SYSTEM DESIGN ASPECTS OF A SPACEBORNE WIDE-ANGLE OPTOELECTRONIC STEREO SCANNER

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Commission I, Working Group 3

KEY WORDS: Spaceborne Sensor, Optical Sensor, Stereo Imaging, Camera System Design

ABSTRACT

Three line stereo scanners working in push-broom mode are of high interest for future remote sensing camera developments. This contribution deals with some basic considerations concerning the geometric, spectral, and radiometric design of such a camera. These considerations are applied to the design of the Wide-Angle Optoelectronic Stereo Scanner WAOSS for the Russian mission Mars-96 (Bild&Ton, 1992), (Sandau, 1994). For this stereo camera the essential components as optics, filters, CCD line arrays, analogue and digital signal processors are derived.

INTRODUCTION

Because it is easier to build long CCD line arrays with a large number of elements than CCD matrices with similar features in two dimensions, push-broom scanners will play an important role for spaceborne cameras. According to this type of camera design the stereo information will be generated within the image plane of a single objective by means of three CCD lines (see figure 1).

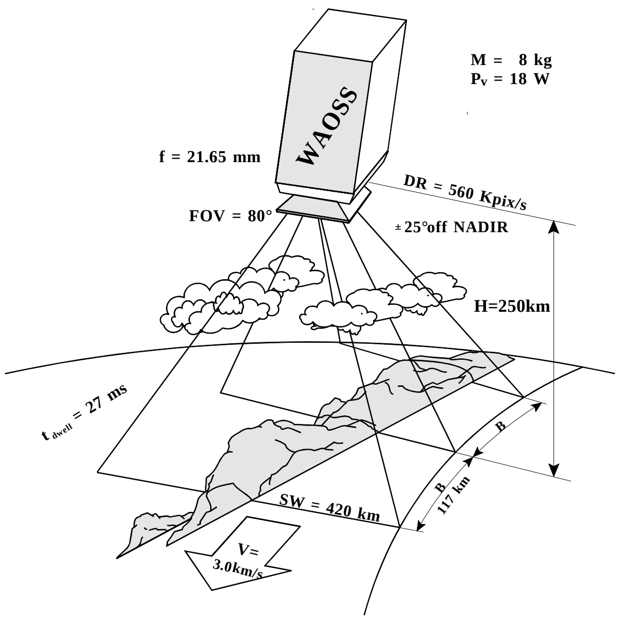

Figure 1: WAOSS Stereo Imager-Principle

Due to the movement of the satellite with the camera, each of these lines senses a certain object or area with a given time shift and under a different viewing angle. However, the time shift is so small that the illumination conditions may be considered constant. Such three line scanners may be used for topographic mapping from space based platforms. For this type of cameras special design considerations have to be taken into account from the systems point of view. Looking at all essential aspects, an over all system optimization may be achieved due to the derivation of the necessary component like optics, filters, CCD line arrays, analogue and digital signal processors meeting the actual scientific requirements with the actual available high end technology. This contribution describes the essential design aspects in terms of geometric, radiometric, and spectral relations for observation fulfilling the scientific requirements. As an concrete design example serves the Wide-Angle Optoelectronic Stereo Scanner WAOSS to be used in the Russian Mars-96 mission.

SCIENTIFIC OBJECTIVES

The most important requirements to the camera are to be derived from the scientific objectives. These scientific requirements have to be met under the actual orbit conditions. In the case of the mission Mars-96, it will be a highly elliptical orbit which results in the necessity of the real-time control of the position dependent camera parameters. These camera parameters are for instance the altitude dependent ground resolution which should be kept constant over a wide altitude range by pixel binning (electronic zoom), or the velocity dependent imaging (integration) time. For simplification, in this contribution these conditions are reduced to the circular orbit conditions. The primary task of WAOSS is to globally image the planet Mars with a ground resolution of a few hundred meters. The main emphasis of this camera is on broad surface coverage, rather than on high spatial resolution. So WAOSS shall be capable of global topographic mapping as well as imaging temporal changes in the atmosphere and on the surface. The planned mission duration of one Martian year (about 2 Earth years) will enable observation during all of the Martian seasons. Therefore, seasonal and weather related changes at the Martian surface (e. g. ice coverage, albedo patterns) and the generation and propagation of clouds and dust storms can be investigated. In the case of WAOSS, there are three major objectives.

1. Synoptical imaging of the dynamics in the Martian atmosphere and on the surface with a ground pixel sizes of 1000 m x 1000 m.

2. Global topographic mapping of the Mars with ground pixel sizes as small as possible.

3. Such a synoptical imaging camera is also used to support the data interpretation from other remote sensing instruments like the Planetary Fourier Spectrometer PFS and Thermoscan.

REQUIREMENTS ON THE SENSOR SYSTEM

The camera has to meet a number of requirements coming from the spaceborne experiment situation. First of all, it has to be very robust to withstand the launching stresses in the mechanical-dynamic sense as well as in the thermal sense. Moreover, there are some other requirements which have strong influence on the systems concepts like:

- Minimum mass and volume
- Minimum power consumption

High reliability because maintenance and repair are impossible.

All the aspects mentioned have to be taken into account in the whole design process. In the following parts we will only come back to these aspects if it has essential influence on the component selection or system optimizing process.

GEOMETRIC DESIGN OF THE 3 LINE STEREO SENSOR SYSTEM

The geometric design aspects of a three line scanner are strongly related to the scientific requirements. They have influence on

- the CCD array selection,
- the design of the focal plate module,
- the lens design, and
- the electronics design.

1. CCD selection

The first step in the geometric design process are the considerations which lead to the selection of suitable CCD line arrays. In our case we have two requirements to be considered:

- small pixel size to allow as high as possible ground resolutions in the topographic mapping mode
- large pixel number to allow a large field of view FOV.

The Thomson THX 7808B is a good compromise with

- a pixel size = 7 µm x 7 µm
- pitch (pixel distance) ξ = 7 µm
- number of active pixels npix = 5184

The active line length of $d = npix \cdot \xi = 36.288$ mm allows to select a lens from usual picture size camera lenses.

2. Parameters for optics and focal plate design

To determine the focal length f, we can use either the necessary field of view FOV or the ground pixel size X as the input parameter. Using

the ground pixel size x = 80 m,
the orbit altitude H = 250 km,
and the convergence (stereo) angles $\gamma = \pm 25°$

as input parameters, we can derive the optics parameters

- focal length

$$f = \xi \cdot \frac{X}{H} = 21.7 \text{ mm} \qquad (1)$$

- instantaneous field of view

$$IFOV = 2 \cdot \arctan\left(\frac{X}{2H}\right) = 0.32 \text{ mrad} \qquad (2)$$

- field of view

$$FOV = 2 \cdot \arctan\left(\frac{d}{2f}\right) = 80° \qquad (3)$$

- and total field of view

$$TFOV = 2 \cdot \arctan \sqrt{\tan^2\gamma + \tan^2\frac{FOV}{2}} = 87.7° \qquad (4)$$

Related to the FPM we obtain

- distance of the stereo CCD lines from the nadir looking CCD line

$$D = f \cdot \tan\gamma = 10.1 \text{ mm}, \qquad (5)$$

which leads to the photo active FPM area of

$$2D \cdot d = 20.2 \text{ mm} \cdot 36.3 \text{ mm} \qquad (6)$$

With the now known values, the ground related parameters are

- swath width

$$SW = H \cdot \frac{d}{f} = 420 \text{ km} \qquad (7)$$

- basis length (distance of two successive CCD line projections on the ground)

$$B = H \cdot \frac{D}{f} = 117 \text{ km} \qquad (8)$$

- achievable height resolution

$$\Delta Z \approx \frac{1}{C} \cdot X \cdot \frac{f}{2D} \geq 1.1 \cdot X \qquad (9)$$

with

$0 \leq C \leq 1$ the scene dependent correlation factor.

3. Parameters for electronics design

To derive the parameters necessary as inputs for the electronics design, we have to take into account the actual planetary data, in our case the Mars related data

$R_o = 3394$ km (Mars radius)

$M_o = 0.64 \cdot 10^{24}$ kg (Mars mass)

$G = 6.67 \cdot 10^{-11} \frac{m^2}{kg \cdot s^2}$ (gravitational constant)

With these input parameters we obtain

- orbit period

$$T = 2\pi\sqrt{\frac{(R_o + H)^3}{G \cdot M_o}} \approx 1.9\ h \qquad (10)$$

- ground track velocity

$$v = \frac{2\pi \cdot R_o}{T} = 3.1\ \frac{km}{s} \qquad (11)$$

dwell time (time between two successive ground pixels)

$$tdwell = \frac{x}{v} = 25.8\ ms \qquad (12)$$

- data rate from the FPM (n CCD = 3 is number of CCD lines)

$$DR = \frac{nCCD \cdot npix}{tdwell} \approx 600\ Kpix/s \qquad (13)$$

- minimum observation time to obtain the stereo information for one basis length (T_B is time to fly over one basis length)

$$T_{3D} = 3 \cdot T_B = 3\ \frac{B}{v} = 113\ s \qquad (14)$$

- data volume for the 3D information of one basis length

$$V_{3D} = DR \cdot T_B = 67.8\ MPix \qquad (15)$$

THE SPECTRAL DESIGN

The spectral design of the sensor system is determined by the spectral requirements. For the wide angle investigation of the Mars they are characterized above all by

- spectral range: - visible and near infrared, the high red reflectance range of the Martian surface should be included,
  - different for nadir and stereo line for real-time cloud detection,
  - center wavelength of stereo line at 690nm (identical to channels of the High Resolution Stereo Camera HRSC)
- bandwidth: panchromatic, about 200nm,
- characteristics: steep edges desirable (close to rectangular).

The spectral design is an iterative process with several loops to meet all requirements under the given technological constraints. There are three main phases of this process:

1. filter pre-selection by evaluation of catalogue values (first approach)
2. modelling of the spectral system response (includes the spectral characteristics of optics, filters and sensors)
3. fine tuning of bandwidth, center wavelength and spectral system response.

For the filter pre-selection one has to distinguish between glass filters and interference filters. A very rough rule of thumb could be: for narrow bandwidth requirements use interference filters and for wide-angle Field-of-Views use glass filters. Tab. 1 gives an overview over the advantages and drawbacks of the two general kinds of filters.

For the WAOSS camera only glass filters are feasible because of the wide incidence angle on the filters. A combination of infrared filter (KG1) with a blue (BG38) and a red filter (OG570), respectively, are used. The infrared filter protects the CCD from unwanted charge generation and the blue or red filter gives the desirable spectral characteristic for cloud detection.

The modelling of the spectral system response is based of catalogue values and measurements of the characteristics of the optical components and the sensors. It gives the guideline for fine tuning and shows the system performance parameters before calibration. Fig.2 shows the characteristics of the two different glass filter combinations for the nadir line and the two stereo lines of WAOSS and the dashed line shows the transmission of the optics.

Tab.1: Advantages and disadvantages of glass filters and interference filters

Advantages	Disadvantages
GLASS FILTERS	
low impact of inclined entrance ray	limited filter assortments
robustness and long-term stability	very limited bandpass characteristics feasible
high transmission within a large bandwidth	fine tuning not possible
INTERFERENCE FILTERS	
any narrow bandwidth feasible	near parallel incidence of light required
spectral fine tuning feasible	sensitive against environmental impacts
steep edges in the spectral characteristics feasible	additional glass blocking filters necessary

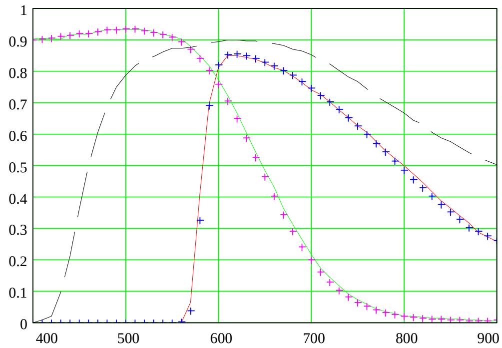

Fig.2: Theoretical (line) and measured (+) transmission of the WAOSS filters and of the WAOSS optics (dashed)
nadir line filter combination: 1mm KG1 and 1mm BG38
stereo filter combination: 1mm KG1 and 1mm OG570

The spectral characteristics of the optics and filters are convoluted with the spectral responsivity of the different CCD sensors. For example the resulting total system response (including optics, filters, CCDs) is shown in fig.3.

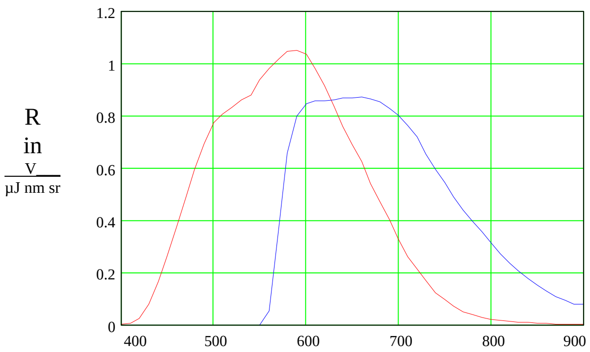

Fig. 3: Spectral system response of WAOSS nadir and stereo channels

The fine tuning process emphases the coincidence of the center wavelength of the stereo line with few HRSC channels at 690nm and emphases the balanced signal generation in all channels at typical Martian targets (dark and bright regions) (Brieß, 1992a).
A comparison between the results of the spectral design in figure 3 and the requirements shows:

- the high red reflectance range of the Martian surface at more then 600nm is used by both channels and gives the possibility for stereo matching and reconstruction of the data (common spectral range),
- the blue sensible nadir line in combination with the red sensible stereo lines allow the real-time distinction of condensate clouds from dust clouds (water clouds are best visible with the blue filter dust with the red filter),
- the integral centre wavelength of the stereo lines is 690nm to meet the requirements on compatibility with certain HRSC channels,
- the half-value bandwidth are:
  blue channel (nadir line): 470-670 nm
  red channel (stereo lines): 580-770 nm
- using glass filters a steep edge filter characteristic is only for the cut-on filter (red) feasible, there are no steep cut-off glass filters.

THE RADIOMETRIC DESIGN

The radiometric design of the sensor system has to meet the corresponding requirements derived from the scientific objectives, above all the requirements on

- signal-to-noise-ratio,
- dynamic range and
- the image quality

under the real experiment conditions and constraints. For a problem fitted design it is necessary to develop

- a sensor model,
- a target model (for instance of the Martian surface and atmosphere),
- and a model of distortions.

The sensor signal s_i can be modeled like follows:

$$s_i = \frac{\pi}{4k^2} \frac{\cos(\varepsilon)^{ld}}{K(1+M^2)} t_{int} \int T_{opt}(\lambda)\, R_i(\lambda)\, L_i(\lambda)\, d\lambda + \sigma_{sign} + \sigma_{sys} \quad (16)$$

with
- k = f-number (here 4.5)
- K = conversion factor (here 1.44µV/e$^-$)
- M = scale factor (f/H)
- ε = view angle of pixel i
- ld = limb darkening of lens (here 3.82)
- $T_{opt}(\lambda)$ = Transmission of lens and filters
- $R_i(\lambda)$ = Responsivity of pixel i of the CCD
- $L_i(\lambda)$ = input radiance of pixel i
- σ_{signal} = signal noise (photon noise)
- σ_{sys} = sensor system noise

For the estimation of the sensor signal a model of the spectral radiance L(λ) of the target (Mars) is developed. Fig.3 gives three typical examples of Martian target radiance at clear atmosphere (supposition: Lambert scattering only). It was computed basing of results of reflectance spectroscopy (McCord, 1971), (Binder, 1972), (McCord, 1977), of measurements of the Viking orbiter (Soderblom, 1978) and lander (Huck, 1977) and other scientific sources (Singer, 1979), (Moroz, 1978).
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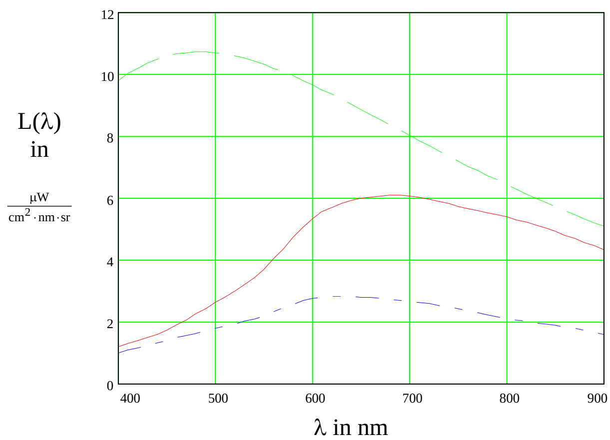

Fig.3: Model of Martian spectral radiance of bright regions (line: Terra Arabia), dark regions (dash-dot: Syrtes Major Planitia) and condensate clouds (dashed line) at clear atmosphere

The modeling of the spectral radiance of Mars on the satellite is a complex task. It is not be elaborated on this point. If all parameters of the equation are known, especially the CCD parameters by measurements like conversion factor, the pixel related responsivity, the dark signal and the system noise parameters, then a signal estimation for each pixel under certain illumination conditions (L(λ)) will be possible.

Besides the sensor model and a target model a model of the distortions, above all the noise are necessary for the estimation of the system noise characteristics, especially the signal-to-noise-ratio. The system noise terms can be divided into additive and multipliable acting distortion. The main terms of the noise components are depicted in fig.5 roughly. It is a coarse simplification for the SNR estimation, more details are in special references (Carnes, 1972), (Nishida, 1989).

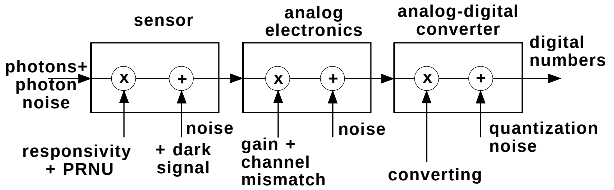

Fig.5: Model of the main noise sources of the CCD sensor system

The noise terms can be summarized up into

- a pixel-related multiplication factor (gain or relative photo response of the pixel i)
- the signal dependent photon noise
- the fixed pattern noise of the CCD
- the temporary total system noise (r.m.s. noise)

like it is shown in fig.6.

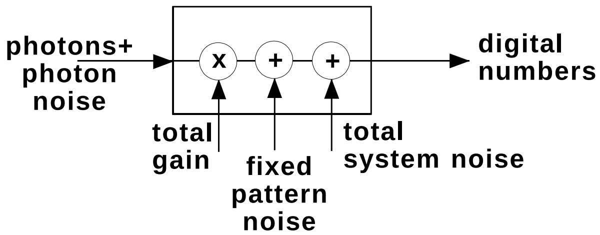

Fig.6: Simplified sensor system noise model

After the determination of these noise parameters the expected signal-to-noise-ratio (SNR) can be an estimated like follows. Note, the sensor control offers the option of pixel binning (macro pixel generation) for improvement of the SNR.

$$\mathrm{SNR} = \frac{s_i}{\sqrt{\sigma_{si}^2 + \sigma_{fp}^2 + \sigma_{sys}^2}} \sqrt{m_a} \qquad (17)$$

with
s_i = sensor signal
m_a = macro pixel factor
σ_{si}^2 = variance of signal electrons (photon noise, Poisson distributed)
σ_{fp}^2 = variance of the photo-response non-uniformity (fixed pattern noise)
σ_{sys}^2 = variance of the total system noise (r.m.s. noise), transformed at sensor input

The influence from the photo-response non-uniformity (PRNU) of the CCD sensor on the SNR for 2 different full well numbers is shown in fig.7. Typical PRNU values of CCDs are between 5% and 10%. It can be seen, the maximum SNR can be reached by correction of the PRNU to a value ≤ 0.05%. In this case the SNR is only determined by the system r.m.s. noise and the photon noise (compare fig.5 and 6).

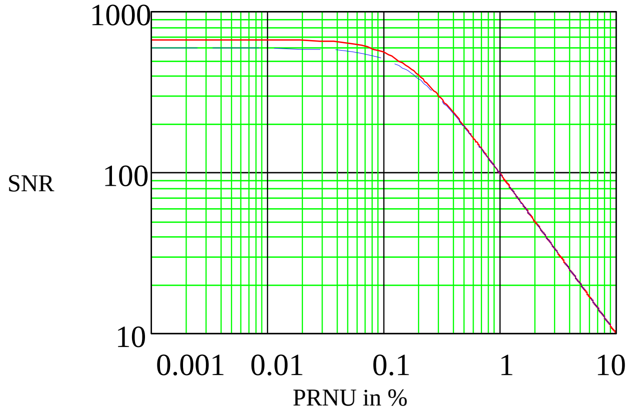

Fig.7: Influence of the photo-response non-uniformity (PRNU) of the CCD on the signal-to-noise-ratio (SNR) at two different full well numbers (dashed line: 400 000e$^-$, line: 500 000e$^-$), (Brieß, 1992b)

The PRNU correction can be realized before the quantization of the signal (analog correction), immediately behind it (digital correction) or after the signal transmission during the ground data processing. To avoid information losses the last option requires a loss-less data compression and the digital correction requires at least a 14-bit analog-digital converter (under the constraints low power and space qualified). For the WAOSS sensor a special analog processor was developed to correct the PRNU immediately behind the location of noise generation (CCD).

A wide dynamic range (DR) gives the opportunity to take high quality images at various illumination conditions (dark Martian regions, bright polar caps, bright clouds). It is limited by the following factors:

$$\mathrm{DR} = \frac{FW - ads \cdot t_{int}}{\sqrt{\sigma_{fp}^2 + \sigma_{sys}^2}} \qquad (18)$$

with
FW = full well electron number
ads = average dark signal generation rate
t_{int} = integration time
σ_{fp}^2 = variance of the dark signal (fixed pattern noise)
σ_{sys}^2 = variance of the total system noise (r.m.s. noise), transformed at sensor input

The full well capacity and the average dark signal generation rate of a certain CCD are pre-determined by the production process. The controllable integration time is determined by the observation conditions (max.30ms) and the total system noise by the analog channel (fig. 5 and 6). The fixed pattern noise in this case is the dark signal non-uniformity (DSNU). Measurements of the CCD parameter under worst case operation conditions (20°C) show the necessity of the correction of the average dark signal. Because the DSNU was less then 20µV/ms in any case of operations a DSNU correction was not necessary. It is shown in fig 8. If the DSNU ≤ 30µV/ms the dynamic range (DR) is determined by the other parameters only.

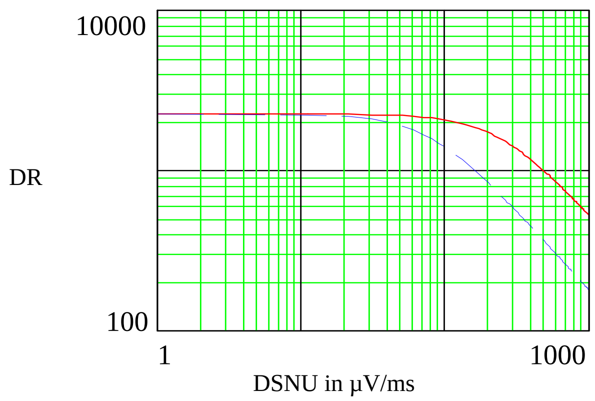

Fig.8: Dynamic range (DR) of the sensor in dependence of the dark signal non-uniformity (DSNU) at an integration time of 10ms (line) and 30ms (dashed line), (Brieß, 1992b)

The third essential parameter of the radiometric design consists in the image quality of the system. A measure of the image quality is the modulation transfer function MTF. The MTF of an electro-optical system is the absolute value of the optical transfer function, the Fourier transform product of the point spread function (Goodman1968), (Papoulis, 1968).
The advantage of introducing the MTF as quality parameter consists in the option to multiply all MTF components of sub-units to one system-MTF. The system-MTF of the WAOSS camera in operation is the product of the MTF of the optics, the CCD geometry, the blurring due to the motion and the electronics:

$$MTF_{tot} = MTF_{opt} \cdot MTF_{ccd} \cdot MTF_{blu} \cdot MTF_{el} \qquad (19)$$

with MTF_{opt} = MTF of optics and filters
MTF_{ccd} = MTF of the CCD
MTF_{blu} = MTF of blurring
MTF_{el} = MTF of electronics

The MTF of the electronics should be neglectable. The MTF_{blu} can be reduced on a neglectable value if the integration time ≤ 0.1 ·dwell time.

The most important MTF values are the MTF of the CCD and the MTF of optics. The pixel geometry determines the MTF of the CCD at first approximation. The MTF of the optics has two main components:

- the MTF of the diffraction limitation (depends on the f-number and the wavelength) and
- the MTF of the aberrations:

$$MTF_{opt} = MTF_{diffr} \cdot MTF_{aber} \qquad (20)$$

In the visible wavelength in most of the cases the optics is not diffraction limited. The aberrations determine the MTF of the lens system distinctively.

In the end the following practical approximation can be used for the estimation of the total MTF of a CCD sensor system:

$$MTF_{tot} \cong MTF_{pix} \cdot MTF_{aber} \cdot (MTF_{diff} \cdot MTF_{blu}) \qquad (21)$$

with MTF_{pix} = MTF of pixel geometry
MTF_{aber} = MTF of aberrations of the optical system

The blurring of the sensor system and the diffraction limitation have to take into account only in special cases. Fig.9 gives an impression of the influence of the different terms on the total system MTF. The pixel geometry determines the MTF approximately.

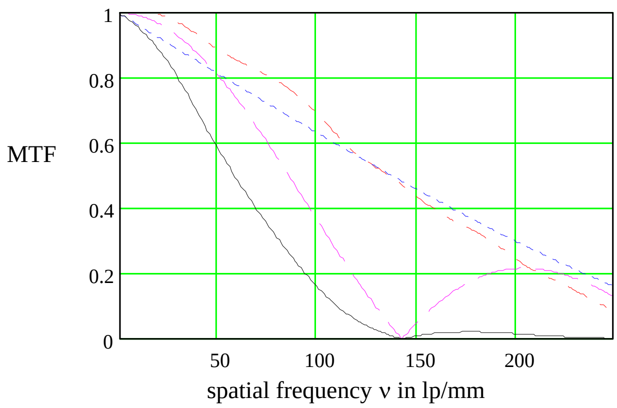

Fig.9:Influence of some sub-system MTF's on the total system MTF of WAOSS at 650nm
line : total system MTF
dashed line : pixel geometry MTF
dash-dot : MTF of the optical aberrations of WAOSS
dots : MTF of diffraction limitation

A very important part of the MTF analysis consists in consideration to the sampling theorem (Shannon, 1948). The sampled image can be reconstructed without sampling errors if

$$\nu_{max} < \frac{1}{2 \cdot \xi} = 72 \text{ lp/mm} \qquad (22)$$

with ν_{max} = maximum spatial frequency at the image plane
ξ = pixel distance.

That means, the image in the object plane (target point) has to be filtered by the atmosphere and the optics up to a maximum spatial frequency at the image plane = 72 lp/mm (line pairs per mm). If the MTF of the atmosphere do not limit spatial frequency of the signal to this value, the optical system should be slightly defocused.

SUMMARY

1. The geometric design starts with computing of all non-given geometric parameters from the requirements.

2. The spectral design is characterized by an iteration process with consideration of all spectral components (optics, filters, sensors).
   Glass filters are used for the determination of wide spectral bands and at wide filed of view requirements
   Interference filters are used at low inclined incident light rays only.

3. The radiometric design includes

- a parametric sensor model
- model signals from the target objects
- noise models for signals and instrument
- the conversion into digital numbers
- the estimation of the signal-noise-ratio
- the estimation of the dynamic range
- a MTF system evaluation.

The following important items were not mentioned in this contribution, but they are not neglectable:

- polarization design
- optic design
- linearity of the system
- problems at inclined rays
- stray light
- design of special features for the elliptical orbit
- design of special redundancy structures.

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Presented at the

ISPRS Symposium "Primary Data Acquisition and Evaluation"

September 12-16, 1994

Villa Olmo, Como - Italy