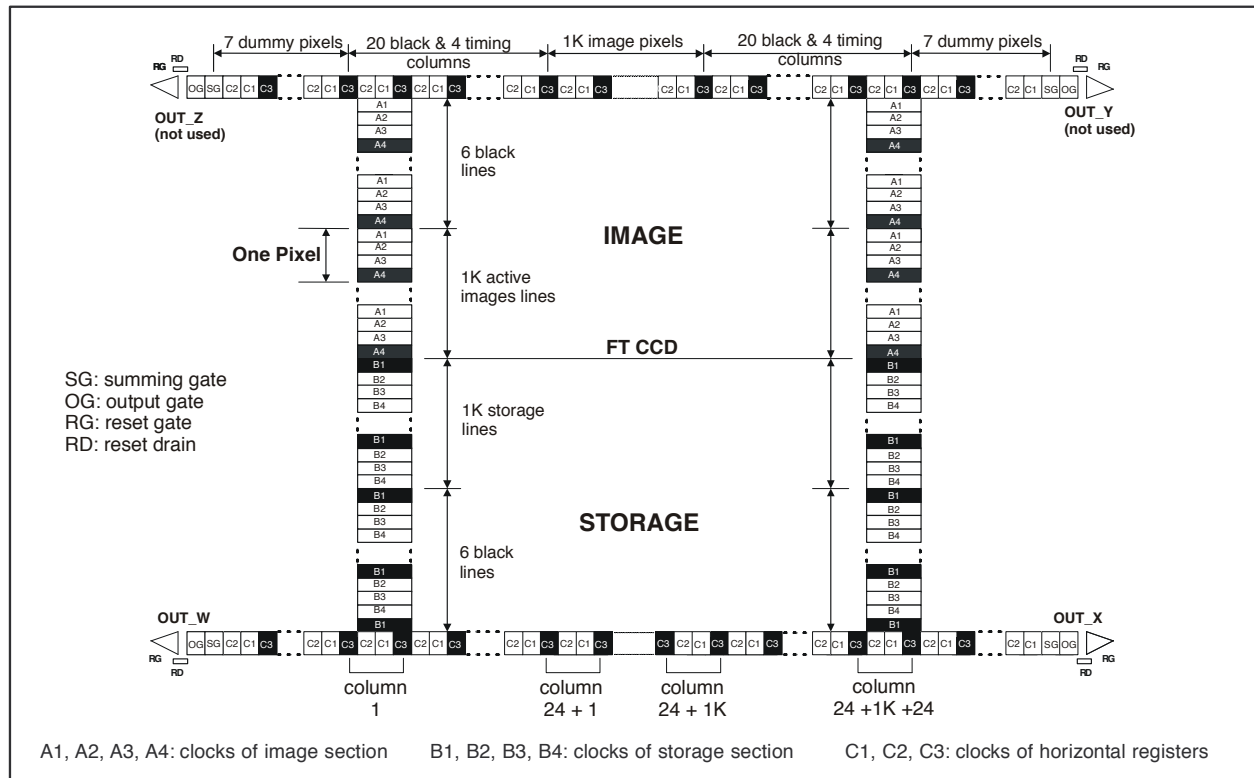


Figure 2 - Detailed internal structure

1M Frame Transfer CCD Image Sensor

FTT1010M

Specifications

ABSOLUTE MAXIMUM RATINGS ¹		MIN	MAX	UNIT	
GENERAL:					
storage temperature		-55	+80		°C
ambient temperature during operation		-40	+60		°C
voltage between any two gates		-20	+20		V
DC current through any clock (absolute value)		-0.2	+0.2		μA
OUT current (no short circuit protection)		0	10		mA
VOLTAGES IN RELATION TO VPS:					
VPS, SFD, RD		-0.5	+30		V
VCS, SFS		-8	+5		V
All other pins		-5	+25		V
VOLTAGES IN RELATION TO VNS:					
SFD, RD		-15	+0.5		V
VCS, SFS, VPS		-30	+0.5		V
All other pins		-30	+0.5		V
DC CONDITIONS ^{2,3}		MIN [V]	TYPICAL [V]	MAX [V]	MAX [mA]
VNS ⁴	N substrate	20	24	28	15
VPS	P substrate	1	3	7	15
SFD	Source Follower Drain	16	20	24	4.5
SFS	Source Follower Source	-	0	-	1
VCS	Current Source	-5	0	3	-
OG	Output Gate	4	6	8	-
RD	Reset Drain	13	15.5	18	-
AC CLOCK LEVEL CONDITIONS ²		MIN	TYPICAL	MAX	UNIT
IMAGE CLOCKS:					
A-clock amplitude during integration and hold		8	10		V
A-clock amplitude during vertical transport (duty cycle=5/8) ⁵		10	14		V
A-clock low level			0		V
Charge Reset (CR) level on A-clock ⁶		-5	-5		V
STORAGE CLOCKS:					
B-clock amplitude during hold		8	10		V
B-clock amplitude during vertical transport (duty cycle=5/8)		10	14		V
OUTPUT REGISTER CLOCKS:					
C-clock amplitude (duty cycle during hor. transport=3/6)		4.75	5	5.25	V
C-clock low level		2	3.5		V
Summing Gate (SG) amplitude			10	10	V
Summing Gate (SG) low level			3.5		V
OTHER CLOCKS:					
Reset Gate (RG) amplitude		5	10	10	V
Reset Gate (RG) low level			3		V
Charge Reset (CR) pulse on Nsub ⁶		0	10	10	V

¹ During Charge Reset it is allowed to exceed maximum rating levels (see note 5)² All voltages in relation to SFS³ Power-up sequence: VNS, SFD, RD, VPS, others⁴ To set the VNS voltage for optimal Vertical Antiblooming (VAB), it should be adjustable between minimum and maximum values⁵ Three-level clock is preferred for maximum charge; the swing during vertical transport should be 4V higher than the voltage during integration⁶ A two level clock (typically 10V) can be used if a lower maximum charge handling capacity is allowed⁶ Charge Reset can be achieved in two ways:

- The typical CR level is applied to all image clocks simultaneously (preferred).
- The typical A-clock low level is applied to all image clocks; for proper CR, an additional Charge Reset pulse on VNS is required. This will also affect the charge handling capacity in the storage areas.

1M Frame Transfer CCD Image Sensor

FTT1010M

Timing diagrams (for default operation)

AC CHARACTERISTICS	MIN	TYPICAL	MAX	UNIT
Horizontal frequency ($1/Tp$) ¹	0	18	40	MHz
Vertical frequency	0	450	1000	kHz
Charge Reset (CR) time	2	20		μs
Rise and fall times: image clocks (A)	10	20		ns
storage clocks (B)	10	20		ns
register clocks (C) ²	3	5	1/6 Tp	ns
summing gate (SG)	3	5	1/6 Tp	ns
reset gate (RG)	3	5	1/6 Tp	ns

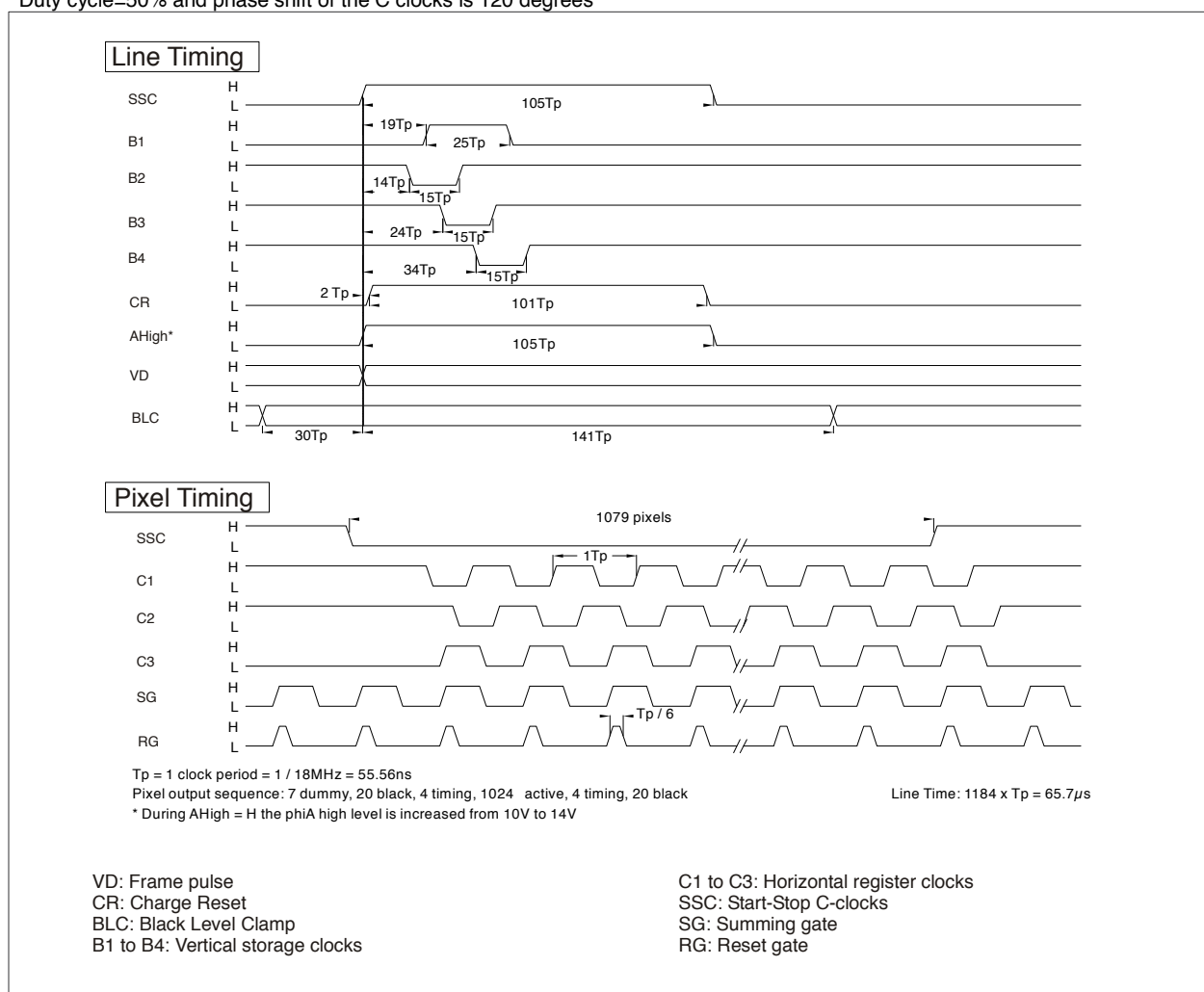
¹ TP=1 clock period² Duty cycle=50% and phase shift of the C clocks is 120 degrees

Figure 3 - Line and pixel timing diagrams

1M Frame Transfer CCD Image Sensor

FTT1010M

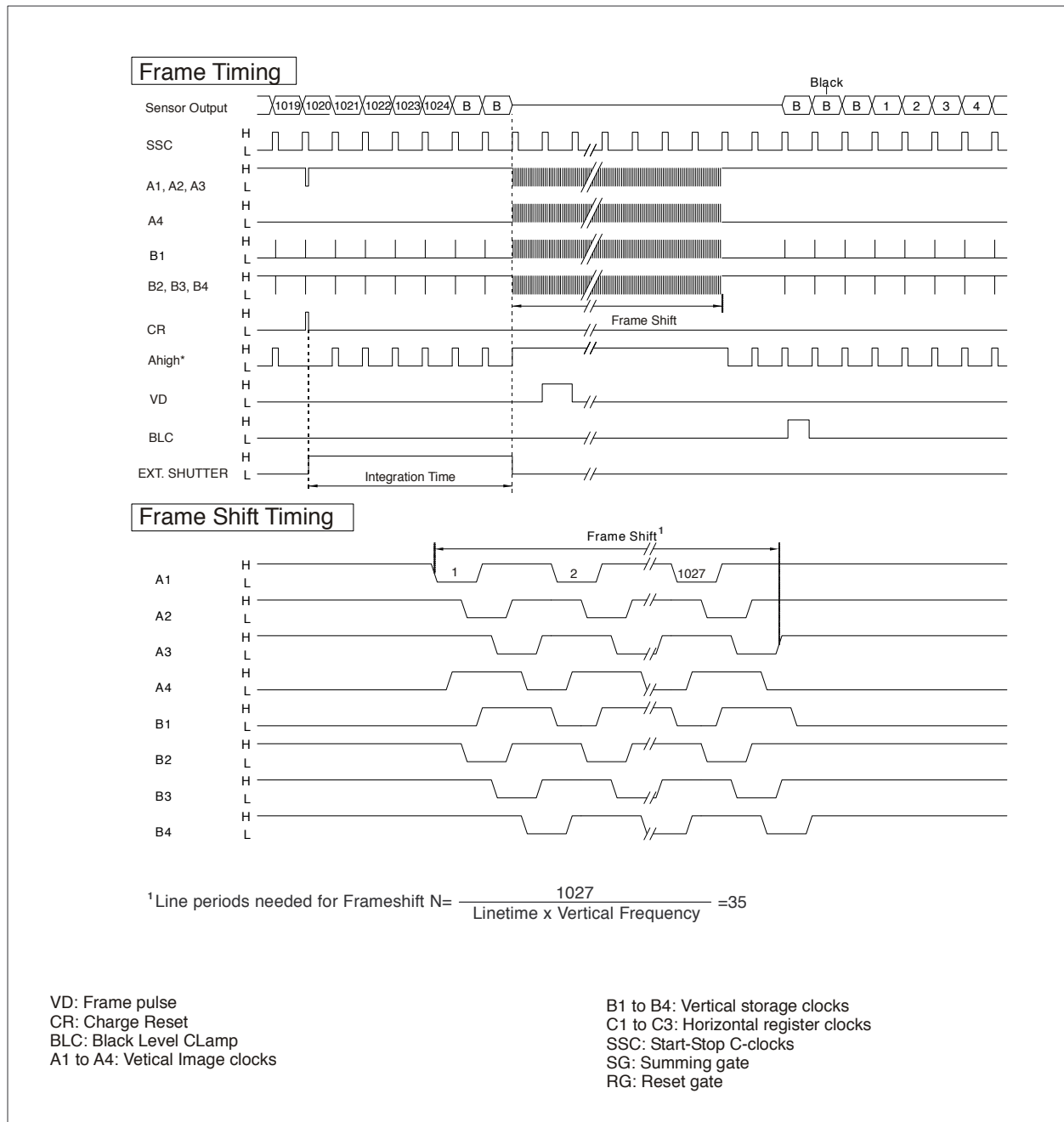


Figure 4 - Frame timing diagrams

1M Frame Transfer CCD Image Sensor

FTT1010M

Line timing

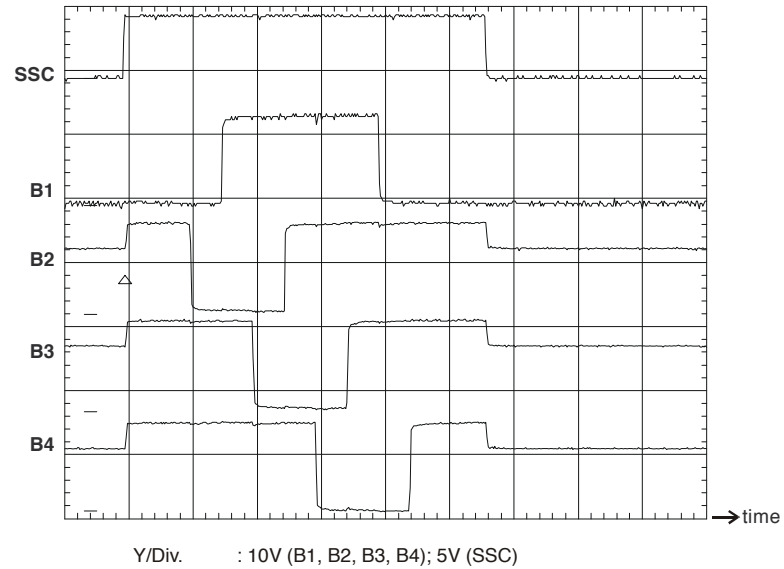


Figure 5 - Vertical readout

Pixel timing

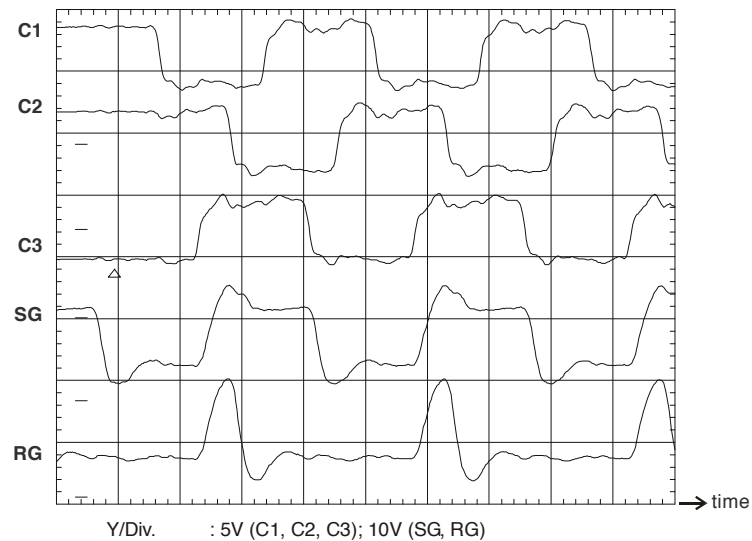


Figure 6 - Start horizontal readout

1M Frame Transfer CCD Image Sensor

FTT1010M

Performance

The test conditions for the performance characteristics are as follows:

- All values are measured using typical operating conditions.
- VNS is adjusted as low as possible while maintaining proper Vertical Antiblooming
- Sensor temperature=60°C (333K)
- Horizontal transport frequency=18MHz
- Vertical transport frequency=450kHz
- Integration time=10ms
- The light source is a lamp of 3200K in conjunction with neutral density filters and a 1.7mm thick BG40 infrared cut-off filter. For Linear Operation measurements, a temperature conversion filter (Melles Griot type no. 03FCG261, -120 mired, thickness: 2.5mm) is applied.

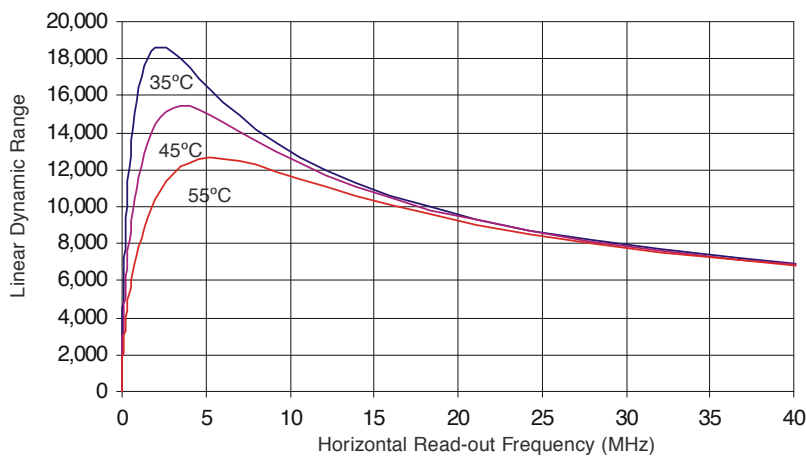
LINEAR OPERATION	MIN	TYPICAL	MAX	UNIT
Charge Transfer Efficiency ¹ vertical		0.999995		
Charge Transfer Efficiency ¹ horizontal		0.999999		
Image lag			0	%
Smear ²		-39	0	dB
Resolution (MTF) @ 42lp/mm	65			%
Light sensitivity	180	250		kel/lux*s
Low Pass Shading ³			2.5	%
Random Non-Uniformity (RNU) ⁴		0.3	5	%

¹Charge Transfer Efficiency values are tested by evaluation and expressed as the value per gate transfer.

²Smear is defined as the ratio of 10% of the vertical transport time to the integration time. It indicates how visible a spot of 10% of the image height would become.

³Low Pass Shading is defined as the ratio of the one- σ value of the pixel output distribution expressed as a percentage of the mean value output (low-pass image).

⁴RNU is defined as the ratio of the one- σ value of the highpass image to the mean signal value at nominal light.



Linear dynamic range is defined as the ratio of Q_{lin} to read-out noise (the latter reduced by Correlated Double Sampling).

Figure 7 - Typical Linear dynamic range vs. horizontal read-out frequency and sensor temperature

1M Frame Transfer CCD Image Sensor

FTT1010M

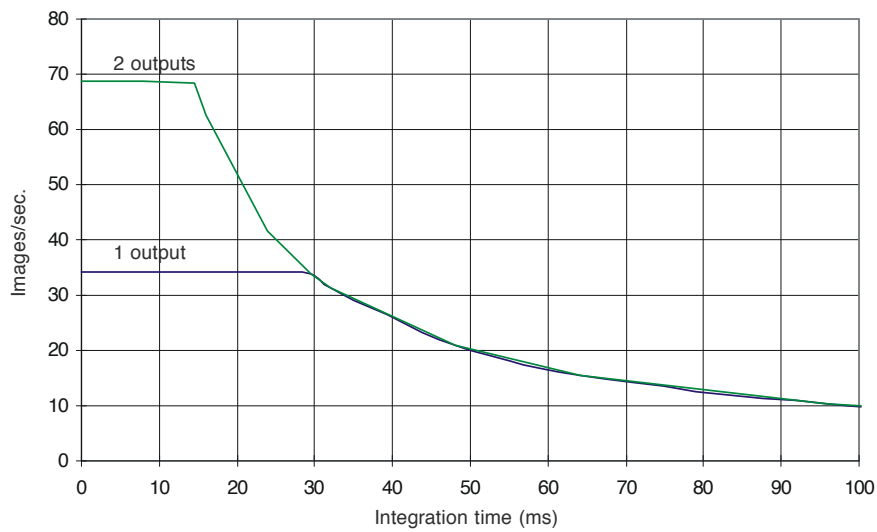


Figure 8 - Maximum number of images/second versus integration time

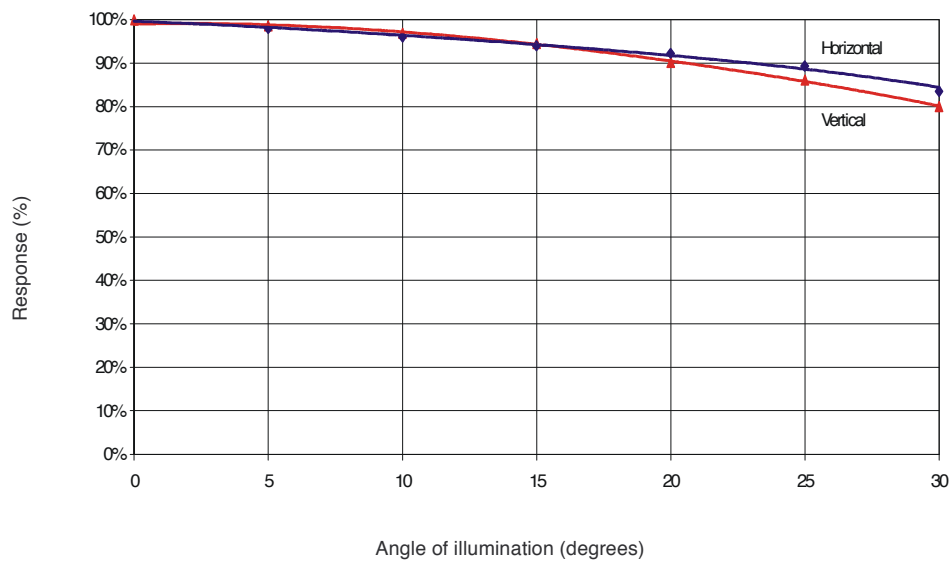


Figure 9 - Angular response versus angle of illumination

1M Frame Transfer CCD Image Sensor

FTT1010M

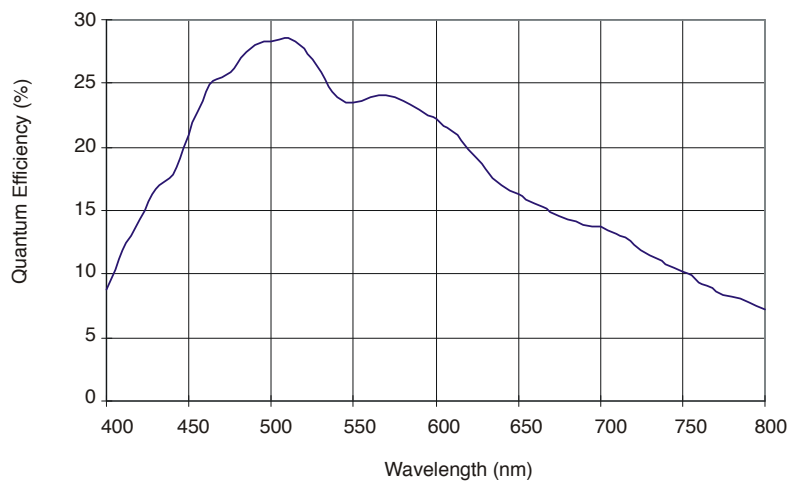


Figure 10 - Quantum efficiency versus wavelength

1M Frame Transfer CCD Image Sensor

FTT1010M

LINEAR/SATURATION	MIN	TYPICAL	MAX	UNIT
Full-well capacity saturation level (Qmax) ¹	250	500	600	kel
Full-well capacity linear operation (Qlin) ²	200	350		kel
Charge handling capacity ³		600		kel
Overexposure ⁴ handling	100	200		x Qmax level

¹Qmax is determined from the low-pass filtered image.

²The linear full-well capacity Qlin is calculated from linearity test (see dynamic range). The evaluation test guarantees 97% linearity.

³Charge handling capacity is the largest charge packet that can be transported through the register and read-out through the output buffer.

⁴Overexposure over entire area while maintaining good Vertical Antiblooming (VAB). It is tested by measuring the dark line.

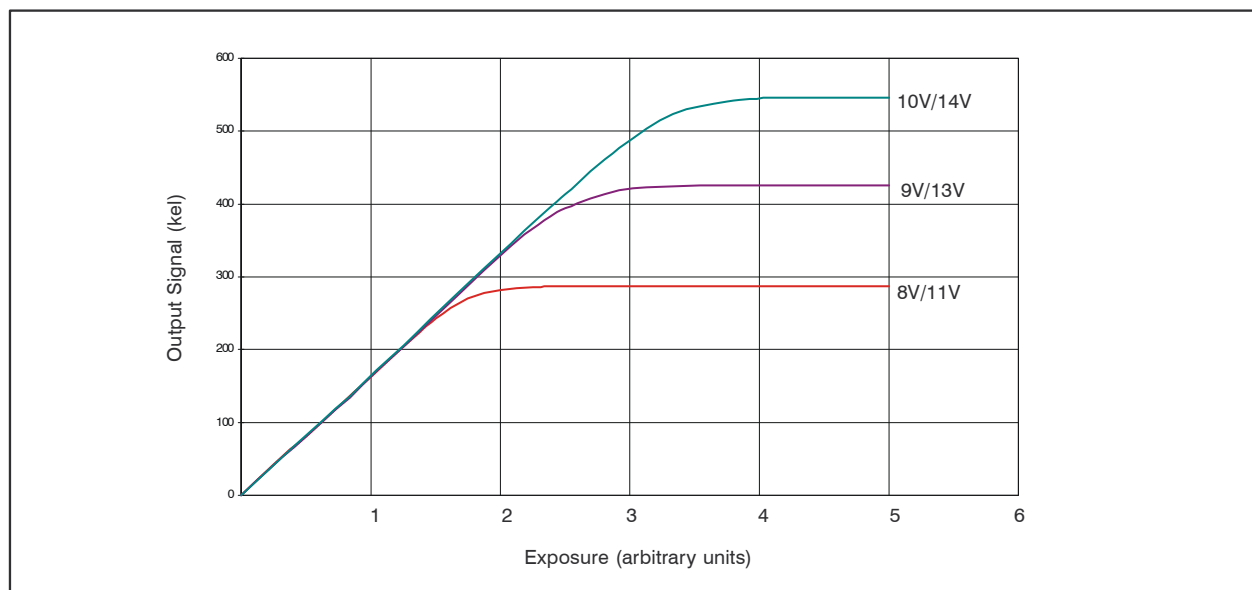


Figure 11 – Charge handling versus integration/transport voltage

1M Frame Transfer CCD Image Sensor

FTT1010M

OUTPUT BUFFERS	MIN	TYPICAL	MAX	UNIT
Conversion factor	6	8	12	$\mu\text{V}/\text{el}$
Mutual conversion factor matching (ΔACF) ¹		0	2	$\mu\text{V}/\text{el}$
Supply current		4		mA
Bandwidth		110		MHz
Output impedance buffer ($R_{\text{load}}=3.3\Omega$, $C_{\text{load}}=2\text{pF}$)		400		Ω

¹Matching of the four outputs is specified as ΔACF with respect to reference measured at the operating point ($Q_{\text{lin}}/2$)

DARK CONDITION	MIN	TYPICAL	MAX	UNIT
Dark current level @ 20°C		10	30	pA/cm^2
Dark current level @ 60°C		0.3	0.6	nA/cm^2
Fixed Pattern Noise ¹ (FPN) @ 60°C		15	25	el
RMS readout noise @ 9MHz bandwidth after CDS		25	30	el

¹FPN is one- σ value of the high-pass image.

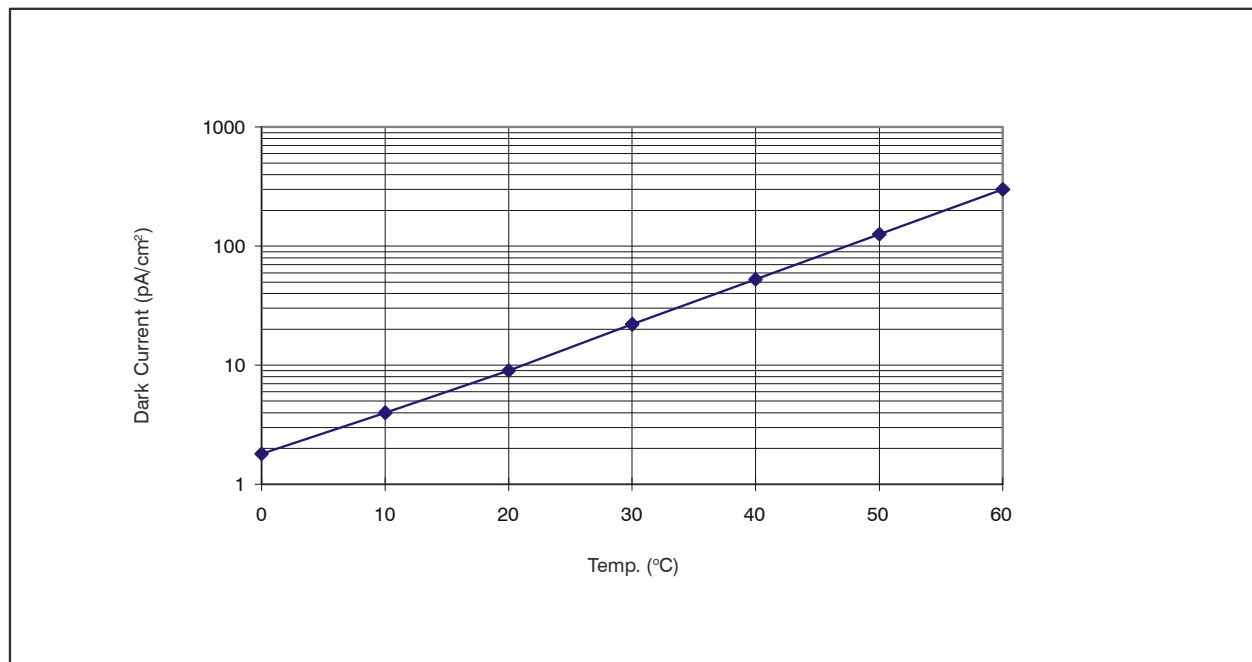


Figure 12 – Dark current versus temperature

1M Frame Transfer CCD Image Sensor

FTT1010M

Application information

Current handling

One of the purposes of VPS is to drain the holes that are generated during exposure of the sensor to light. Free electrons are either transported to the VRD connection and, if excessive (from overexposure), free electrons are drained to VNS. No current should flow into any VPS connection of the sensor. During high overexposure a total current of 10 to 15mA through all VPS connections together may be expected. The PNP emitter follower in the circuit diagram (figure 12) serves these current requirements.

VNS drains superfluous electrons as a result of overexposure. In other words, it only sinks current. During high overexposure, a total current of 10 to 15mA through all VNS connections together may be expected. The clamp circuit, consisting of the diode and electrolytic capacitor, enables the addition of a Charge Reset (CR) pulse on top of an otherwise stable VNS voltage. To protect the CCD, the current resulting from this pulse should be limited. This can be accomplished by designing a pulse generator with a rather high output impedance.

Decoupling of DC voltages

All DC voltages (not VNS, which has additional CR pulses as described above) should be decoupled with a 100nF decoupling capacitor. This capacitor must be mounted as close as possible to the sensor pin. Further noise reduction (by bandwidth limiting) is achieved by the resistors in the connections between the sensor and its voltage supplies. The electrons that build up the charge packets that will reach the floating diffusions only add up to a small current, which will float through VRD. Therefore, a large series resistor in the VRD connection may be used.

Outputs

To limit the on-chip power dissipation, the output buffers are designed with open source outputs. Outputs to be used should therefore be loaded with a current source or more simply with a resistance to GND. In order to prevent the output (which typically has an output impedance of about 400Ω) from bandwidth limitation as a result of capacitive loading, load the output with an emitter follower built from a high-frequency transistor. Mount the base of this transistor as close as possible to the sensor and keep the connection between the emitter and the next stage short. The CCD output buffer can easily be destroyed by ESD. By using this

emitter follower, this danger is suppressed; do NOT reintroduce this danger by measuring directly on the output pin of the sensor with an oscilloscope probe. Instead, measure on the output of the emitter follower. Slew rate limitation is avoided by avoiding a too-small quiescent current in the emitter follower; about 10mA should do the job. The collector of the emitter follower should be decoupled properly to suppress the Miller effect from the base-collector capacitance.

A CCD output load resistor of 3.3Ω typically results in a bandwidth of 110MHz. The bandwidth can be enlarged to about 130MHz by using a resistor of 2.2kΩ instead, which, however, also enlarges the on-chip power dissipation.

Device protection

The output buffers of the FTT1010M are likely to be damaged if VPS rises above SFD or RD at any time. This danger is most realistic during power-on or power-off of the camera. The RD voltage should always be lower than the SFD voltage.

Never exceed the maximum output current. This may damage the device permanently. The maximum output current should be limited to 10mA. Be especially aware that the output buffers of these image sensors are very sensitive to ESD damage.

Because of the fact that our CCDs are built on an n-type substrate, we are dealing with some parasitic npn transistors. To avoid activation of these transistors during switch-on and switch-off of the camera, we recommend the application diagram of figure 12.

Unused sections

To reduce power consumption, the following steps can be taken. Connect unused output register pins (C1...C3, SG, OG) and unused SFS pins to zero Volts.

More information

Detailed application information is provided in the application note AN01 entitled "**Camera Electronics for the mK x nK CCD Image Sensor Family**".

1M Frame Transfer CCD Image Sensor

FTT1010M

Device Handling

An image sensor is a MOS device which can be destroyed by electro-static discharge (ESD). Therefore, the device should be handled with care.

Always store the device with short-circuiting clamps or on conductive foam. Always switch off all electric signals when inserting or removing the sensor into or from a camera (the ESD protection in the CCD image sensor process is less effective than the ESD protection of standard CMOS circuits).

Being a high quality optical device, it is important that the cover glass remain undamaged. When handling the sensor, use fingercots.

When cleaning the glass we recommend using ethanol (or possibly water). Use of other liquids is strongly discouraged:

- if the cleaning liquid evaporates too quickly, rubbing is likely to cause ESD damage.
- the cover glass and its coating can be damaged by other liquids.

Rub the window carefully and slowly.

Dry rubbing of the window may cause electro-static charges or scratches which can destroy the device.

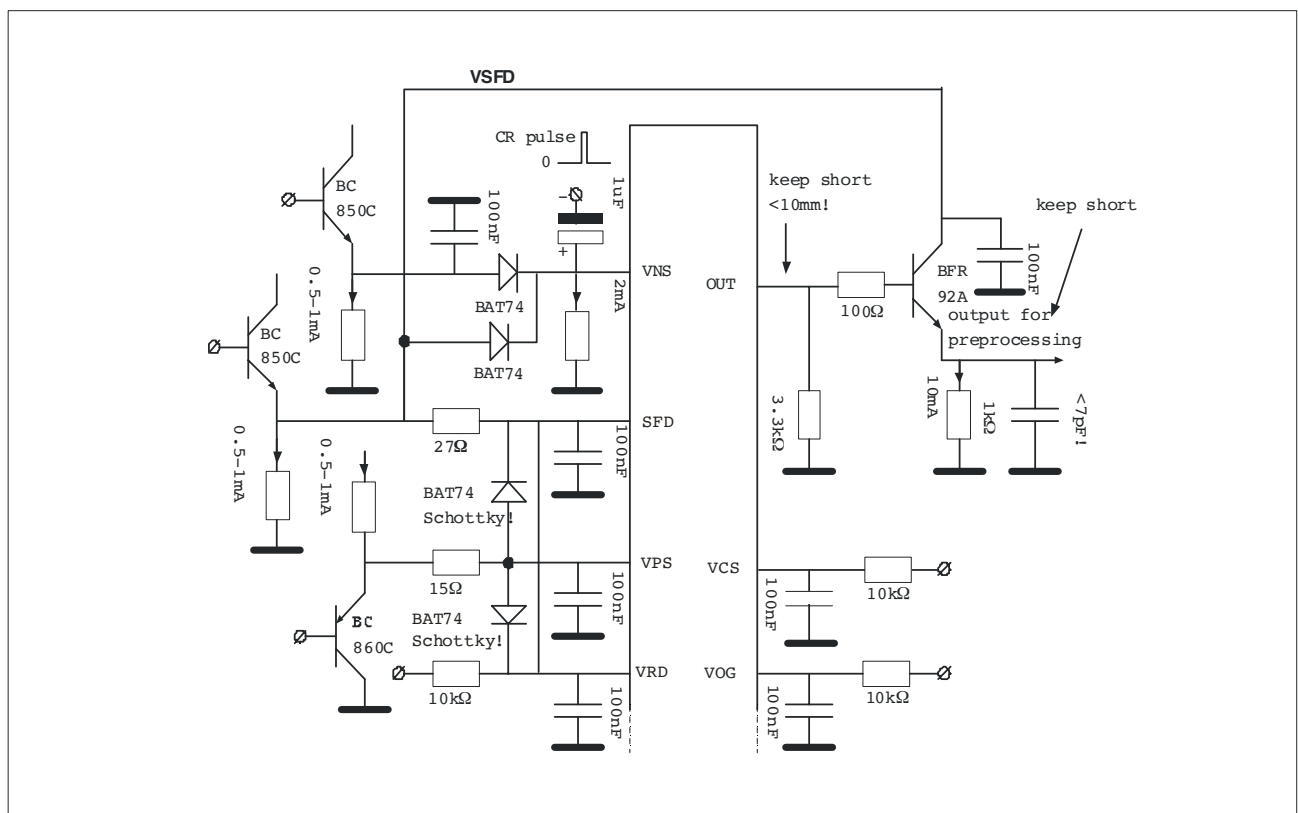


Figure 13- Application diagram

1M Frame Transfer CCD Image Sensor

FTT1010M

Pin configuration

The FTT1010M is mounted in a Pin Grid Array (PGA) package with 80 pins in a 15x13 grid of 40.00 x 40.00 mm². The position of pin A1 is marked with a gold dot on top of the

package. The image clock phases of quadrant W are internally connected to X, and the clock phases of Y are connected to Z.

SYMBOL	LINEAR/SATURATION	PIN # W	PIN # X	PIN # Y	PIN # Z
VNS	N substrate	A12	A3	J2	F11
VNS	N substrate	D11	B2	F3	H12
VNS	N substrate	E11	D3	-	J11
VNS	N substrate	E12	E2	-	-
VNS	N substrate	-	E3	-	-
VPS	P substrate	C11	C3	G3	G11
SFD	Source Follower Drain	A13	A1	J1	J13
SFS	Source Follower Source	A10	B5	J4	H9
VCS	Current Source	A11	A4	J3	J10
OG	Output Gate	B13	B1	H1	H13
RD	Reset Drain	B12	B3	H2	H11
A1	Image Clock (Phase 1)	-	-	F1	F13
A2	Image Clock (Phase 2)	-	-	G2	G12
A3	Image Clock (Phase 3)	-	-	F2	F12
A4	Image Clock (Phase 4)	-	-	G1	G13
B1	Storage Clock (Phase 1)	D13	D1	-	-
B2	Storage Clock (Phase 2)	C12	C2	-	-
B3	Storage Clock (Phase 3)	D12	D2	-	-
B4	Storage Clock (Phase 4)	C13	C1	-	-
C1	Register Clock (Phase 1)	B9	A6	H5	J8
C2	Register Clock (Phase 2)	B8	A7	H6	J7
C3	Register Clock (Phase 3)	A8	B6	J6	H8
SG	Summing Gate	B10	A2	H4	J12
RG	Reset Gate	A9	A5	J5	J9
OUT	Output	B11	B4	H3	H10
NC	Not Connected	B7		H7	

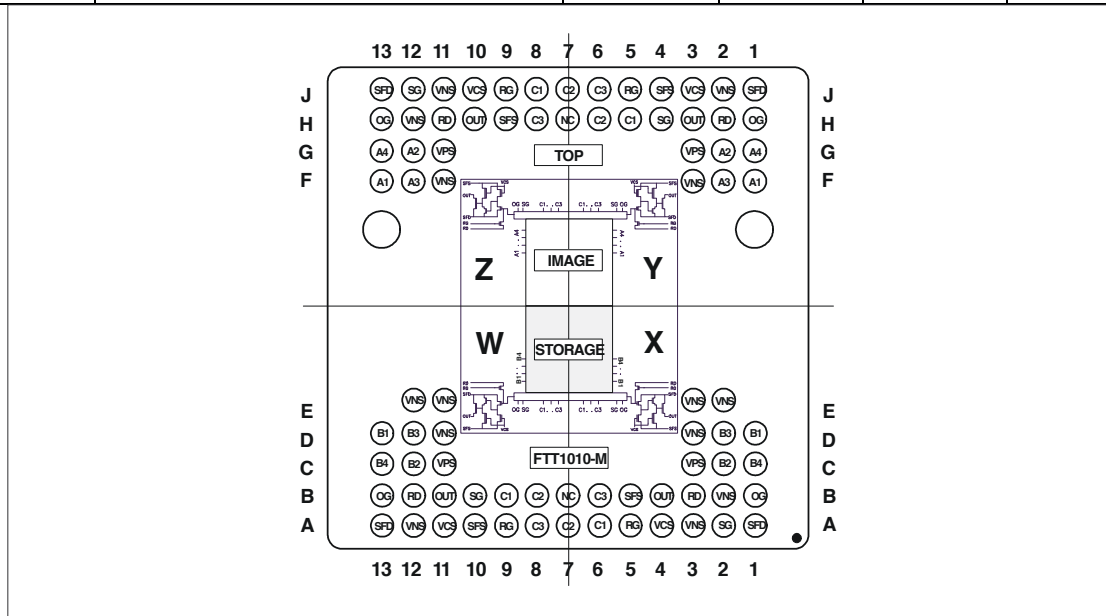


Figure 14 - Pin configuration (top view)

1M Frame Transfer CCD Image Sensor

FTT1010M

Package information

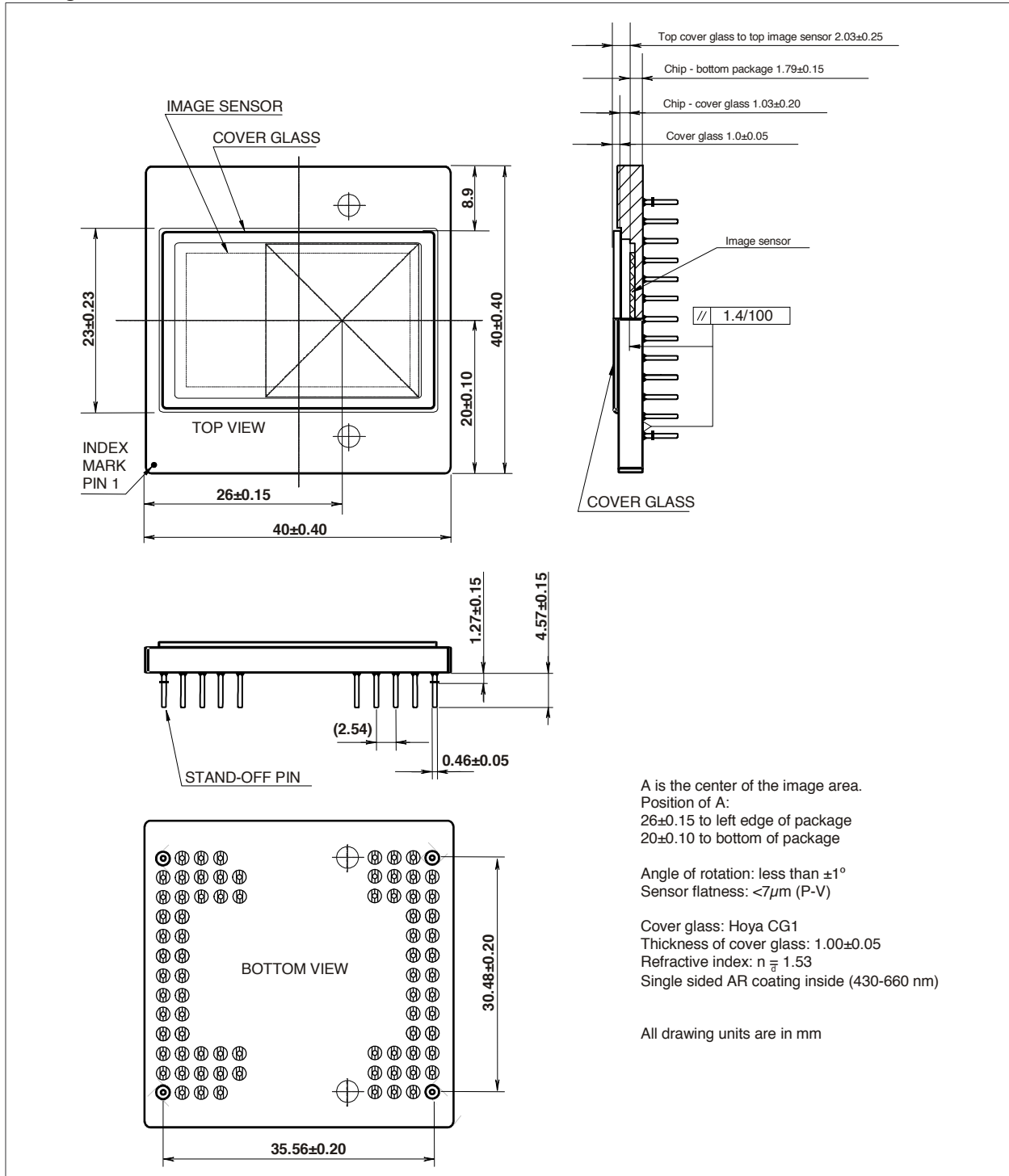


Figure 15– Mechanical drawing of the PGA package of the FTT1010M

1M Frame Transfer CCD Image Sensor

FTT1010M

Order codes

The sensor can be ordered using the following code:

FTT1010M sensors		
Description	Quality Grade	Order Code
FTT1010M/TG	Test grade	9922 157 35231
FTT1010M/EG	Economy grade	9922 157 35251
FTT1010M/IG	Industrial grade	9922 157 35221
FTT1010M/HG	High grade	9922 157 35211

**Defect Specifications**

The CCD image sensor can be ordered in a specific quality grade. The grading is defined with the maximum amount of pixel defects, column defects, row defects and cluster defects, in both illuminated and non-illuminated conditions. For detailed grading information, please contact your local DALSA representative.

For More Information

For more detailed information on this and other products, contact your local rep or visit our Web site at <http://www.dalsa.com/sensors/products/products.asp>.

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This information is subject to change without notice.



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