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Design of an Electro-Optical Imaging Payload for a Small Spacecraft

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Abstract— **Remote sensing satellites require very accurate pointing to specific locations of interest with high resolution and small latency. Therefore, the space imaging systems attempted to achieve the possible highest ground resolution with minimum cost as possible. The most promising prospects for high resolution imaging are connected with passive optical sub-systems, especially push broom one. In this paper, design process of an electro-optical imaging payload is described considering the limited weight and small volume in addition to minimum power consumptions. The electro-imaging payload scanning system is push broom with ground resolution 7.8 meters which operates in three multispectral bands and one panchromatic band at satellite altitude 668 km. The panchromatic band covers a wide spectral range from 500-885 nm. The images of the four bands have to be of the same ground scene. Because of the limited weight of the camera (22.2 kg), the multispectral consists of only one single optical system large F-Number (F5) and provided with spectrum splitter.**

To receive the radiation reflected from the earth surface, a linear CCD array will be used which has more than 6000 pixels with a square pixel elements of 10*10 microns, so it is equivalent to 46.8 km across track direction and 7.8 m along track direction on the ground.

***Keywords*: MTF, SNR, push broom, detector, imaging payload.**

I. INTRODUCTION

High resolution mapping system follows the trend to smaller Ground Sample Distance (GSD). The increasing number of sp[ace borne imaging systems in the last decade [1] shows that an increasing numbers of countries are dealing with space borne technology and that there an increasing need for mapping systems for different applications [2].

In this paper we consider a GSD of 7.8 m as an enhanced microsatellite according to the Study Cost-Effectiveness Earth Observations Missions [3].

Smaller GSD needs larger focal lengths. The physics behind optical systems allows only a restricted number of tricks to overcome the problems of large focal length optics in terms of volume and mass. The size of the focal plane depends on the detector system size and is part of the equation concerning optics, volume and mass.

Some parameters of previous kinds of similar remote sensing cameras in comparison of the camera of satellite EgyptSat-1 are shown in Table 1.

Satellite	**Spatial Resolution (m)**	**Spectral Bands (nm)**	**Swath (km)**	**Weight (kg)**
Land Sat 8				
MSS	60	4 (500-1100)	185	64
TM	30	7 (450-2350)	185	243
SPOT (HRV)				
MSS	6.0	4 (450-890)	60	250
PAN	1.5	1 (450-745)		
EgyptSat-1				
MSS	7.8	3 (500-885)	46.8	22.2
PAN	7.8	1 (500-885)		

Table 1: Some parameters of the MS (Multispectral) cameras of different Satellites

The digital Pan & multispectral camera consists of 4 main subsystems; the optical system, spectrum splitter, the focal plane equipment and the electronics. The Schmidt cassegrain optical system includes some lenses, mirrors and others which have to be designed in some parameters such as radius of curvature, separation between lenses and mirrors, thickness of the lenses elements and etc.

The focal plane equipment has two main parts has four similar linear array detectors; each detector has more than 6000 pixels with a square pixel elements 10*10 microns. Each CCD linear detector is fixed at the focal plane and the continuous scanning method of the ground scene with a swath width 46.8 km with speed about 7.5 km/sec.

The main specifications of the CCD camera are shown in table 2.

Parameter	Value
Ground resolution	7.8 m
Swath Width	46.8 km
Panchromatic band	500-885 nm
Spectral bands	500-590 nm 605-680 nm 785-885 nm
Orbital altitude	668 km

Bite rate for each band	46.08 Mb/sec.
Power Consumption	70 Watts

Table 2: Main specifications of the CCD camera of Satellite EgyptSat-1

II. DESIGN OF AN ELECTRO-OPTICAL PAYLOAD

Electro-Optical payload design process consists of:

1. Determine Mission Requirements,
2. Select preliminary aperture,
3. Determine target radiance,
4. Choose detector candidates,
5. Optical Link Budget, SNR considerations,
6. Determine Focal Plane architecture and scanning schemes,
7. Select F# and Optical System design,
8. Complete preliminary design and check MTF,
9. Determine Test Equipment Requirements.

Determine Mission Requirements

Figure (3) shows that the Earth surface illumination when the wave length equal 0.4 microns is almost 30%, less than when wave length equal 0.5 microns, and the atmospheric fog brightness is 10-15% and atmospheric fog brightness for different Sun angles above horizon.

The atmospheric fog influences the quality of the received image, as it reduces the general contrast of the image and signal/noise ratio. This leads to the details of low contrast regions in the image.

Another important reason for the choice of the spectral band region is according atmospheric coefficient.

Determine aperture diameter

The aperture is the opening in a camera that allows light to expose the sensor (film, CCDs…). The amount of light that gets through the aperture determines what an image will look like. The larger the aperture, the more light it collects and the brighter (better) image will be. Greater detail and image clarity will be apparent as aperture increases. Aperture diameter is determined by:

$$D = 2.44\ \text{Wave length}.\ f.\ Q / d$$

where Q is quality factor. Quality factor is the ratio of pixel size to diameter of diffraction disk D_{Airy}, defined as: $Q = d / D_{Airy}$. Q typically varied between 0.5 and 2.

For $Q < 1$, the resolution is limited by diffraction in optics, while for $Q > 1$, the resolution is limited pixel size. As a starting point for the design, select $Q = 1$.

Determine target radiance

Target radiance is the total amount of received spectral radiance of the target at the orbital altitude (H). It can be calculated by using the different parameters such as: the solar / lunar spectral radiance at orbit altitude (H) from the earth surface or target, the atmospheric transmittance in the path (target to sensor), spectral reflection coefficient of target, and the sum of the multiple scattered solar and atmospheric emitted radiance into the path.

Detectors

The easiest for realizing is scanning of the systems based on the multi-element linear photo detector, for example linear CCDs, photographic plate. In this case equipment via an axle is directed to the Earth, usually to the nadir. The linear photo detector (CCDs) of the camera is situated vertically to the flight direction. Scanning and electrical signals reading is performed in series from all the elements of the photo detector line and then a new period storage and reading begins.

III. TECHNICAL SPECIFICATIONS

As it is mentioned above, instead of having different cameras for each spectral bandwidth, a common optical system with a beam splitting system is used. Thus, because it is required four spectral bandwidths, we are obliged to use four detectors.

A Schmidt Cassegrain optical system is favored because the focal length is large and the field of view is also large to use a reflective system. Hence by the choice of a high speed Schmidt Cassegrain objective, the size and weight of the system is more compact.

In multispectral CCD camera the single optical system comprises of the followings:

- Primary and Secondary mirrors that collect beams reflected from the imaged object to form image at system focal plan.
- Primary and secondary compensators that compensate aberrations.
- A thermo-baro compensator corrects for defocusing the whole system.
- Baffles immune a system against the direct stray rays.

The number of lenses depends on the design of optical system to reduce aberration as much as possible in order to have better image quality.

As discussed above, when the light passes through the optical system, it is distributed into four spectral bands by the beam splitter system. Then they are directed to focus on four similar CCD line arrays. The CCD elements produce electric charges as they are exposed to light. These electrical charges are proportional to the amount of light illumination that appears as analogue voltage. The analogue voltage has to be sampled to be converted into digital data using ADC circuitry associated to the CCD chip. Then after data compression, it is ready to be transmitted by the data transmission system. According to the required specifications, some parameters have been calculated and the results are shown in table 3.

Parameter	**Value**

Number of the CCD's pixels	➢ 6000 pixels
Pixel size	10 *10 microns
FOV = Field of View	4° 7'
IFOV = Instantaneous of Field of View	12 mic.rad
Focal length	860 mm
F-number	5.5
The operating spatial frequency=500/(10*2)	25 lp/mm

Table 3 some calculated parameters

One of the most important parameters of optical system is F-number. It is the ratio of the focal length to the entrance of pupil effective diameter. It limits the amount of incident light entering the optical system and consequently determines the illumination in the image focal plane. Because of the limitation of camera weight, we have to choose an F-number as large as possible so that it decreases the illumination in the focal plane. Thus the optical system design has to be optimal to achieve the best image quality and high signal to noise ratio (having smallest amount the beam losses by using special glasses and highest sensitive detectors).

IV. OPTICS

The focal length of high resolution space systems is determined by the physics laws and they have more weight and volume that is not appropriate for small satellites concept. Even if we can design a camera having a weight compatible to a micro- satellite spacecraft, the volume of optical system for high resolution space imagers is a problem; therefore we were obliged to extend the satellite to enhanced micro-satellite spacecraft category. The progress in production of optical systems and its testing facility enables now the utilization of highly efficient low mass and volume optical telescopes for space missions. That progress can be briefed in the followings:

- Using of aspheric lenses in refractive telescopes,
- Using of folded arrangements for reflective telescopes (for example TMA),
- Using of sophisticated catadioptric telescopes.

Presented Schmidt Cassegerain high-resolution objective achieved the following specifications;

Specifications	Value
Focal length	860.132 mm
Back Focal length	110.7 mm
Effective Entrance Pupil Diameter	155.685 mm
Distortion at FOV	0.11%
FOV	4°
Total length	367.47 mm
Effective Screening Coefficient	0.409

V. DETECTOR

For mapping purposes the Pixel size of the detector is projected via the focal length to the ground pixel size, the smaller the detector element x the smaller the focal length f to obtain the same ground pixel size. The smaller the detector size, the less energy is obtained; if the sensitivity of the pixel element is not sufficient to obtain the required SNR, TDI is necessary to be applied otherwise to keep the pixel size that is capable to obtain the required SNR.

Impact of staggered configurations – Volume and mass of optics depends significantly not only on the focal length and aperture, but also on the size of the image field that is determined by the detector extensions. Using staggered line arrays for the detector and high quality optics, each of the detector length and the focal length can be halved as HRS camera payload in SPOT-5 Satellite.

VI. DATA VOLUME AND TRANSMISSION RATE

The required data rate for imaging payloads depends on the resolution, covering area, accuracy and number of detectors. When the satellite is in low-Earth orbit, the satellite motion itself allows easy scanning of the earth in the orbit plane. A separate mechanism in the sensor scans perpendicular to the orbit plane. The sensor generates an image composed of minimum resolvable elements called pixels. If the resolution element's diameter on the ground is d meters, directly below the satellite, the pixel size is d/h radians where h is the satellite's altitude. The width of the sensor's scan angle, perpendicular to the satellite orbit is $Ø_x$ in radians [9].

The data rate, DR, generated by the sensor is:

$$\mathrm{DR} = \frac{Ø x V h s b}{d 2\ q}$$

Where: $Ø_{:}$ width of the sensor's scan, perpendicular to satellite's altitude in radians,

V : satellite's ground track speed, d: minimum diameter of pixel image projected on ground,

h : satellite's altitude, S : number of samples per pixel

b : number of bits per sample (2b amplitude levels),

q : frame efficiency fraction of time for data transmission (typically 0.90 to 0.95).

VII. VOLUME AND POWER CONSUMPTION

For mapping purposes, the pixel size of the detector is projected via the focal length onto the ground pixel size. The smaller the detector elements x, the shorter the focal length can be implemented. Impact of staggered – Volumes and mass of optics depends significantly not only on the focal length and aperture, but also on the image field size determined by the detector extensions.

Using staggered line arrays, the following effects occur:

- Length of line detector is reduced,
- Focal length can be halved,

- Optics need to be high quality for twice as many line pairs per millimeter necessary for the pixel size.

Staggered CCD-line arrays are used for instance in the SPOT 5 mission cameras HRS.

The progress in microelectronics has enabled more sophisticated equipment designs. The key to realize the reductions in mass, power and volume lies in utilization of industry- based microelectronics packing technologies, including:

- Multichip module technology (MCM),
- Three- dimensional MCM stacking,
- Die Stacking for memory.

The advanced microelectronics packing technologies have been widely used. The effects have been remarkable. Therefore, in future design the camera weight, volume and power consumption would be more less [10].

VIII. MODULATION TRANSFER FUNCTION (MTF)

Some major features are considered that influence the image quality from the spatial resolution point of view. A very effective way to describe the image quality is to use the MTF approach by multiplying all the image quality influencing MTF components of a linear system (or quasi linear system). The total MTF for the electro-optical camera can be estimated which may base on different effects (such that optics, CCD,…) in order to have the system MTF [5].

In general there are 3 factors determining MTF of multiple-unit receiver on CCD basis:

- Geometry MTF determined by the photo sensitive element size and pitch between them,
- Diffuse MTF given by spectral dependency of the silicon absorption and further charge diffusion spread,
- MTF determined by inefficiency of charge transfer in the register.

MTF geometrical multiply is as follows:

$MTF_g(v) = \sin(\pi . v . d) / \pi . v . d$

Where d is the pitch between elements,

v is the spatial frequency

CCD MTF at Nyquist frequency (50cycles/mm) for narrow-band irradiation sources are as follows: Transfer Function becomes worse a little as in table 4

No.	Wavelength, mm	MTF
1	550	0.6
2	650	0.5
3	725	0.4
4	800	0.3
5	900	0.24

Table 4: CCD MTF at Nyquist frequency (50 cycles/mm)

IX CONCLUSION

The presented paper showed the problems related with imaging payload design. This paper deals with important parameters for imaging payload (for remote sensing satellites) such as, spatial resolution, MTF, SNR, pointing accuracy and stability.

Our schedule was processed in different stages such as mission definition, mission requirements, preliminary design, optically and electronically systems design, laboratory experiments, fabrication and quality control.

The design and performance evaluation the imaging payload for the remote sensing satellites technology has been described. It has been done on top-level system performance requirements and proposed approach for this purpose based on SNR detection and MTF analyses. The imaging payload design was designed as push broom scanner flying in a sun-synchronous polar orbit of 668 km altitude and ground resolution (GSD) 7.8 m for the panchromatic band and the three multispectral bands.

REFERENCES

[1] Jacobsen, K., "High Resolution Satellite Imaging Systems – an Overview." *PFG 6L2005, 487-496*.

[2] Segert, T., DAnziger, B. and Geithner, M, “The Dobson Space Telescope – A time shared Telescope for VEO and Earth Observation , “Paper IAA-B4-0605 of the fourth International IAA Symposium on small satellites for Earth Observation , April 7 -11, 2003, Berlin , German.

[3] Kramer, H. J. , “ Observation of Earth and its Environment – Survey of Missions and sensors“, 4th edition , Springer, Heidelberg, New York 2002.

[4] Warren, J. Smith, *Modern Optical Engineering*, McGraw-Hill, 1990.

[5] www.ee.surrey.ac.uk/Research/CSER/UOSAT/papers/icdsc_ws/

[6]www.rosa.ro/romanian/documents/Volum/Session3/MN_SWEETING.htm

[7] Pedrotti, Frank L. and Pedrotti, Leno S., *Introduction To Optics*, Prentice-Hall PTR, 1996.

[8] Hecht, Eugene and Zajac, Alfred, *Optics*, Addison- Wesley Pub. Co., 1974.

[9] Holst, G. C., “Electro-Optical Imaging System Performance”, SPIE Optical Engineering Press 1995.

[10] Alkalai, L. And Davison, J. (Eds), "Measure Network-Integrated Microelectronics Study” Final Report, JPL D-11192, January 7, 1994.

[11] Richards, O.W., *Consideration of Physical Optics, Optical Design*, Military Standardization Handbook, Defense Supply Agency Washington 25, D.C., 1962.

[12] Melles Griot Catalog, *Optics, Opto-Mechanics, Lasers, Instruments*, 1995/96.

[13] Larson, Wiley J. and Wertz, James R., *Space Mission Analysis and Design*, Second Edition, Microcosm, Inc. & Kluwer Academic Publishers, 1992.

[14] Kawada, Y., Takami, Y., Matsumura Y. and Fujita, T., *New Micro Satellite Concept For Observation Missions*, Acta Astronautica Vol. 46, Nos. 2-6, pp. 159-167, 2000.

[15] Royal Meteorological Institute of Belgium: Department of Aerology,http://remotesensing.oma.be/RadiometryPapers/article2.html, 2002.

[16] http://www.geol.vt.edu/profs/jas/pdf/4101-heat.prof, October 2002.

[17] http://www.earthmatrix.com/sciencetoday/solar-constant.html, July 2002.

[18] http://www.valdosta.edu/~grissino/

[19] Richards, John A., *Remote Sensing Digital Image Analysis An Introduction*, Springer-Verlag Berlin Heidelberg, 1986.

[20] Underwood, Craig and Unwin, Martin, *Spacecraft Design Project*, Lesson Notes University of Surrey Center for Satellite Engineering Research.

[21] Mende, S. B., Heetderks, H., Frey, H.U., Lampton, M., Geller, S. P., Abiad R., Siegmund, O.H.W., Tremsin, A.S., Spann, J., Dougani, H., Fuselier S. A., Magoncelli, A. L., Bumala, M.B., Murphree, S. and Trondsen, T., *Far Ultraviolet Imaging From The Image Spacecraft. 2. Wideband FUV Imaging*, Space Science Reviews 91: 271-285, 2000.64

[22] Holst, Gerald C., *CCD Arrays, Cameras, and Displays*, SPIE Optical Engineering Press, 2nd Edition, 1998.

[23] Berry, Richard, *Choosing and Using a CCD Camera*, Willmann-Bell, Inc., 1992.

[24] ZEMAX Optical Design Program User's Guide Version 10.0, Focus Software, Inc., http://www.focus-software.com, 1990-2001.

[25] Walter, Ingo and Schönekeß, Jörg, *Application Of Micro-Mechanic Devices For Motion Compensation of Space-Borne CCD- Imaging Systems*, Acta Astronautica Vol. 46, Nos. 2-6, pp. 269-277, 2000.

[26] Ciccarelli, A., Davis, B., Jardin, W. Des, Doan, H., Meisenzahl, E., Pace, L., Putnam, G., Shepherd, J., Stevens, E., Summa, J. and Wetzel, K., *Front-illuminated full-frame charge-coupled device image sensor achieves 85% peak quantum efficiency*, Eastman Kodak Company, Rochester, NY 14650-2010, 1999.

[27] Schroeder, Daniel J., *Astronomical Optics*, Academic Press, 2nd Edition, 2000.

[28] Richards, E. Hopkins, Hanau, Richard, *Aberration Analysis And Third Order Theory*, Military Standardization Handbook, Defense Supply Agency Washington25, D.C., 1962.

[29] Fischer, R. E., *Optical Design: Principles of Optical Systems Layout*, SPIE The International Society for Optical Engineering, 1993.

[30] Goody, Richard M. and Yung, Y.L., *Atmospheric Radiation Theoretical Basis*, Oxford University Press, 2nd Edition, 1989.

[31] Melles Griot Catalog, *The Practical Application of Light*, 2000.

[32] Spindler & Hoyer Catalog, *Precision Optics*, 1989.