February 2003

2. Real Image, picture taking systems 4 hours

Aim:

Real image: distortion, point of principle
Creating mathematical image coordinates from measurements

Theory:

Principals of picture taking systems (Photography, CCD)
Camera types for photogrammetrical purposes
extended form of the co linearity equation (distortion, point of principle)
calibration

2.1. Principles of picture taking systems

The picture taking systems differs depending on the type of image presentation – analogue or digital, geometry of image forming and on the physical principal of image registration.
For the analogue method for image presentation it is commonly used parallel form for image forming. Only for strip cameras the sequential method between strips is applied. For digital presentation of image it is essential that image is presented as matrix of elementary picture elements – called pixels. For every pixel it is assigned only unique value of picture characteristics – usually it is the rey level value for monochromatic images or color value for color images. For normal color images the color intensity and saturation could be omined in three or four bytes word. There are used different systems for color presentation – index by indexes in color look up tables, RGB – red, green, blue coding, CMYK – cyan, magenta, yellow coding or HSB (hue, saturation, brightness) coding. The method of image forming could be parallel or sequential. For sequential methods it is possible to form image element by element or, or parallel in lines and sequential for lines.

2.1.1. Photogrammetric optic

The simplest way to apply principles of central projection is to use dark box with small hole in the center of one of their sides. The photosensitive material is on the opposite side. Such camera is free of distortion. It produces very sot images andan works with very bright objects (lamps, candles and so on).

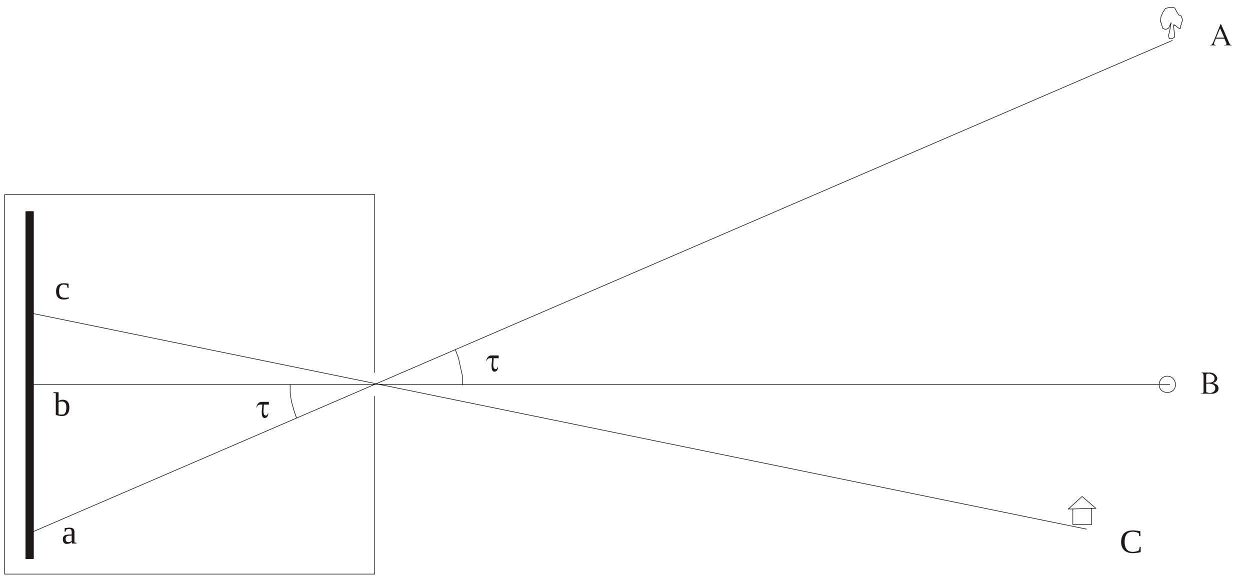


Figure 2.1. Simple camera

The main disadvantage of such type camera is unpossibility to control brightness and to achieve sharp images. To solve this the camera objectives are constructed. The objectives are complex systems of lenses with asymmetric surfaces. Some lenses are combinations of different glasses to ensure that imaging error to be corrected to the greatest possible extend. An example of such objective is shown on the figure 2.2.

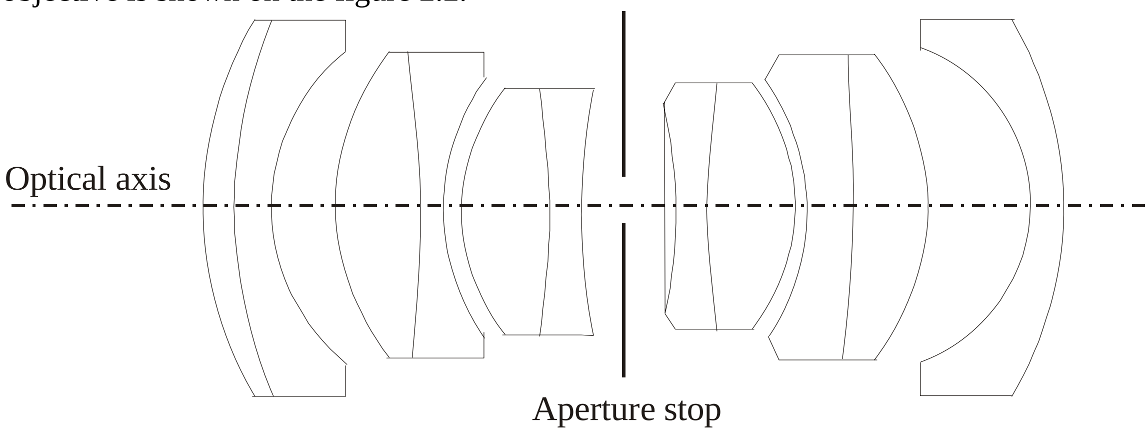


Figure 2.2. Cross-section of photogrammetric objective

The theory of geometrical optics defines the focal length *f* (respectively the power *p*, which is reciprocal to the focal length) as the function of surface radius of lens and the coefficient *n* of the material (glass) corresponding to the surrounding air.

$$\frac{1}{f} = p = (n-1).\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{2.1}$$

Coefficient n is so called refraction index. It is defined as light velocity in two materials: vacuum, air, glass, water.

Relative value of refraction index is defined as

$$n_{ij} = \frac{c_i}{c_j} \tag{2.2}$$

where c_i and c_j are velocities of light in two materials.

If the refraction index is defined relatively to vacuum, it absolute value of refraction index

$$n_i = \frac{c_{vac}}{c_i} \tag{2.3}$$

Finally for relative refraction index we obtain

$$n_{ij} = \frac{c_j}{c_i} = \frac{n_i}{n_j}$$

The main low of geometrical optics gives the relation between index refraction and angles of falling an drefraction.

$$n_i.\sin\varepsilon_i = n_j.\sin\varepsilon_j \qquad \text{or} \qquad \frac{\sin\varepsilon_\text{i}}{\sin\varepsilon_\text{j}} = \frac{n_j}{n_i} = n_{ij}$$

This principle is shown geometrically on figure 2.3

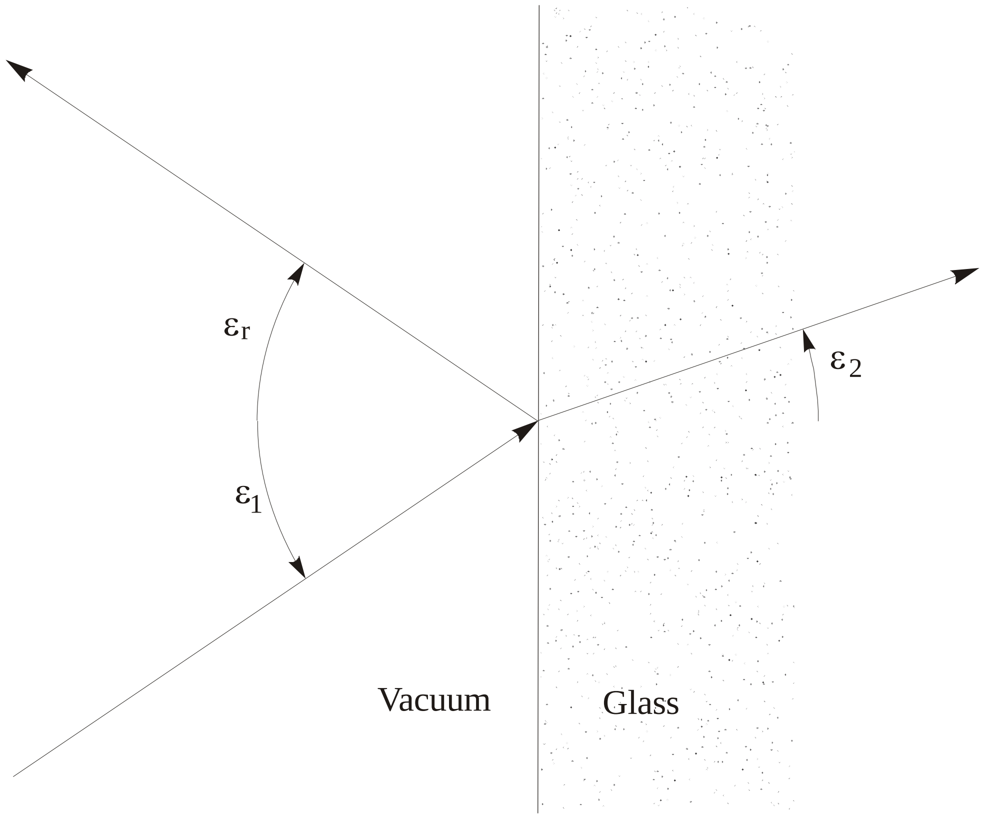


Figure 2.3. Light refraction

For the reflection the coefficient have values $n_2 = -n_1$ and the angle of reflection is equal of the angle of falling

$$\varepsilon_r = \varepsilon_1$$

The law of refraction allows explaining the lens properties.

The geometric theory of optical systems postulates two principal planes for the combinations of lenses. This two principal planes are object-space principal plane H and image-space principal plane H'. These panes reproduce each other in scale 1:1 and are perpendicular to the optical axis. For the optical system of type air-glass-air there are two optical principal points, i.e. the intersections of the principal planes with the optical axis OO', which coincide with the two nodal points N and N'. These points are defined in such way that the central rays (passing trough the nodal points) have the same angles of falling and rising τ to the optical axis (in the object space and in the image space).

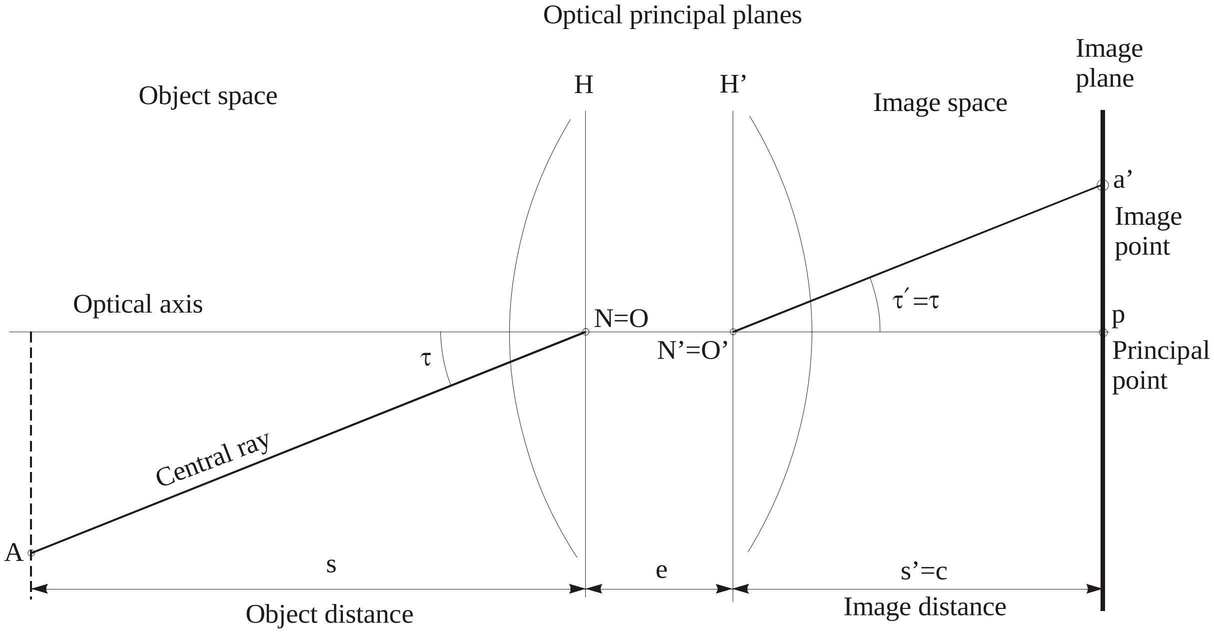


Figure 2.3. Idealised geometrical image

For main relation for good focusing is known as Newton's condition

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

It could be presented in Newtonian form

$$x.x' = f^2$$

$$\textit{where} \quad x = s - f$$

$$x' = s' - f$$

If object lies near to focal position in the object space, then the focused image lies behind the focal plane. In most practical situation the object distance is very large. So it is possible to denote

$$s \to \infty \quad s' = f = c$$

These two possible positions of object point and image points are shown on figure 2.4.

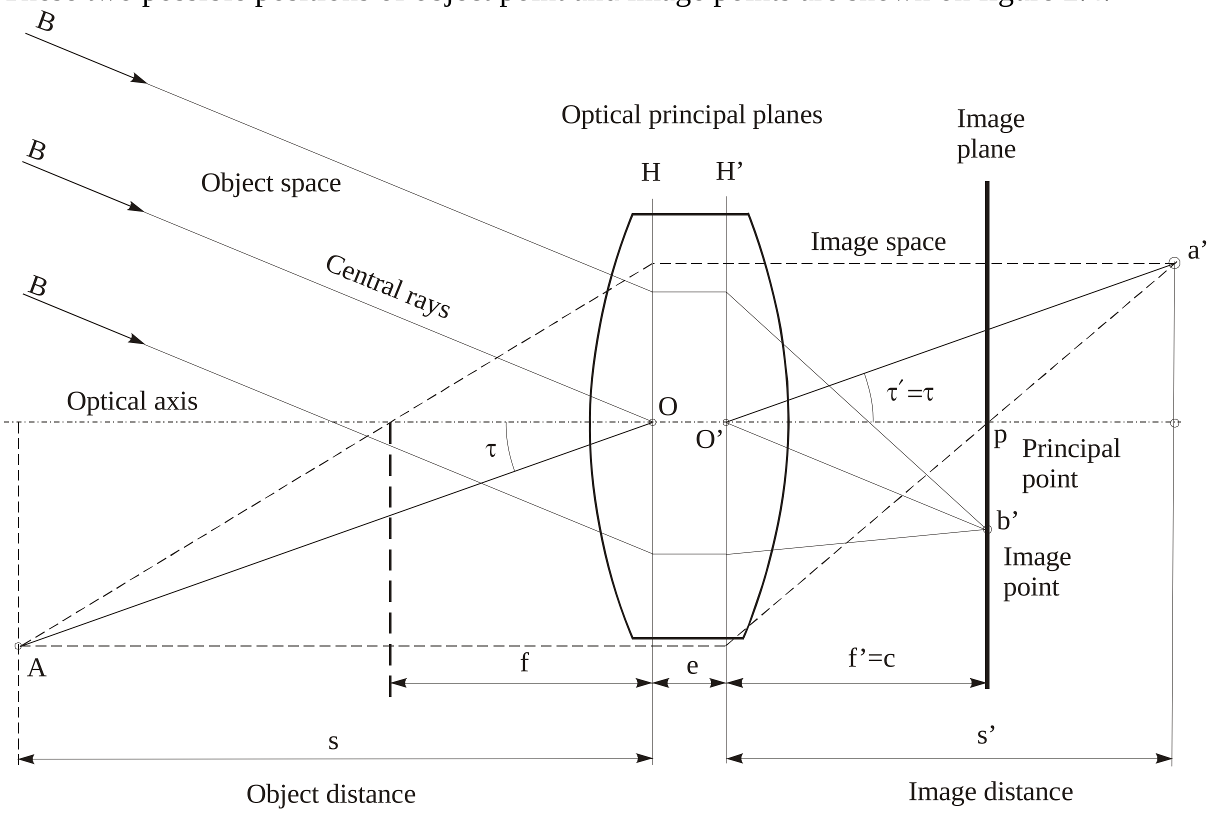


Figure 2.4. Images for near point and point at infinity

2.1.2. Errors of photogrammetric objectives

Spherical aberration. The failure of lens system to produce a point image in the image space of a monochromatic axial point source of light in object space is called spherical abberation. The reason for the spherical aberration is that rays from an object point (in this case at infinity (do not intersect at a single point after passing trough the lens. The measure of spherical aberration is the distance from the Gaussian focal point F_2 to the point of intersection of two corresponding rays such as a_1 and a_2.

Astigmatism. In the general case a pencil of rays from an object point, refracted or reflected at large angle of incidence by an optical surface, refocus into two astigmatic line segment images, displaced somewhat one another along the principal ray. Each of the two line segments will be perpendicular to the principal ray, and though separated, the two line images will lie at an azimuth of 90 degrees to one another. Ideally, in the final image space the astigmatism, as measured by the separation of the astigmatic line segment, can be designed to vanish and the respective astigmatic foci will lie together on the prescribed image plane throughout the field. Such a system is said to be “anastigmatic” and to have a flat field.

Coma. With respect to the aerration known as coma the chief ray has additional importance in defining the location of the apex of the fan of rays shown typically as pure coma. In the presence of pure coma, ray intersections in the entrance pupil at equal plus and minus heights will form ray-pairs that intersect the image plane in a common point progressively displaced from the intersect of the principal ray according to increasing zone height in the pupil.

Chromatic Aberrations. Because of the variation of refractive index with wavelength for all transparent materials, he many quantities associated with Gaussian and Seidel optics having to do with image position, size and quality are all to some degree a function of wavelength. S a result a ray of white light in object space refracted at a lens surface becomes a small spectral fan of ays owing to dependence of the index of refraction on the wavelength. Fortunately the designer has at his disposal a large variety of types of optical glass types from a number of manufacturers. The designer is thus free to choose glass types that in combination can correct for chromatic aberration as well as for the monochromatic aberrations.

Distortion. Distortion has to do with the position of the image point in the image plane but not with the image quality. The distortion is of great importance for the photogrammetry.

The real photogrammetric objective and the idealized model of it differ significantly.

1. The optical axis should contain the centers of all spherical lens surfaces.

2. The angles τ are defined in the center of the entrance pupil and not in the nodal points. Since the entrance pupil usually does not lie in the principal plane H, it follows that τ' is not equal to τ.

3. The mechanically realized principal distance s'_m defined by the focal plane frame of the camera differs slightly from the optical principal distance s’.

4 The image plane is not rigorously perpendicular to the optical axis.

In essence the angles τ' in image space are not equal to the angles τ in object space. It is defined mathematical projection center O'_m which lies at a perpendicular distance c, the principal distance, from the principal point of autocollimation PP_A and which reproduces the angles τ as closely as possible. Residual errors lead to optical distortions $\Delta\rho$.

The definition of image projection center and distortion error is shown on figure 2.6

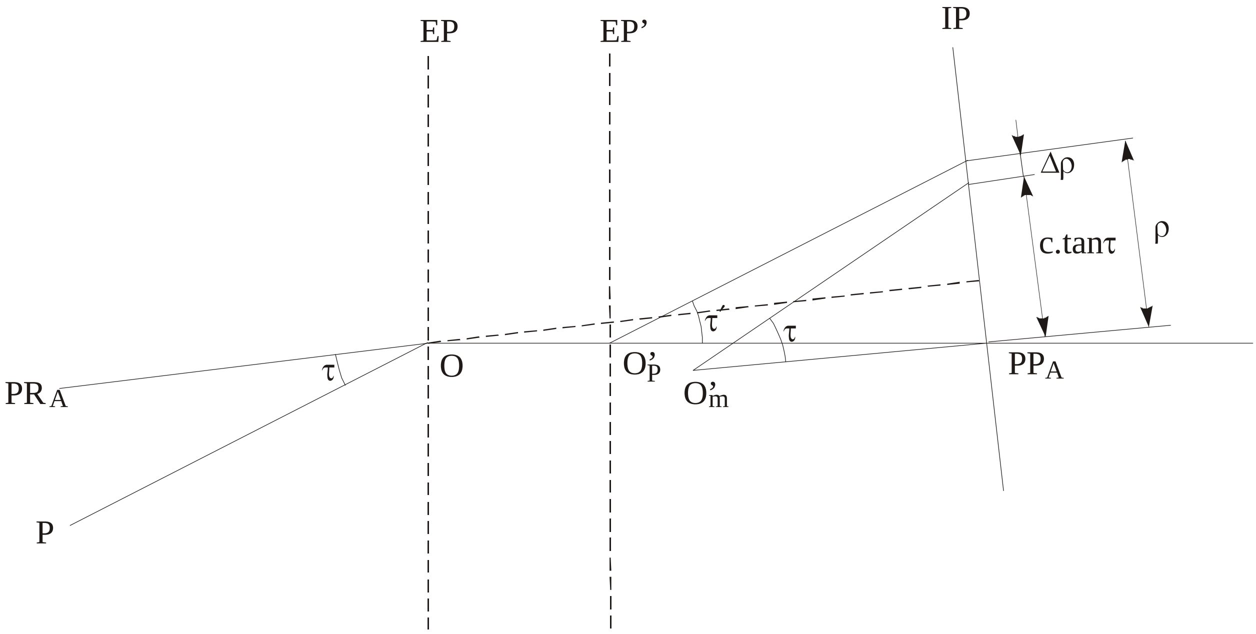


Figure 2.5. The definition of the image-space projection center

where PR_A – autocolimation principal ray

PP_A – principal point of autocolimation in image plane;
IP – image plane;
EP – entrance pupil;
EP' – exit pupil;
O'_P – phisycal projection center;
c – principal distance;
ρ – image point offset;
Δρ – radial distortion.

$$\rho = \sqrt{(\xi - x_p)^2 + (\eta - y_p)^2}$$

The co-ordinates of principal point must be extended to include the radial optical distortion Δρ

$$\rho = c.\tan\tau + \Delta\rho$$

Photogrammetric cameras are calibrated in a laboratory (Laboratory calibration) with help of an optical goniometer.

2.1.3. Photographic registration

The photographic registration is based on usage of photo chemical process. After the exposure the emulsion is changed in the way as the lightning areas have more destruction of argentums. This image is invisible. This image to became visible the developing is made. The cross section of photographic material is shown on the figure

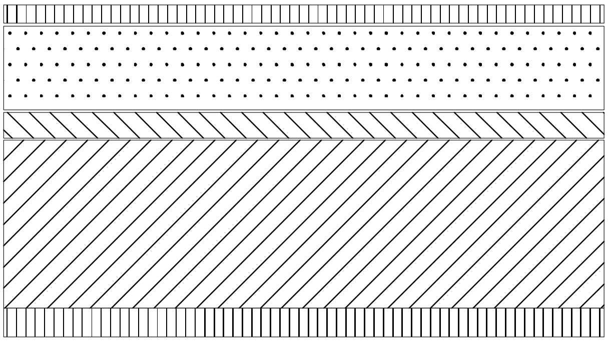


Figure 2.6. Cross-section of photographic material

Base of photographic material could be glass or plastic. Glasses rarely used in aerial photogrammery., except for the tests. Glass is heavy, easy breakable, relatively unflat but stable. The adhesion of light-sensitive emulsion is less efficient than with film and therefore deformations of the emulsion tend to be larger. Drop during drying can cause local tensions. The deformations of the emulsion become to up ±20µm. Glass plates are commonly used in terrestrial photogrammetry, where there are required only few photographs at a time. Some terrestrial cameras re equipped with film cassettes or magazines.

The visible part of electromagnetic spectrum covers wavelengths from 40nm to 700nmapproximately. The usage of different part of wavelengths for interpretation is very important but it main subject of remote sensing methods. The photographic process covers relatively narrow range of spectrum from 300nm to 1000nm, i.e. the part from ultraviolet (UV) to the near infrared (IR). It des not cover the medium of the thermal infra-red. If all wavelengths of visible light are uniform in intensity, the eye sees white light. This white light can be split into a large number of monochromatic spectral lines which are seen as saturated “spectral colors”. If we group these in bandwdths of 100nm, we obtain the three “mixed” colors – blue, green and red, and the three additive primary colors. Other colors can be created by adding the various proportions of tese three primary colors. The niform mixture of three primary colors produces white. The addition of pairs of additive primary colors produces the subtractive eprmary colors – cyan, yellow and magenta. These colors are called subtractive as they are created by subtracting one primary color from the white light.

Cyan = blue + green = white – red

Yellow = green + red = white – blue

Magenta = red + blue = white - green

Such subtraction is achieved by filters. When the white light falls on the filter the transmitted part gives the name f the filter. The absorbed part, which is called complementary color will give white if it is added to the filter color. Schematic diagram of this division is shown on figure 2.7

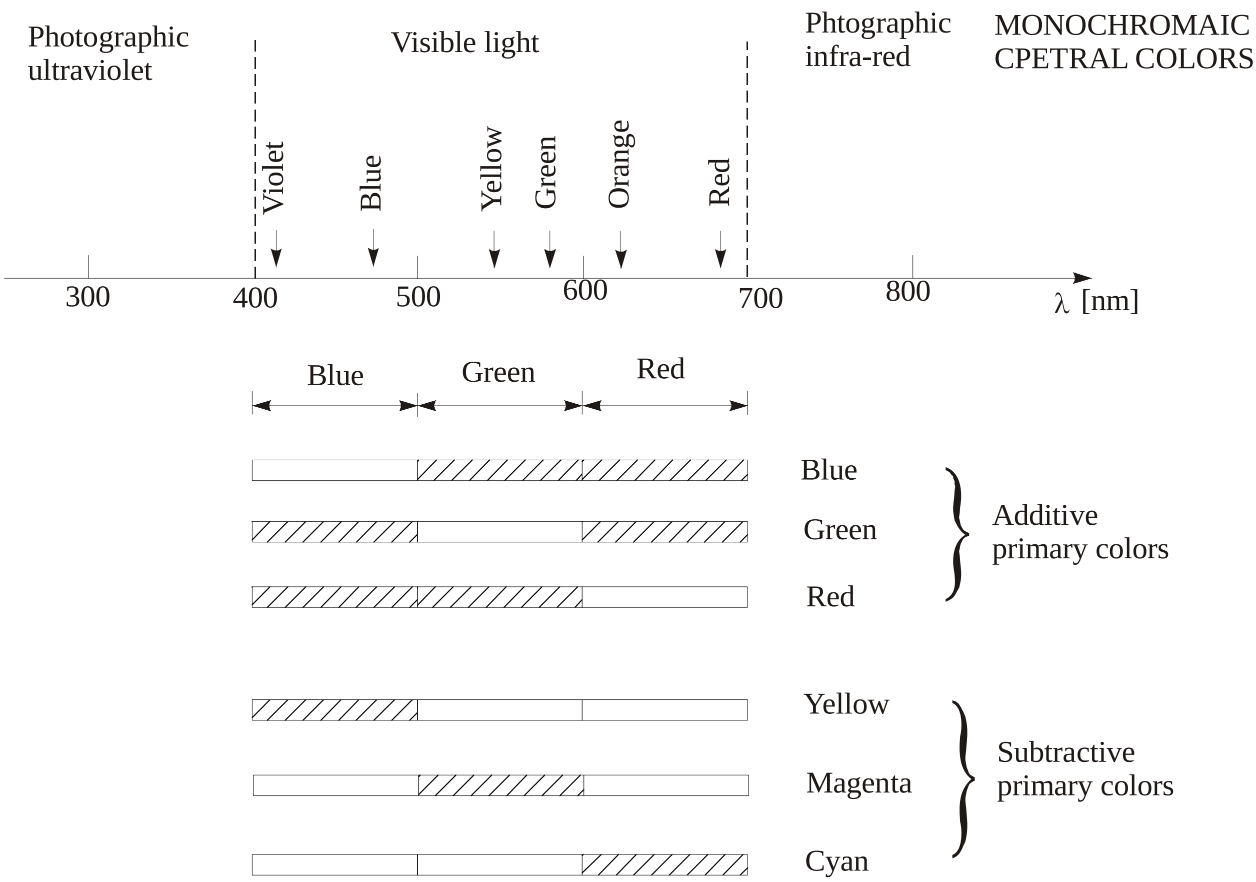


Figure 2.7. The spectral range of photography

2.1.5. Black and white photographic process

The exposure produces a latent image in the layer of light sensitive silver halide crystals (AgBr, AgCl, AgI e.c., embedded in the gelatine of the emulsion. This latent image can be made visible by negative development process (for example hydroquinone, alkalis and potassium bromide). The silver is separated from the bromine. The unexposed silver bromide is converted in a fixing bath (sodium thiosulfate - = hypo) into a silver salt easily soluble in water and released. The remainder of about 5% is then removed by washing. Only metallic silver retain finally in the exposed photograph, with the areas of high exposure blacker tat those of lower exposure. In the reversal process the exposed silver bromide is released in the predevelopment (bleaching), while the unexposed silver bromide remains. It is then uniformly exposed and finally developed as a positive, fixed and washed. The uniform intermediate exposure can be replaced by chemical processing with sodium sulphide (instant photo process).

Gradation. Relation between exposure H and density D of a negative or positive process is of great practical importance for the judging of photographic materials, processes and results. The proportion between transmitted trough the film luminous flux Φ and the constant incoming flux

Φ_0 is measured by densitometer. The ratio Φ / Φ_0 is called the transparency τ, and the reciprocal value $\Phi_0 / \Phi = 1/\tau$ is scaled the opacity O. The logarithm of the opacity is the density D.

$$\tau = \frac{\Phi}{\Phi_0}, \quad (0 \le \tau \le 1)$$

$$D = \log\frac{1}{\tau} = \log O$$

A density D=2 means that only 1/100 f incoming luminous flux is transmited, for D=1 one tenth. A density D=0 indicates complete transparency or $\tau = 1$.

Film sensitivity (speed). The sensitivity or speed of the photographic emulsion is defined as the reciprocal of that exposure $H_{\Delta D}$ which produces a defined density difference ∆D above fog level, under precise conditions of radiation, exposure and development. The German standards institute (DIN) defines a logarithmic system, so called DIN speeds according to the following equation

$$S_{DIN} = 10.\log\frac{H_0}{H_{\Delta D=0.1}}$$

where $H_0 = 1$ lxs (Unit exposure), $H_{\Delta D}$ [lxs]

The American Standards Association (ASA) adopts an arithmetic system rather ten logarithmic

$$S_{ASA} = 0.8\frac{H_0}{H_{\Delta D=0.1}}$$

In the USA it is defined another standard AFS=Aerial Film Speed

$$S_{AFS} = \frac{2}{3}\frac{H_0}{H_{\Delta D=0.3}}$$

2.1.6. The color photographic process

Black and white films record only grey tones, but color films contain further important information. Colour films are composed of three light-sensitivity layers which are so treated in development tat each layer becomes a colour filter.

Another color film is color infra-red, or false color, which has layers sensitive to infra-red, green and red, rather than to blue, green and red light. These layers are coupled to the colors cyan, yellow and magenta so that in white transmitted light the colors red, blue and green appear, though these do not correspond to the natural colors of the object. Since all tree layers are sensitive to blue light, a yellow filter must be used. A yellow filter in the film is therefore not necessary.

Spectral sensitivity. The layers of black and white and colour films are sensitised by various chemicals (mostly catalysers) for light of particular ranges of wavelength. **Orthochromatic** emulsions are sensitive to blue-green light ad therefore suitable for red object details. They can be developed under a red safety light. **Panchromatic** emulsions reproduce the full visible spectral range in the naturally corresponding grey tones. They must be developed in complete darkness. **Infra-red** sensitive black and white emulsions are also sensitive to wavelengths from blue to red and must therefore be exposed through infra-red filters.

Normal colour and false colour films are primarily used for photointerpretation, though they are all suitable for aerial photogrammetry since they have significantly fine grain and thin layers.

Optical and photographic resolution

The resolving power or resolution is expressed in lines/mm (lines per mm) and specifies how many lines per mm an just be distinguished from their adjacent spaces of equal width. The diffraction limited point separation of $\delta = k/2\ \mu m$ gives therefore, a theoretical optical-photographic limit of resolution

$$R_{\max} = \frac{10^3\ [\mu m/mm]}{\delta[\mu m]} = \frac{2000}{k}\ \text{[L/mm]}$$

where k is aperture stop of the objective

$$k = \frac{f}{d}$$

Optical blurring is the influence of lens errors (spherical and chromatic abberation, field curvature, astigmatism, coma. It can be reduced by small aperture. Optimal values are achieved when sum of optical and diffraction blurring is minimal.

Contrast and contrast transfer

Absolute contrast is defined as

$$k = \frac{I_{\max}}{I_{\min}} \quad with\ \ 1 \le K \le \infty$$

Relative object contrast is defined by

$$C = \frac{I_1 - I_2}{I_1 + I_2} \quad (0 \le \mathrm{C} \le 1)$$

2.2. Properties of digital images

Analogue images used in photogrammetry use the combination of optical camera and photographic emulsion, which has very high resolution and good photometric characteristics. That way this images are widely used in photogrammetry. Development of powerful computers and advanced technologies for creating of digital images allow to use them in many fields of photogrammetric works ad especially for close range and satellite photogrammetry.

The advantages of sing digital images are:

- images can be displayed and measured on standard computer display deices;
- measurement systems are stable and need no calibration;
- image enhancement can be applied;
- automation can be applied;
- operations can be carried out in real time, or near real time.

A digital image is basically an array of grey values such that each element g_{ij}, has a distinct value and varies with position x,y. Each element of the array has a finite size $\Delta x \times \Delta y$, and usually $\Delta x = \Delta y$. Every such element is called pixel (picture element) and values Δx and Δy are the sampling intervals.

The grey level value, which is essentially continuous on an analogue image is quantized in dgital image.

Intensity – this is the brightness of the image at a particular point (measured in lumens). It is represented by *f(x,y)*.

Grey value: a recorded vale of over the greyscale. The number of levels could be different. If they are two the image is binary. More often grey value takes one of 256 levels and could be stored in a byte. The grey values are called some times digital numbers (DN).

Density: express the degree of darkness on the developed film. Digitally it is recorded as grey level.

Sampling is the process of exchange the continuous 2D field of intensity (or density) of input analogue image with set of discrete values (usually with matrix form) called samples.

There is no loss of information if sampling is taken with the twice-greater value than the maximum frequency involved in the original analogue wave.

$$f_s \geq 2.f_h$$

In terms of sampling interval this means

$$\Delta x_s \leq \frac{1}{2.W_h}$$

This is the Naiquist theorem for sampling.

The quantisation is the process of where the measured value is also divided into discontinuous steps, or grey levels, so that there are errors in quantisation. Grey levels are usually quantised into a binary scale, with the most common range being 256 levels or 8 bits. The transformation curve could e linear r nonlinear. The dynamic range (DR) is typically defined as a ratio of the maximum output signal V_{sat}, or saturation level, to be room mean dark square noise level on the imager, $V_{dark,rms}$:

$$DR = 20.\log\left[\frac{V_{sat}}{V_{dark,rms}}\right]$$

and usually is expressed in decibels (dB).

Charge coupled devices

CCD is the most commonly used device for recording the image. CCDs are arranged as liner arrays or two dimensional arrays. Linear arrays are used to scan the scene and this introduces time-dependent geometry, which is dependent on the low of scanning (geometrical and time depending). Area CCDs produce directly 2D digital images and by its’ geometry are corresponding to the photogrammetric cameras that have central projection. Due to the limitations f technology there are some limits on the number of elements. That’s way for satellite image are often used linear CCDs, but for close range photogrammetry. The size of area CCD is of about 5120x5120 and pixel is smaller than 1μm. The cost is also limitation so for practical purposes areas 3000x2000 with 9x9μm are more commonly used. Linear elements have up to 12000 pixels with size of 8μm.

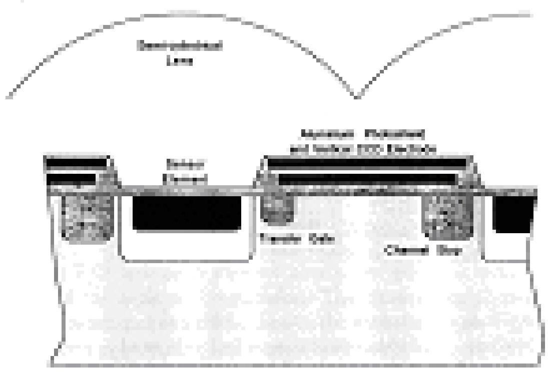


Figure 2.8. CCD cell structure

The removing the information from CCD areas is based on moving of the charge into the cell structures

The amount f stored data is also important. The amateur camera has 752x480 that will need only of 360kB but area of 3000x2000 need 6 Mb. In comparison a single photograph scanned with resolution of 7.5μm needs of almost 1 Gb.

The resolution of digital image at the object space depends on the resolution of CCD and the scale factor

$$\Delta X = \Delta x.m = \Delta x.\frac{Y}{c}$$

If the resolution is defined in dpi (dots per inch)

$$\Delta x = \frac{25.4.10^{-3}}{r}$$

Finaly for the resolution in object space obtain

$$\Delta X = \frac{25.4.10^{-3} Y(H)}{r.c}$$

For example of SPOT line scanner with 6000 elements, $\Delta x = 13\mu m$, c=1082mm, H=630km we obtain

$$\Delta X = \frac{13.10^{-6}.830.10^{3}}{1082.10^{-3}} = 9.97 \approx 10m$$

For close range images it is more difficult to calculate the resolution in the image because different objects lie at different distances from the camera.

The comercial CCD cameras has arrays with capacity from 2Mpixels to 6 Mpixels or more

Table 2.1

Producer	Model	Format	Size in pix	Pixel size [μm]	Type	Time for image [s]
Canon	PowerShot Pro70	6x4.5	1536x1024	4x4	Still video	0.5
Hewlett Packard	Photosmart 812		2272 x 1712		CCD,digital	
Kodak	Megaplus-4.2i	18x18	2029x2048	9x9	CCD,digital	0.5
Hewlett	Photosmart		2608x1952		CCD,digital	0.

Packard	935					
Kodak	DCS 460	28x18	3060x2036	9x9	Still-Video	0.6
Imetric	Icam 6	37x25	3072x2048	12x12	CCD,digital	0.2
Rollei	ChipPack	31x31	2048x2048	15x15	CCD,digital	10
Kodak	Megaplus 16.8i	37x37	4096x4096	9x9	CCD,digital	2
Imetric	Icam 28	86x49	7168x4096	12x12	CCD,digital	1.7
RJM	JenScan	9x7	4488x3072	2x2	Micro-Scan	5
Jenoptik	Eyelike	29x29	6144x6144	5x5	Micro-Scan	40
Rollei	Gamma S12	56x56	3500x3500	16x16	Line-Scan	180
Rollei	RSC	52x52	4500x4500	11x11	Reseau-Scan	>300
KWD	Rotascan Noblex	360°,60	42379x8600	7x7	Panorama-Scan	>600
Zeiss	UMK High Scan	166x120	15414x11040	11x11	4 CCDs, Macro-Scan	330

Table 2.2

Capacity	H	V
2 Mega	1636	1236
3,2 Mega	2140	1560
4 Mega Pix	2384	1734
5 Mega Pix	2608	1952
6 Mega Pix	3088	2056

The geometrical characteristics of CCD are very stable but they need of calibration.

The fundamental component of every solid state sensor is the image detector element, also known as a photodetector. The photo multiplier tubes were first developed in 1920s, whilst more reliable silicon based phototransistors became available in 1950s. The modern solid state imager uses a sensor composed of a semiconductor substrate which can store and transmit electric charge. The sensor is divided into an array of sensor elements, sometimes known as sels, which are either the photodiode or the MOS capacitor type. The charge of each sensor element must be transferred out of the sensor so that it can be measured. There are three schemes for charge read out which are in use for commercially available sensors.

1. MOS capacitor and CID sensors se sense lines connected to read out registers and an amplifier. These sensors are capable of random access to sensor elements and the read out process is not destructive.

2. CCD image detectors use principle of charge transfer from element to element like a bucket brigade Charge coupling refers to the process by which pairs of electrodes are used to transfer the charge between adjacent potential wells. The electrode voltages are manipulated in sequence which passes the accumulated charge from one well to the next. AT the end of the line of sensors the charge I transferred to output registers and scanned by an amplifier. There are used two phase and three phase CCDs.

3. Virtual phase CCDs are a later innovation in the technology which eliminates a number of gate electrodes by addition of implanted dopings to change the profile of potential in the silicon substrate. Virtual phase CCDs improve the charge capacity and have lower noise and also reduce the surface topography. The open pinned phase CCD is a combination of virtual phase and three phase which further reduces noise.

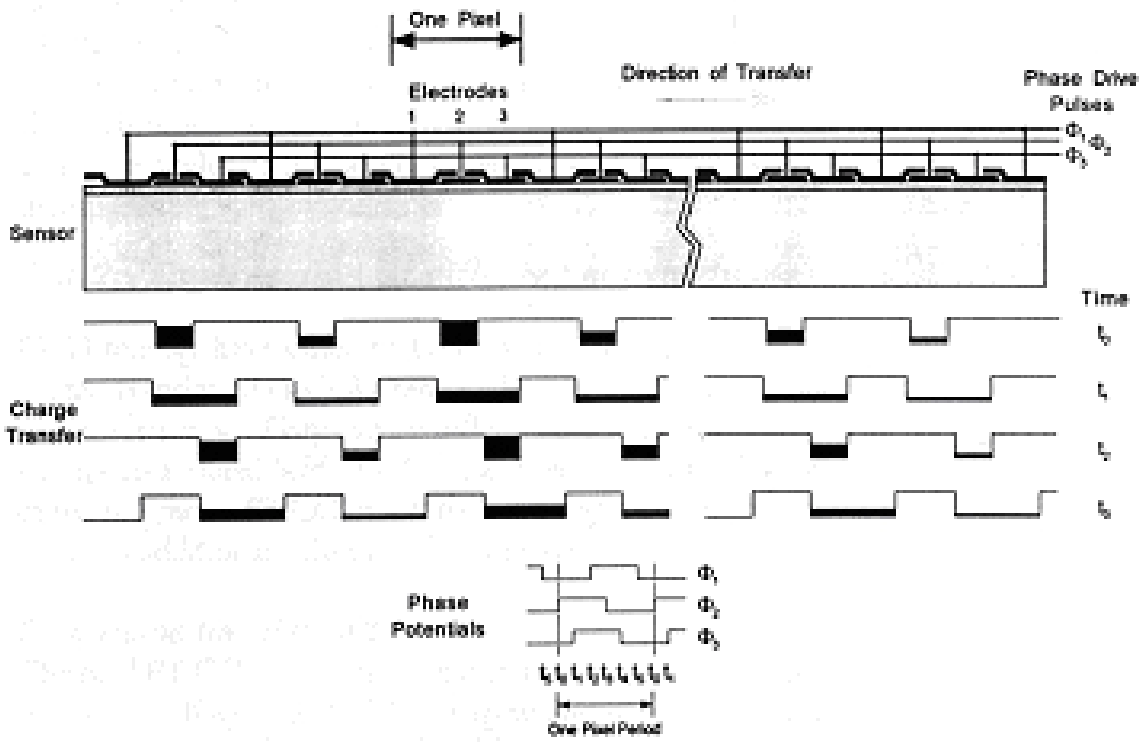


Figure 2.9. CCD charge movement

Scanners

There are three main types of scanners. These are:

Drum scanners using the flying spot principle.

Linear area scanners. Most of the modern commercial scanners are of this type

CCD area sensors mounted on comparators or special platforms

Table 2.3

model	producer	utilization	base	convertor	raster µ	size (mm)
MAK IV	Photomation	Photogr.	drum		2-10	
FEAG-200	KARL ZEISS JENA	Photogr..	drum	FEM	10-40	240x240
PS1	ZEISS	Photogr.	Flat-bad	CCD color filters 2048	7.5	260x260
SCAI	ZEISS	Photogr.	Flat-bad	CCD (color)	7-(224) 3630	250x275 (+film)
DSW 100	Leica-Helava	Photogr.	Flat-bad	CCD color kit 4096	8-(75)	250x250
DSW 300	Leica-Helava	Photogr..	Flat-bad	CCD 2029õ 2044	4 6350	270x270 (+film)
T2000 XL	Agfa				12 2000	457x305
HP Scan Jet Iicx	Hewlett Packard	Business	Flat-bad	CCD color	63.5	216x297
HP Scan Jet 4	Hewlett Packard	Business	Flat-bad	CCD color	42 600	216x297
UMAX		Business	Flat-bad	CCD	42	216x297
RS1-C	Rollei				6 4230	240x240
AutoSet-1	GSI				3 8470	240x240

The parameters that are important for image scanners are:

- Geometry;
- Image resolution;
- Image noise;
- Dynamic range;

- Color reproduction;
- Data compression;
- Instrument handling.

2.3. Camera types for photogrammetrical purposes

The main division of cameras is to terrestrial and aerial cameras.

2.3.1. Terrestrial cameras

Every photo from terrestrial camera must has

Fducial marks

Principal distance

Additve constant to principle distance if the focusing is changed

Camera number for identification.

The following auxiliary information can be helpful

Photo or base number

Station identification

Identification of photogrammetrc case (normal, left averted, right averted, convergent or general)

Date, time object description.

There are two main types of terrestrial cameras stereometric and independent. Stereometric cameras are two cameras mounted on the same base. They could be with a fixed base r with various distances. The common used distance is 120 cm, but baselengths of 40 cm ad 20 cm are available too. Cameras with various distances is Wild PBA 32 for two Wild P 32. Industrial camera of ZEISS Jena which has two UMK tat could be moved ad fixed. More widely used are stereometric cameras with fixed base – Wild (Leica), ZISS Oberkochen, ZEISS JENA, Kelsh, Galileo and other firms.

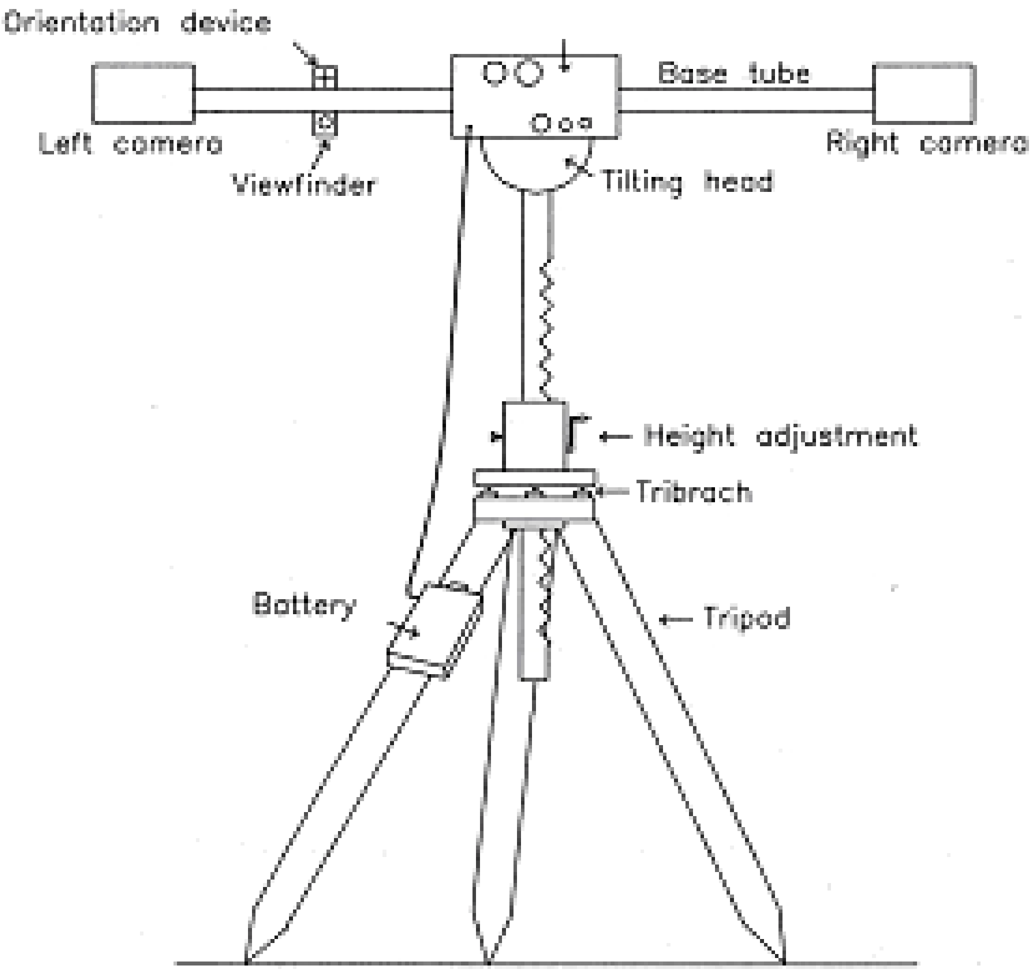


Figure 2.10. Stereometric camera

Stereometric cameras Wild C120, Wild C 40 baselenghts 120 cm and 40 c, c=64mm, for photographic plates 64mm x 89 mm (usable format 60mm x 80mm).

ZEISS cameras SMK 120 and SMK 40 baselengths 120cm and 40cm, c=60mm, for plates 89mm x 11mm (usable format 80mm x 95mm) fixed focus (9m and 4 m) and fixed aperture f/11.

Table 2.4

Circle of confusion u [mm]	Depth of field ($s_f - s_n$) [m]			
	SMK 120		SMK 40	
	s_n	s_f	s_n	s_f
0.025	5.3	28.4	3.5	5.7
0.050	3.8	∞	2.5	10.0

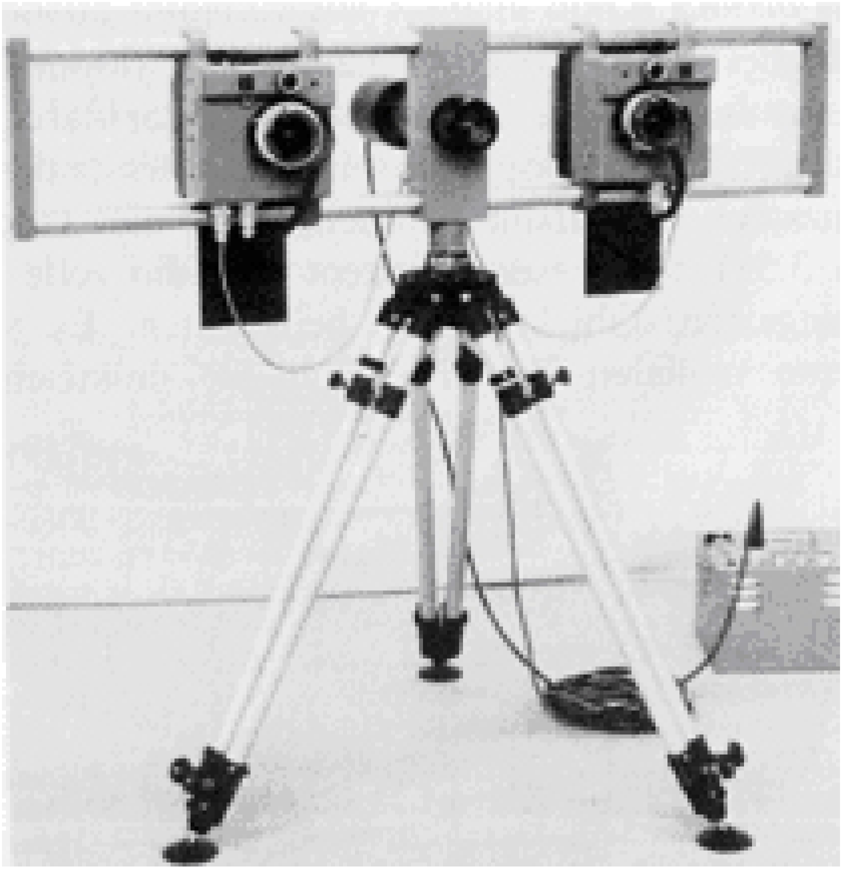


Figure 2.11. Stereometric camera Kelsh K460

Other type of terrestrial cameras are **independent cameras**

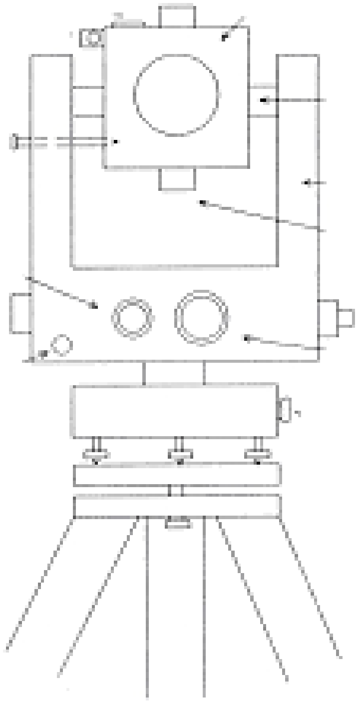


Figure 2.12. Independentant metric camera

Wild P 31 is produced in three modifications.

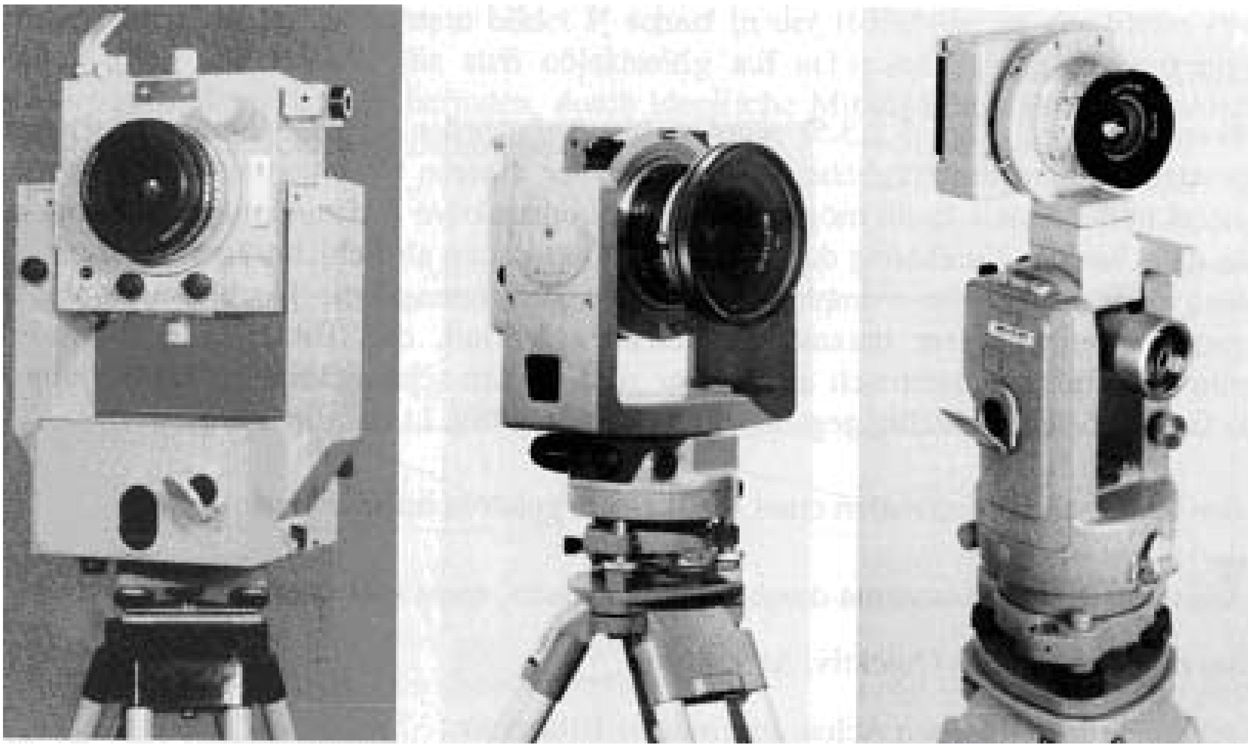
Table 2.5

Field angle	unit	superwide	wide	normal
Principal distance c	mm	45	100	202
Aperture stops	-	5,6…22	8…22	8…22
Exposure times	s	B, 1,…1/500		
Usable format	mm	92x118	84x117	90x118
Principal point displacement	mm	0	19	12
Standard focusing	m	7	25	25

Wild P 32 is a smaller precision camera with c=64mm, format 64mm x 89mm.
UMK of ZEISS Jena is universal metric camera for formats 13cm x 18cm. It is produced in 5 modifications.

Table 2.6

Field angle	unit	Superwide	Wide, near focus	Wide, far focus	Normal	Narrow
Principal distance	mm	65	99	99	200	300
Aperture stops	-	5,6…32	8…32	8…32	8…32	11…32
Focusing distance	m	8	1.4…∞	3.6…∞	5.6…∞	50
Distortion	µm	±5	±1	±1	±4	±2



ZEISS UMK 1318 Wild P31 Wild P32

Figure 2.13.

The classification of photogrammetric cameras into terrestrial and aerial is most conveniently for practice. From methodology point of view more important is the following classification.

- Metric cameras for photogrammetry;
- Semi-metric cameras, not intended for measuring purposes;
- Non-metric cameras with lower accuracy.

Depending on the possibility for inner orientation:

- Fiducial mark cameras
- Reseau cameras
- Frame cameras;
- False-frame cameras.

One of widely used metric cameras is the reseau camera Hasselblad

Figure 2.14. Hasselblad MK 70

CCD Cameras has large diversity

Special type of cameras are slit scan cameras. Their principle is shown on the next figure.

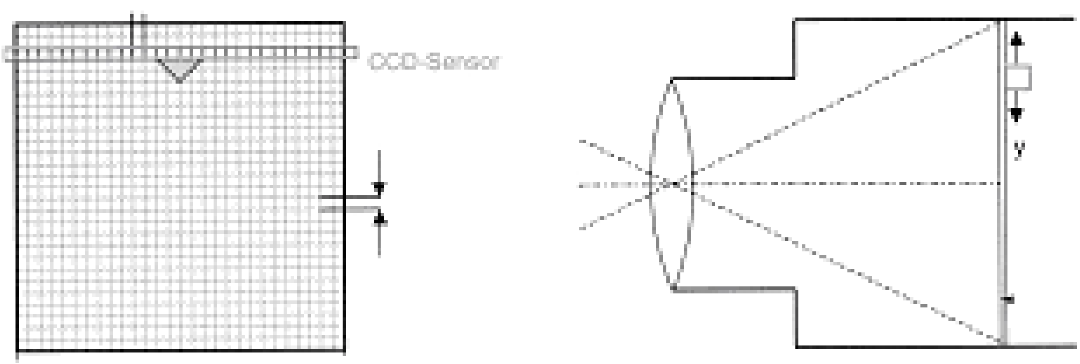


Figure 2.15. Principle of Line scanning camera

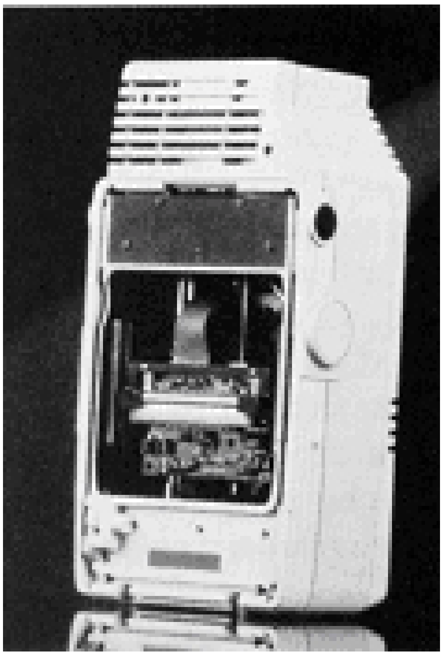


Figure 2.16. Scanning camera Rollei 6008

Anoter principle of scanning I based on usage of small area scanner that is moving in the image area. The accurate position is established by reseau marks.

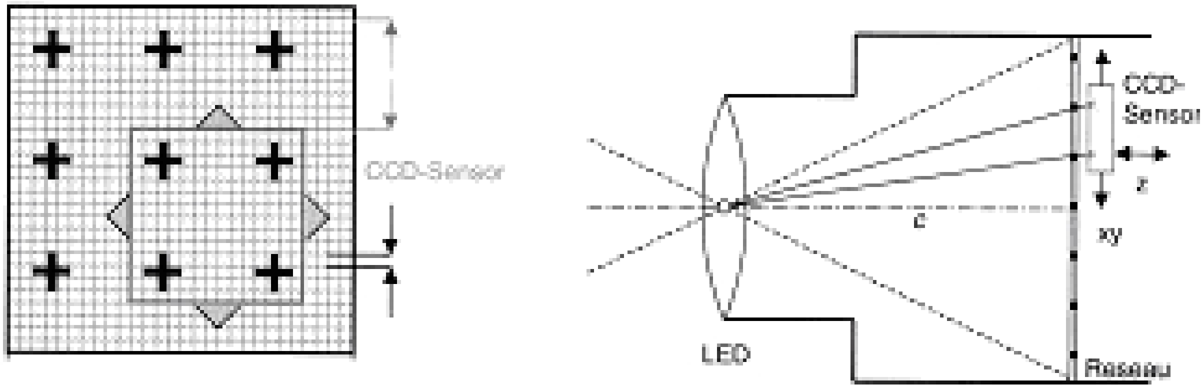


Figure 2.17. Principle of reseau scanning

Cameras build on this principle are Rollei RSC and UMK High Scan of Zeiss.

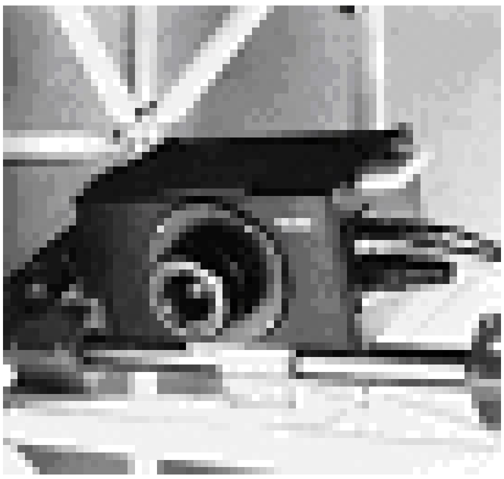


Figure 2.18. Reseau scanning camera Rollei RSC

2.3.2. *Aerial Cameras*

Depending on their construction the aerial cameras could be frame cameras. They are common types of cameras. Another possible types are panoramic and strip cameras.

The panoramic cameras may be divided into three general categories:

a) direct scanning cameras with swinging (or rotating lenses);

b) cameras that scan by means of rotating mirrors or prisms;

c) optical bar type cameras with folded, rotating optics and moving films.

The strip cameras exposes a continuous photograph of the terrain by passing the film over a stationary slit in the focal plane of the lens at a speed synchronized with the velocity of the ground image across the focal plane. The rays from the single point will be focused as a single point on the film throughout the time of exposure. The duration of the exposure T_E is defined on the film speed V_F and the width of the slit W:

$$T_E = \frac{W}{V_F}$$

Multi spectral cameras (or multi band cameras) are designed to produce photos in deferent bands of wavelengths. They have three main types of construction:

a) multi-camera installation;

b) multi-lens cameras;

c) beam-splitter cameras.

The multi-spectral cameras are designed specially for the purposes of interpretation and are object of Remote Sensing data capturing methods.

Metric aerial cameras

The two main objects of aerial photography are photogrammetry and photo-interpretation. For photo interpretation the main requirement is a high quality of detail reproduction. For photogrammetry the geometry is just as important as image quality Metric aerial cameras are therefore more universally used than the other types of cameras. The requirement for exact geometry forces the use of central shutter. The cameras with focal-plane shutter do not ensure central projection for the whole image. This is not ensured in the continuous strip cameras and in the optical-mechanical scanners. Multispectral cameras consist of several cameras (four or six), which are mounted together with parallel axes in a single unit.

Requirements for aerial cameras. Include possibilities for use 24V direct current, to satisfy radio-interference conditions, the requirements for the outer orientation must be met.

He mounting of the camera must ensure:

- Possibility for leveling and for keeping the leveling (by gyroscopes and leveling sensors);
- Compansation of drift (by rotation in κ).
- The camera must has good navigation equipment;
- Overlap regulator;
- Good intercomunication system;
- Visual signalisation for the moment of exposure;
- Compensation of film motion;
- High speed central shutters
- Flash exposure of fiducial marks

For the purposes of good inner orientation are important the following things

Principal distance is fixed;

Image format is usually 23cm x23cm

Vacuum holding of film during the exposure;illumination of fiducial marks;

Number of fiducial marks more then 4;

Additional fiducial marks for orientation of photo after exposure.

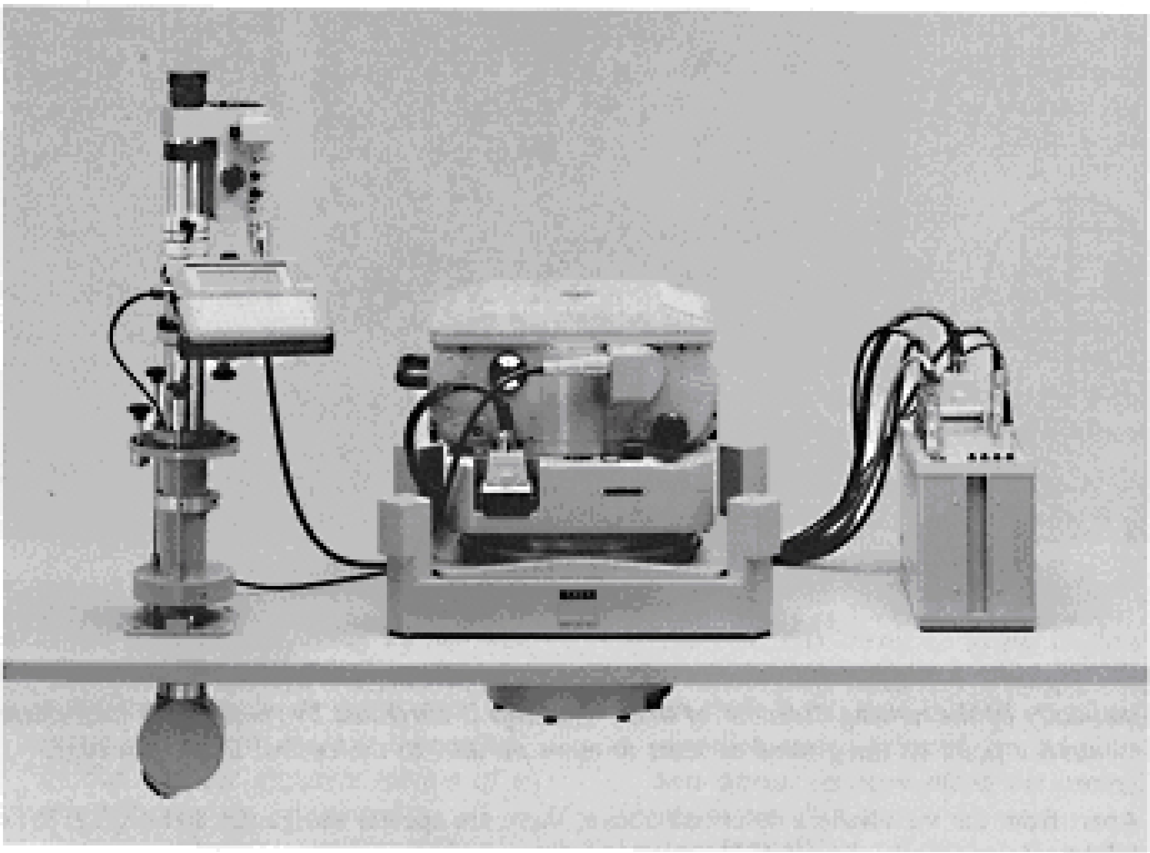


Figure 2.19. Aerial camera RMK TOP 15/23

There is a large amount of cameras. ZEISS Oberkochen offers RMK TOP 15/23, ZEISS Jena offered LMK cameras with focal lengths 89, 152, 210 and 30mm, Wild produces series RC30 with 88, 152, 210 and 310mm focal lengths of the objectives.

The comparison of different objectives and preferable area of application is shown in table 2.7

Table 2.7

Field angle	Narow 33 gon	Normal 62 gon	Intermidiate 85 gon	Wide 100 gon	Super-wide 140 gon
Principal distance [mm]	600	303	210	152	88
Ratio of principal distance to image diagonal	2:1	1:1	2:3	1:2	1:4
Base-height ratio (B/H) for 60% overlap	1:6.6	1:3.3	1:2.3	1:1.6	1:0.95
Model area (h-constant)	6	25	50	100	290
Flying height above ground (area=constant, scale=constant)	400	200	150	100	60
Applications or criteria for selection	Trend to Longer focal lengths	← Interpretation ← Photo-maps ← High mountains ← Cities Aerial triangulation → Flight costs → Reconnaissance flights → Height accuracy →			Trend to shorter focal lengths

2.3. Extended form of the co-linearity equation

As it was mentioned in real photogrmmetric system the principal point does not coincides with the origin of the coordinate system defined by the fiducial marks.

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} x - x_p \\ y - y_p \\ -c \end{bmatrix}$$

The other source of errors if emulsion deformation. When the distances between opposite edges of camera frame are known then it is possible to make simple correction

$$x' = k.x \quad y' = k.y \quad \text{where k=}\frac{S_c}{S_m}$$

where Sc is calibrated distance, and Sm is measured distance.

It is possible to calculate different correction coefficients by x and y axis.

$$x' = k_x.x \quad k_x = \frac{S_{cx}}{S_{mx}}$$
$$y' = k_y.y \quad k_y = \frac{S_{cy}}{S_{my}}$$

The common expression used for correction of film deformation is based on the known coordinates of fiducial marks respectively to the coordinate system of camera frame.

The common transformation is projective one

$$x' = \frac{a_x.x + b_x.y + c_x}{d.x + e.y + 1}$$
$$y' = \frac{a_y.x + b_y.y + c_y}{d.x + e.y + 1}$$

Applying of projective transformation requires more then 4 fiducial marks to ensure enough measurements for of 8 coefficients by least square method.

It most commonly used affinity transformation

$$d = e = 0$$
$$x' = a_x.x + b_x.y + c_x$$
$$y' = a_y.x + b_y.y + c_y$$

In this case the coefficients of transformation could be presented in the form

$$a_x = k_x.\cos\alpha \quad b_x = -k_x.\sin\alpha$$
$$a_y = k_y.\sin(\alpha - \beta) \quad b_y = k_y.\cos(\alpha - \beta)$$

It is possible to use transformation with 5 unknowns, defined as

$$a_x = k_x.\cos\alpha \quad b_x = -k_x.\sin\alpha$$
$$a_y = k_y.\sin\alpha \quad b_y = k_y.\cos\alpha$$

If we use only four parameters, this corresponds to 2D similarity transformation

$$ax = by = k.\cos\alpha$$
$$ay = -bx = k.\sin\alpha$$

The case of four and six parameters are most commonly used depending on the type of really presented deformation. This could be choose based on the errors in fiducial marks for these two types of transformations.

Sometimes the transformation only with three parameters could be applied.

$$ax = by = \cos\alpha$$
$$ay = -bx = \sin\alpha$$

For cameras with reseau marks it is possible to use two approaches. The first one is to use the error in the nearest reseau mark

$$x' = x + (x_r - x_m)$$
$$y' = y + (y_r - y_m)$$

Another approach uses calculation of errors over the image plate based on least square method.

$$x' = x + a_0 + a_1.x + a_2.x^2 + a_3.y + a_4.y^2 + a_5.xy$$
$$y' = y + b_0 + b_1.x + b_2.x^2 + b_3.y + b_4.y^2 + b_5.xy$$

The problem here is the choice of the order of polynomial used for approximation.

Another source of errors is the curvature of plates or film at the time of exposure. The errors could be expressed in the form depending on displacement in radial direction.

$$\Delta r = \Delta h \frac{r}{c - \Delta h}$$
$$\Delta x = \frac{x}{r}.\Delta r \quad \Delta y = \frac{y}{r}.\Delta r$$

The most important error in coordinates is due to the lens distortion. The distortion is characterized by two distinct components – radial and tangential.

The influence of radial distortion is shown on the next figure

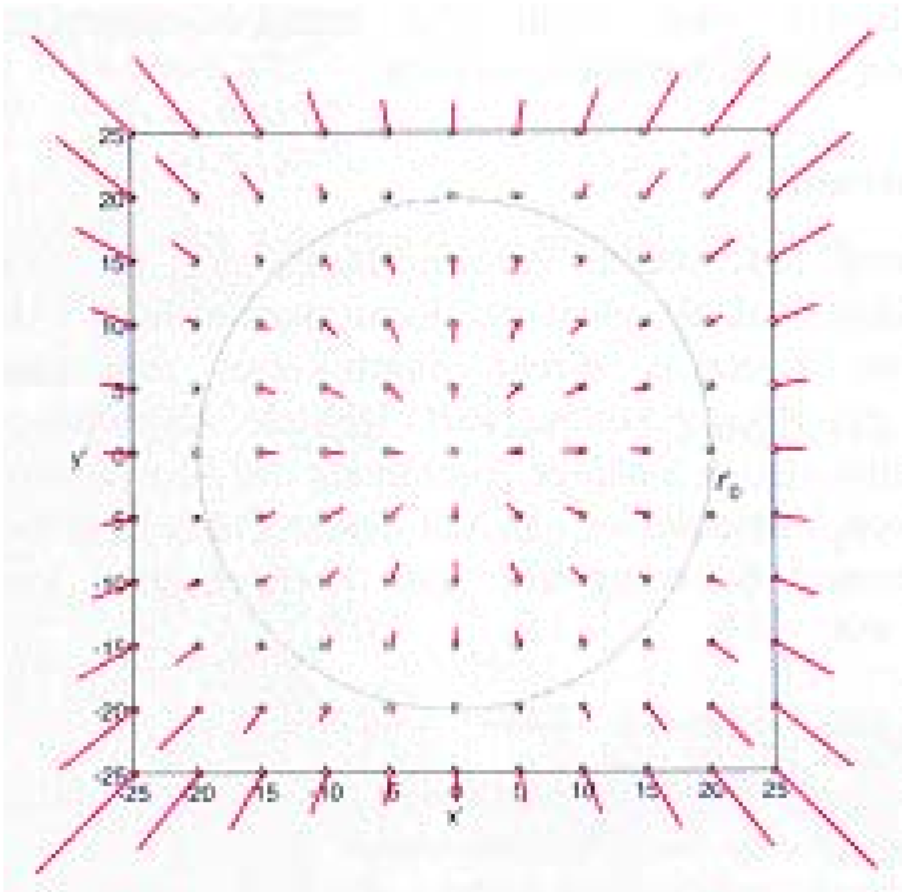


Figure 2.20 Radial distortion displacement

The errors are greater at the corners of the image.

The radial distortion is presented as odd-powered polynomial such as

$$\Delta r = K_1.r^3 + K_2.r^5 + K_3.r^7 + ...$$

The distortion could be presented for different positions of axis of calibration. If choose position from condition of balance of distortion curve this change the value of camera constant too.

$$\Delta r = K_0.r + K_1.r^3 + K_2.r^5 + K_3.r^7 + ...$$

The coefficient K_0 is obtained from

$$K_0 = -(K_1.r^2 + K_2.r^4 + K_3.r^6 + ...)$$

The principle distance in this case is changed to new value c*

$$c^* = c.(1 - K_0)$$

The coefficients of radial distortion are expressed referring the principal point.

$$r = \sqrt{(x = x_p)^2 + (y - y_p)^2}$$

The terms for correction take the form

$$x'' = x'.[1-(K_0 + K_1.r^2 + K_2.r^4 + K_3.r^6 + ...)]$$
$$y'' = y'.[1-(K_0 + K_1.r^2 + K_2.r^4 + K_3.r^6 + ...)]$$

where x' and y' are corrected due to the principal point position

$$x' = x - x_p$$
$$y' = y - y_p$$

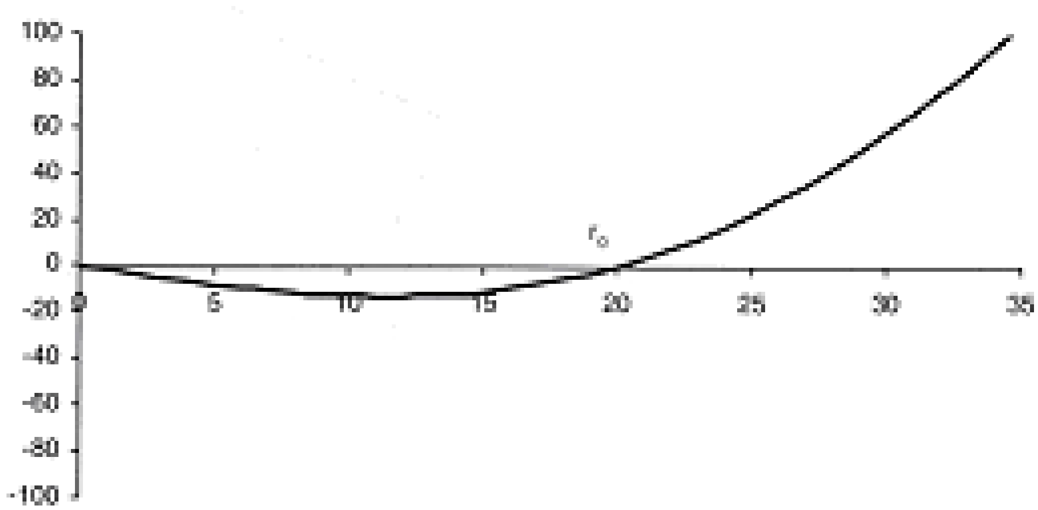


Figure 2.21. Graphic presentation of radial distortion

Unfortunately, the actual lenses are subject to various degrees of decentration, that is the centers of curvature of their optical surfaces are not strictly colinear. This defect introduces error that is termed decentering distortion. This distortion has both radial and tangential component and can be described analytically by the expressions

$$\delta_r = 3(J_1.r^2 + J_2.r^4 + ..)\sin(\Phi - \Phi_0)$$
$$\delta_t = (J_1.r^2 + J_2.r^4 + ..)\cos(\Phi - \Phi_0)$$

where angle Φ is the angle of the vector of point

$$\Phi = \arcsin\frac{x - x_p}{r} = \arccos\frac{y - y_p}{r}$$

The angle Φ_0 is the angle of maximum tangential distortion.

The decentering parameters could be transformed in the following way

$$P_1 = J_1.\sin\Phi_0$$
$$P_2 = J_1.\cos\Phi_0$$
$$P_3 = J_2 / J_1$$

The reversal form of these equations gives

$$\Phi_0 = \arctan\frac{P_1}{P_2}$$
$$J1 = \sqrt{P_1^2 + P_2^2}$$
$$J2 = \sqrt{P_1^2 + P_2^2}.P_3$$

If summarize the influence of radial and tangential distortion it is reached to generalized expressions for correction of distortion.

$$\Delta x_d = x'.(K_1.r^2 + K_2.r^4 + K_3.r^6 + ...) + [\mathrm{P}_1(\mathrm{r}^2 + 2\mathrm{x}'^2) + 2P_2 x' y'][1 + P_3.r^2 + ...]$$
$$\Delta y_d = x'.(K_1.r^2 + K_2.r^4 + K_3.r^6 + ...) + [\mathrm{P}_1 x' y' + 2P_2(\mathrm{r}^2 + 2\mathrm{y}'^2)][1 + P_3.r^2 + ...]$$

The projection equations resulting from the properties of undisturbed cental projection may be put in the form

$$x - x_p = -c\frac{r_{11}\lambda + r_{21}\mu + r_{31}\nu}{r_{13}\lambda + r_{23}\mu + r_{33}\nu}$$
$$y - y_p = -c\frac{r_{12}\lambda + r_{22}\mu + r_{32}\nu}{r_{13}\lambda + r_{23}\mu + r_{33}\nu}$$

where r_{ij} are elements of the rotation matrix and λ, μ, ν denotes the direction cosines of the ray joining the projection center with corresponding image (or object) point.

For directional control (as in the case of measurements to the stars) is as follows

$$\lambda = \sin\alpha^*.\cos\omega^*$$
$$\mu = \cos\alpha^*.\cos\omega^*$$
$$\nu = \sin\omega^*$$

where α*, ω* are polar coordinates of the object point (star).

For points in object space with Cartesian coordinates the expressions have the form

$$\lambda = \frac{X - X_o}{R}$$
$$\mu = \frac{Y - Y_0}{R}$$
$$\nu = \frac{Z - Z_0}{R}$$

where R is distance from projection center to the point and X_0, Y_0, Z_0 are coordinates of projection center.

$$R = \sqrt{(X - X_0)^2 + (Y - Y_0)^2 + (Z - Z_0)^2}$$

If replace coordinate values with measured coordinates and errors from distortion we obtain

$$x - x_p = \xi + v_x - x_p + \Delta x_d$$
$$y - y_p = \eta + v_y - y_p + \Delta y_d$$

where ξ, η are measured co-ordinates

v_x, v_y – residuals corresponding to the measured co-ordinates.

It must be mentioned that in expressions for distortion errors can be used measured co-ordinates but not adjusted (as they are not yet known).

If the expressions for image coordinates replace in the colinearity equation we obtain for the case of measurements to the stars

$$\xi + v_x - x_p + \Delta x_d = -c\frac{r_{11}\lambda + r_{21}\mu + r_{31}\nu}{r_{13}\lambda + r_{23}\mu + r_{33}\nu}$$
$$\eta + v_y - y_p + \Delta y_d = -c\frac{r_{12}\lambda + r_{22}\mu + r_{32}\nu}{r_{13}\lambda + r_{23}\mu + r_{33}\nu}$$

For the case of measuring the coordinates to the object points the generalized equations have the form

$$\xi + v_x - x_p + \Delta x_d = -c\frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$
$$\eta + v_y - y_p + \Delta y_d = -c\frac{r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

In this equation it is possible to take into account the refraction errors, which will influence over the direction cosines to the measured points (stars or object points).

This generalized equations could be used not only for determination of space coordinates of the new points (X, Y, Z) and the elements of outer orientation of the photos (cameras) (φ, ω, κ, X_0, Y_0, Z_0) but also for simultaneous calibration of the cameras. In this case the number f unknowns increases with the parameters of inner orientation (x_p, y_p, c).

2.4. Calibration of the photogrammetric camera

Camera calibration could be made in optical laboratories (by goniometers), on special test fields, or simultaneously with adjustment of measurements. The calibration of cameras requires special distribution of control points in the test fields especially if the parameters of distortions must be determined. In common case if only parameters of outer and inner orientation must be determined it is necessary to have control points at least in two planes at the different distances from the projection center of the camera.

The principles of classification of calibration methods may differ. It could be applied optical calibration or photogrammetric calibration. Photogrammetric calibration could be independent calibration and simultaneous calibration. The photogrammetric calibration is based on the usage of the co-linearity equations. Depending on this which parameters are including they exists methods for full calibration or for separate calibration.

The methods for calibration may be divided to preliminary calibration and on job calibration.

Preliminary calibration is **Laboratory calibration**. It is made by optical methods. The optical goniometer is used to execute this calibration. As result of laboratory calibration a camera passport is produced. It contain the fiducial mark coordinates in the camera coordinate system, referring to the man point of symmetry, the coordinates of principle point and camera constant. Additionally are given parameters of distortion and very often the calibration curves for radial distortion for different radial directions.

Photogrammetrc preliminary calibration is arranged as **test field calibration**. It is important to be known that due to the dependency between the camera constant and distance of measurement, it is obligatory to dispose control point in two or more different planes from the projection center f the camera. They exist some special methods for determination of camera distortion. One of tem is so called plumb-line calibration. In this method the square net of vertical and horizontal lies is used. The coordinates of cross points are determined by survey methods. It is important to be emphasized that in this method the camera constant must not be included in calibration as this field lies at the same plane. For CCD cameras are amateur small format cameras that has zoomed lenses (with variable focusing distances) special field with numerous of control targets is suggested (by Wiley and Wong). Practically control points are distributed over the faces and edges of square pyramid which apex is most far from projection center in the camera ray direction.

Methods for simultaneous calibration could be divided into on job calibration and self-calibration methods.

The **on job calibration** methods use additional targets to ensure requirements for calibration. Some times special arrange crosses of marks situated on tripods may be used. It is possible to arrange target on the plates and some similar configurations. The on-job calibration is m0re often is used to determine main calibration parameters – principle point coordinates and camera constant. It s important to be noticed that for close range camera white different focusing distances it is important se different parameters for focusing to different distance. In other cases the same parameters for the same camera could be used.

The **self-calibration** method is the extension of on job calibration when parameters of inner orientation and parameters of distortion are determined simultaneously with the coordinates of new points. It is important to know that in this situation the appropriate configuration of control points is necessary to be ensured. This condition is easier to be satisfied for terrestrial and close range photogrammetry rather then for aerial photogrammetry where the terrain configuration is a restriction for good target configuration.

The number of equations fo case of self-calibration can be estimated by the equation

$$k = 6.n_p + 3.n_c + 6.n_d + 3.n_n$$

where n_p – number of photos;

n_c – number of cameras with different inner orientation parameters;

n_d – number of different cameras (different objectives with own distortion);

n_n – number of new points.

For case of aerial photography where the cameras are focused at the infinity we assume $n_i = n_d$ and very often is equal to 1. For close range photogrammetry the value of n_d depends on different types of cameras and n_i depends not only on the number of cameras but also on the different distances of focusing of cameras. For case of amateur cameras usage it is possible to determine independent parameters of inner orientation for every photo to achieve high accuracy.