Cameras

(K.Kraus Vol.1 § 3.1 - 3.4 - 3.6 - 3.7 ) not in this order
Airborne and terrestrial analogue sensors

So far: theory based on idealized models

Pin hole camera

Exact central projection

Now: real instruments

Distorsions in lenses, films, etc.....

Metric photograph

Elements of Inner Orientation
Airborne and terrestrial analogue sensors

Airborne cameras

Big format photograms (fixed)
Big blocks in normal geometry
Photos taken in motion
Resistant to high stress (pressure and temperature jumps, vibrations)

Terrestrial cameras

Various medium formats
Photos taken with a still support
Normal or convergent geometry
Stereometric cameras (bi-cameras)
CAMERA CLASSIFICATIONS

- METRIC CAMERAS developed for photogrammetric surveys, with stable and measured I.O. \textit{airborne} and terrestrial

- SEMIMETRIC CAMERAS i.o. not completely stable

- NON METRIC CAMERAS (amateur, for low accuracy survey)

DIFFERENT METHODS FOR INNER ORIENTATION DETERMINATION:

- FIDUCIAL MARKS fixed on the image when is taken \textit{airborne} and terrestrial

- RESEEAUX CAMERAS: a thin glass plate bearing a calibrated grid of regularly spaced crosses is imaged in every photo \textit{close range}

- FRAME CAMERAS: sharp image edge
## Terrestrial cameras

Cameras in fixed positions ➔ E.O parameters once measured by field survey

<table>
<thead>
<tr>
<th>INT.ORIENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial marks</td>
</tr>
<tr>
<td>Grid of targets</td>
</tr>
<tr>
<td>Photo frame</td>
</tr>
</tbody>
</table>

Easily levelled on a tripod

Interchangeable with theodolite and targets

Horizontal or vertical tilt possibility at fixed angles
Terrestrial metric cameras

Similar to airborne cameras

• fiducial marks (4)
• film flattening device (vacuum or pressure-plate)
• large format
• high quality optics
possible stereometric

• Examples:
  WILD P31 (102x127 mm)
  Zeiss UMK (130x180 mm)

Stereometric cameras can be = normal case
Terrestrial semi-metric cameras

Have a calibrated objective mounted on amateur body

Professional cameras with medium (60x60mm) format adapted to photogrammetric use

- Reseaux (9 o 121 crosses) example: Rollei 6006
  Defines the image reference system
  Allows corrections of film deformations
  Image coordinates are calibrated for each photogram

- Focusing at fixed distances
- Good quality optics
- Laboratory calibration certificate
- Today also in digital version
Terrestrial non-metric cameras
or
amateur cameras

Common cameras

Can be used in photogrammetry only after self-calibration procedure of all Orientation parameters (Int. and Ext.)
AERIAL CAMERAS

Final requirements

- Exact geometry
- Image sharpness
- High resolution

Working condition

Aerial cameras are mounted into an aircraft

Suppression of radio-interference, work with 28V DC and follow safety flight regulations

- Big dimensions: about 60x60x50 cm, weight about 70-90 kg

- Big format film 23 cm x 23 cm (9” x 9”) and magazine with 120-150m film (500-600 photograms)
PRINCIPAL REQUIREMENTS IN AERIAL CAMERAS

• **fixed principal distance c**
  Photos are taken at big distances (100m - Nx1000m) therefore there is no problem with focusing distance: the objective is focused at infinity.

• **fiducial marks** (reperes) 4 or, better, 8, on the image plane (lightened) + 1 asymmetrically placed inside or at the edge of the image, for the automatic determination of image position

  accurate construction of each component (optics, mechanical parts, for.ex. central shutters)

• **automated device** for flattening of the film, motion and drift corrections

• I.O. parameters by **lab-calibration** and components **stability** respect to vibrations, big temperature changes, thermal expansion
**AERIAL CAMERAS**

Photogrammetric cameras classification according **field angle** of the objectives:

Angle with vertex in projection center O and rays pointing to the ends of image diagonal

For the format 230 mm x 230 mm:

<table>
<thead>
<tr>
<th>Field angle</th>
<th>Reduced Normal</th>
<th>Normal N</th>
<th>WideAngle W</th>
<th>Super - WideAngle SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>60°</td>
<td>90°</td>
<td>120°</td>
<td></td>
</tr>
<tr>
<td>Principal distance c (mm)</td>
<td>600</td>
<td>300</td>
<td>150</td>
<td>90</td>
</tr>
</tbody>
</table>

Big scale survey (ex. urban areas, orthoimages)

Medium and large scale (more commonly used)

Small scale
## AERIAL CAMERAS

C, Z, B and photograms overlapping are geometrically constrained each other.

<table>
<thead>
<tr>
<th>Field angle</th>
<th>Reduced Normal</th>
<th>Normal N</th>
<th>WideAngle W</th>
<th>Super - WideAngle SW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30°</td>
<td>60°</td>
<td>90°</td>
<td>120°</td>
</tr>
<tr>
<td>Principal distance c (mm)</td>
<td>600</td>
<td>300</td>
<td>150</td>
<td>90</td>
</tr>
<tr>
<td>B/Z for 60% overlapping</td>
<td>1:6.6</td>
<td>1:3.3</td>
<td>1:1.6</td>
<td>1:0.95</td>
</tr>
</tbody>
</table>
Auxiliary data imaged with the photogram, digital, or analogical
To reconstruct Int. Or. each photogram must bear:

- **fiducial marks** (to fix the principal point position)
- **the principal distance**
- **camera number** (numero di matricola) referring to the calibration certificate

And many others:

- Fiducial marks (4/8 + 1)
- Circular level
- Time
- Course and fine height indicators
- N camera
- Princ. dist.
- N magazine
- Project name
- Date

6. Photo number
10. Ext. Or. data
11. Overlap
12. Photo-scale
16. Exposure time, aperture
17. Length of image motion
18. Grey wedge
Schematic diagram of an aerial camera

Overlap control
Viewfinder telescope
Control instruments
Spherical level
K-clamp
3 footwcrews for \( \phi \omega \)

Pressure plate
Rollfilm
Lens cone and camera frame

Elettronica di controllo
28 Volt CC
Supporto della camera
Cavo di massa
Supporti anti-vibrazioni
Ventre dell'aereo
Portello di chiusura

Auxiliary data imaged on the photogram

Geographic coordinates \( \phi, \lambda \)
Projection center height
Angles \( \omega, \phi \)
Course and drift

If present: GPS/INS E.O. data
FURTHER REQUIREMENTS IN AERIAL CAMERAS

E.O. requirements

Possibility of reconstruct E.O.:

The camera

• Can be levelled with footscrew or gyros to maintain tilt angles $\omega$ and $\varphi < \pm 5\text{gon}$

• Can be rotated around its vertical axis to compensate drift (to be aligned to the ground track of the aircraft) $\kappa < \pm 3\text{gon} \Rightarrow 3\text{cm in 23cm images}$

• Navigation equipment to hold the flying track, and the flying height

• overlap regulator (to maintain overlapping also in montainous terrains) linked with automatic computation of ‘scatto’o ‘intervallo di scatto’

GPS/INS data: very important for navigation in poorly mapped regions
• can have a forward motion compensation device
• must have a central shutter so that exterior orientation is uniform over the whole image. This moreover allows to use shorter exposure time (1/150 ÷ 1/1000 s and less)
• The flash exposure of the fiducial marks must coincide with the mean moment of exposure (mean time of shutter opening)
• The film must be kept flat with a vacuum pressure flattening device
• Must be built with materials having the same termal expansion coefficient.

Pilot - Co-pilot - Photographer
But now many operations are remote-controlled or automated, and the pilot alone can operate the camera system.

Minimum interval between two successive shots: min cycle time 2 sec, this limits the base length.
The camera can operate automatically, controlled by the overlapping regulator, or manually.
There is a shot signal for the pilot to leave time to correct track, drift and attitude before the next shot
For checking drift and position are used:

- viewfinder (WILD)
- overlap control (ZEISS)
- special pointers remote-controlled by navigator-photographer

In the viewfinder the operator sees the apparent motion of the ground and:

- Image frame (inquadratura)
- Target point
- Spherical level
- Central line to check drift angle
- Moving lines for overlap regulator

The lines should move at the same apparent speed of the ground. In this case, the operator control the preset overlap regulator along track.

Over mountainous areas apparent speed of motion can vary widely because of great flying height variations. Moving lines extends over the full field of view. (overlapping must be maintained in the highest parts)
The aircraft flies along its nominal course, the side wind drives it along a different course (drift $\alpha$).

In the viewfinder a central point doesn’t stay on the central line.

The course is corrected by an angle $k= -\alpha$, and the camera is rotated on the aircraft of $\alpha$. The real course thus coincides with the planned direction and in the viewfinder a central point lies on the central line.
## ANALOGUE AIRBORNE CAMERAS

**CAMERE METRICHE AEREE**

<table>
<thead>
<tr>
<th></th>
<th>ZI-Imaging 1)</th>
<th>Leica 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Camera name</strong></td>
<td>RMK Top</td>
<td>RC 30</td>
</tr>
<tr>
<td><strong>Image format [cm²]</strong></td>
<td>23 x 23</td>
<td>23 x 23</td>
</tr>
<tr>
<td><strong>Optics</strong></td>
<td>Pleogon A3</td>
<td>UAG-S</td>
</tr>
<tr>
<td><strong>Focal length [cm]</strong></td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td><strong>Field of view [gon]</strong></td>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td><strong>Apertures</strong></td>
<td>1:4 – 1:22</td>
<td>1:4 – 1:22</td>
</tr>
<tr>
<td><strong>Exposure time [s]</strong></td>
<td>1/50 – 1/1000</td>
<td>1/100 – 1/1000</td>
</tr>
<tr>
<td><strong>Film length [m]</strong></td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td><strong>min. Image cycle [s]</strong></td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td><strong>Overall weight [kg]</strong></td>
<td>~ 134</td>
<td>~ 130</td>
</tr>
</tbody>
</table>

1) Intergraph/ZI-Imaging formerly Carl Zeiss  
2) Leica Geosystems formerly LH-Systems, Wild  
3) incl. mount, film magazine, control unit
Airborne camera RC30 (more)

Three objectives (8.8, 15, 30 cm).
Exposure intervals 1/100 s - 1/1000 s.
Max aperture  f/4
Forward Motion Compensation
Film length 120m

Automatic flight planning, navigation and positioning systems with precise positioning of projection centers.

**ASCOT** (Aerial Survey Control Tool)
Allows the automatic flight path following, giving to the pilot a real time control of aircraft and camera positions respect to the planned course.

Directly gives center of projection coordinates to be used in A.T computations.
Taylored selection of imaged information (e.g. auxiliary and external data)
RMK TOP (more)

Focal lengths 15 cm e 30 cm.
Exposure intervals 1/50 s - 1/500 s
Forward Motion Compensation
Rubber vibration damper (better image quality)

Possibility of flight control by GPS/INS system and of precise projection centers positioning for successive A.T.
Can be totally and automatically controlled by the pilot
Taylored selection of imaged information (e.g. auxiliary and external data).
Automatic control of drift and overlap
Will digital aerial cameras substitute analogue cameras?

In the future, but analogue cameras are still widely used:

World use of analogue and digital airborne cameras
INNER ORIENTATION DETERMINATION

A photogrammetric camera objective is an optical system realized combining different kind of lenses. The deviation of its behaviour from an idealized model give rise to various source of image distortions

For an ideal optical system there are two principal planes that have peculiar properties: **principal planes H and H'** (in object space and image space)

The intersections of **H and H'** with the Optical Axis (OA) identify the **nodal points N and N'**

- the ‘central rays’ passing through the nodal points, form the **same angle τ** with the optical axis in the object space and in the image space

**N** is the projection center in the object-space and **N’** is the projection center in the image-space
INNER ORIENTATION

The optics of a metric camera is a thick asymmetric objective.

Individual lenses are made of different types of glass to ensure the greatest possible corrections of imaging errors.

The aperture stop (diaframma), is not in the center of the objective, and limits the effective bundle of rays forming the image points → entrance pupil EP (and exit pupil in image space).

Problem: where is the projection center??

Centers of EP and EP' define the REAL projection centers, in object and image spaces.
INNER ORIENTATION

Real photogrammetric objective is very different from theoretical optical model

REAL image formation geometry

the optical axis OA should contain the centres of all lenses, but small errors sum up

\[ \tau' \text{ is different from } \tau \text{ (because EP and EP' do not coincide with H and H')} \]

- the mechanically realized principal distance \( s' \) differs slightly from the optical principal distance \( s' \)
- Image Plane is not rigorously perpendicular to the optical axis OA, nor to \( PR_A \)
INNER ORIENTATION

MAIN EFFECT: \( \angle \tau' \) is different from \( \tau \)

Correction: define a mathematical projection center \( O'_M \) which lies at a perpendicular distance \( c \) from PPA that reproduces the angles \( \tau \) as closely as possible

In any case there exists a difference in position from real image point \( P' \) and the theoretical position.

The distance is a residual error called optical **distorsion**.

We distinguish two components, one radial \( \Delta \rho \) and the other \( \Delta \tau \) tangential, perpendicular to the first one (**radial, & tangential distortion**).

The tangential distortion (often called ‘decentering distorsion’) is due to non perfect centering of all the lenses forming the camera lens.

Usually the radial distortion \( \Delta \rho \) is much bigger than the tangential one \( \Delta \tau \), that is normally around 5%.
INNER ORIENTATION

Distortion curve

Barrel distortion

Distortion curve

Cushion distortion
INNER ORIENTATION

DECENTERING DISTORSION

In high precision surveys the decentering or tangential distorsion must be taken into account, that derives from a non perfect centering of the lenses composing the optical system.

The effect is that radial straight lines become curves
The following relation holds between radial distance $\rho$ of a point $P'$ respect to PPA and radial distorsion $\Delta \rho$ (in $P'$):

inner orientation equation

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

$$\cot \tau = \rho_{teor}$$
Camera calibration

Radial distortion curves are measured during calibration procedures in a laboratory using a ‘photo-goniometre’

For fixed $\tau$, the corresponding $\rho' = \rho_{\text{obs}} = \rho_{\text{teor}} + \Delta \rho$

are measured, using a calibrated grid (0.1 $\mu$m)
A complete calibration procedure consists of determining the position of PPA and the radial distortion along the four semi-diagonals of the photogram. (To take care of asymmetry)

\[ \text{ctg} \tau = \rho_{\text{teor}} \]

The differences \( \rho_{\text{oss}} - \text{ctg} \tau = \Delta \rho \) are the optical radial distortions.

Usually these four curves are non identical.

The asymmetry is greatly reduced by choosing another axis as reference: the principal axis of symmetry \( \text{PR}_s \).

\( \text{PR}_s \) pass through O and intersects the image plane IP in the Point of Best Symmetry \( \Rightarrow \text{PBS} \).
The reference optical axis becomes PR$_S$ in place of PR$_A$ and:

- $(\xi, \eta)$ refers to PBS
- the new projection center is O$'_M$, and is at distance $c$ from PBS
- radial distortion curves are referred to PBS

In order to model and reduce as better as possible the radial distortions, during the calibration procedure a new (calibrated!) principal distance $c' = c + \Delta c$ is computed, so as the distortion curves are as near as possible to the $\rho$ axis (nearly zero values)

In fact, the effect of varying the principal distance is to rotate the curves around the origin.
Older photogrammetric objectives have mean radial distortion up to \(|\Delta \rho| \leq 30 \mu m\)

Modern objectives are nearly distortion-free \(|\Delta \rho| \leq 2 \mu m\)

So small distortions are corrected only in high precision photogrammetry, taking into account both radial and tangential distortion, together with other photogram deformations.

How radial distortion curve is used:

given (measured) \(\xi\) and \(\eta\), it is possible to compute \(\rho\):

\[
\rho = \sqrt{(\xi - \xi_0)^2 + (\eta - \eta_0)^2}
\]

then \(\Delta \rho\) can be deduced from distortion curve

\[
\rho_{teor} = \rho_{corr} = \rho_{oss} - \Delta \rho
\]

\[
\Delta \rho = \rho_{oss} - c \tan \tau = \rho_{oss} - \rho_{teor}
\]

\(\Delta \rho\) is decomposed into the components \(\Delta \xi\), \(\Delta \eta\):

\[
\Delta \xi = \frac{(\xi - \xi_0)}{\rho} \Delta \rho \quad \Delta \eta = \frac{(\eta - \eta_0)}{\rho} \Delta \rho
\]

These are corrections to be added to image measured coordinates \(\xi\) and \(\eta\):

\[
\xi_{corr} = \xi_{oss} - \Delta \xi
\]

\[
\eta_{corr} = \eta_{oss} - \Delta \eta
\]
• Modello di Fraser, 1999, 10 parametri:
  • c, X₀, Y₀: parametri di O.I. standard
  • K₁, K₂, K₃: distorsione radiale
  • P₁, P₂: distorsione tangenziale
  • b₁, b₂: distorsione affine

  \[ \xi = D\xi - c \frac{NX}{D} \quad \eta = D\eta - c \frac{NY}{D} \]

  • \( D\xi = X₀ + x (K₁ r² + K₂ r⁴ + K₃ r⁶) + \)
  + \( P₁(r² + 2x²) + 2 P₂ x y + b₁ x + b₂ y \)

  • \( D\eta = Y₀ + \eta (K₁ r² + K₂ r⁴ + K₃ r⁶) + \)
  + \( P₂(r² + 2y²) + 2 P₁ \xi \eta \)
CALIBRATION CERTIFICATE

For the physical definition of the image coordinate system fiducial marks are used, imaged in every photograph, that define the fiducial centre FC. But the image coordinates have to be referred to PPA or PBS.

Photogrammetric cameras commonly have PPA, PBS and FC at distances smaller than 20 µm.

The calibration certificate of a photogrammetric camera contains:

- image coordinates of fiducial marks;
- image coordinates of FC, PPA and/or PBS;
- principal distance c;
- the mean radial distortion curve;
- date of calibration;
- information on image sharpness.

⇒ In Italy the calibration certificate has to be renewed every 2-3 years
Principal point of autocollimation (PPA) and principal point of symmetry (PPS) referred to central cross (FC), see diagram

<table>
<thead>
<tr>
<th></th>
<th>x (mm)</th>
<th>y (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPA</td>
<td>-0.006</td>
<td>-0.001</td>
</tr>
<tr>
<td>PPS</td>
<td>-0.004</td>
<td>-0.002</td>
</tr>
</tbody>
</table>

Fiducial marks, referred to central cross (FC)

<table>
<thead>
<tr>
<th></th>
<th>x (mm)</th>
<th>y (mm)</th>
<th></th>
<th>x (mm)</th>
<th>y (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100.001</td>
<td>-100.000</td>
<td>5</td>
<td>-0.002</td>
<td>-111.998</td>
</tr>
<tr>
<td>2</td>
<td>-100.001</td>
<td>-105.999</td>
<td>6</td>
<td>-112.002</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>-105.001</td>
<td>105.000</td>
<td>7</td>
<td>-0.001</td>
<td>112.000</td>
</tr>
<tr>
<td>4</td>
<td>100.003</td>
<td>105.001</td>
<td>8</td>
<td>112.003</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Radial distortion for semi-diagonals referred to PPS

Mean radial distortion

<table>
<thead>
<tr>
<th>Radius (mm)</th>
<th>D (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.000</td>
</tr>
<tr>
<td>100</td>
<td>0.000</td>
</tr>
<tr>
<td>148</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Aperture: 4.5
Filter on goniometer: VIS (400-700 nm)
Filter on camera: -

C.F.L.: 150.314 mm
Camera calibration

Radial distortion can be modelled through a polynomial curve

Photogrammetric sw accept curves given in a discretized tables $\Delta \rho (\rho)$, or in terms of polynomial coefficients : $K_0, K_1$.....(also for semi-metric cameras)

$$\Delta \rho = K_0 \rho^{oss} + K_1 \rho^{3}_{oss} + K_2 \rho^{5}_{oss} + ....$$

$$\Delta \rho = A_1 \rho^{oss} \left( \rho^{2}_{oss} - R^2_0 \right) + A_2 \rho^{4}_{oss} \left( \rho^{4}_{oss} - R^4_0 \right) + ....$$

The film magazine should be included in the calibration too

For high precision works it is advisable to take calibration photographs under the same flying condition, before and/or after normal photographic survey, over a test field with signalized points.
Camera calibration

Cameras for close range are also often calibrated on a spatial test field, computing all parameters of inner and outer orientation together.

(self-calibration)