Orthophoto

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Outline

What is an ortho-photo (ortho-image)?

An ortho-photo (ortho-image) is an image which has been "corrected" for the **geometric** distortions (different projection, lens/sensor distortion, relief) so that it can be used as a map.

This is foundamental for:

- using the image with other maps in a Geographic Information System
- combining the image or the results of its processing (e.g. classification) with other maps
- comparing the image or the results of its processing with points representing the "ground truth"

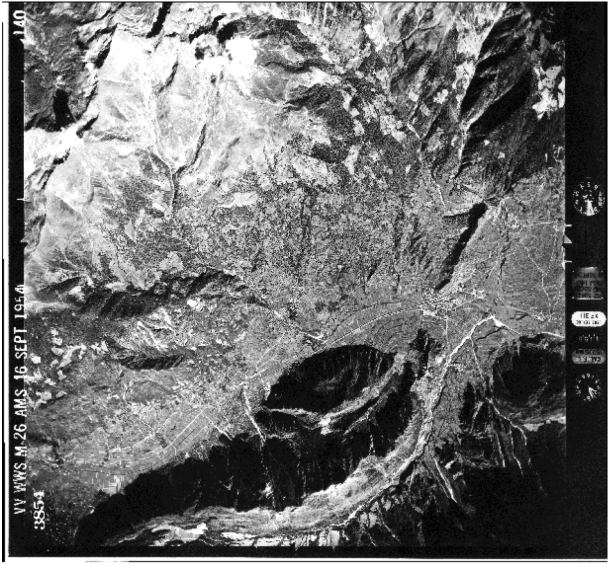
This lecture deals with geometric corrections, not with radiometric corrections, such as those needed for images mosaics.

Why is this important?

The ortho-rectification of aerial and satellite images is important because:

- the high resolution of the images currently available makes the distortions of unprocessed images inacceptable
- images from different platforms and sensors are combined
- images are often combined with spatial information coming from other sources (e.g. GPS, carthography)

Example - Aerial image of central Valsugana I



Frame camera - USAF 1954

Example - Aerial image of central Valsugana II

This image cannot be used with maps because:

- it is only possible to use local plane (xy) coordinates
- this is a *central* projection, therefore scale chages as a function of the distance from the projection of the lens' focus point
- occlusions may be present

While the first problem can be resolved by georeferencing the image using Ground Control Points (GCPs), the latter require the use of ortho-rectification.

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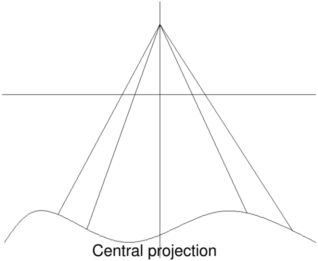
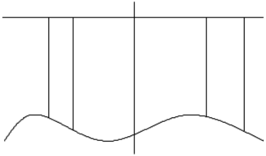
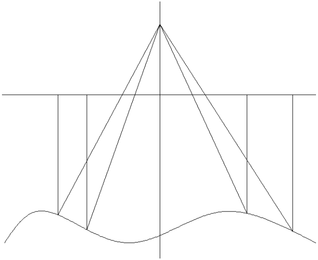
Example - Aerial image of central Valsugana III



Central projection

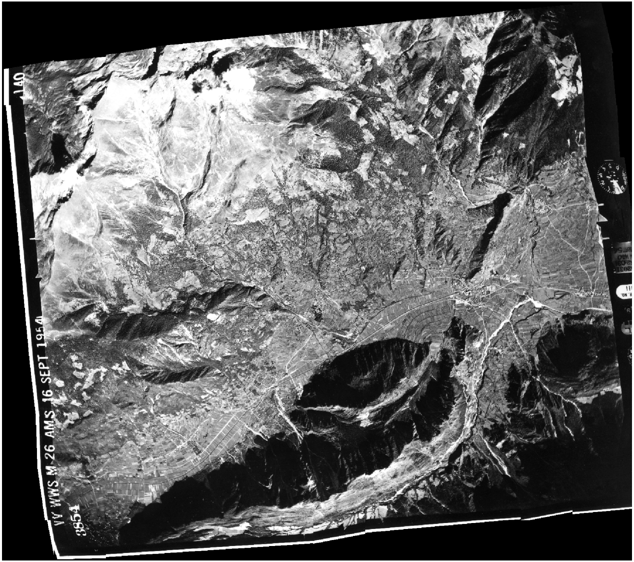


Carthographic projection



Ortho-rectification

Example - Orthophoto of central Valsugana I



Ortho-rectified image

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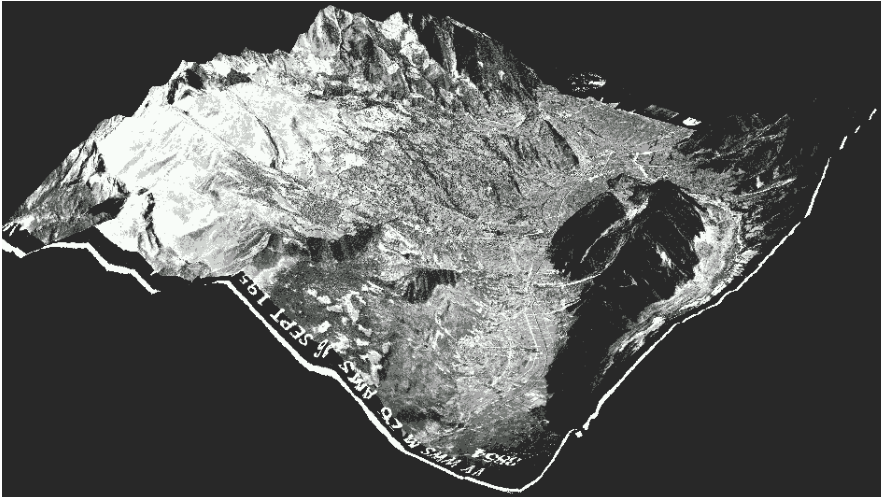
Example - Orthophoto of central Valsugana II



Ortho-rectified image - 3D view

Platforms and sensors

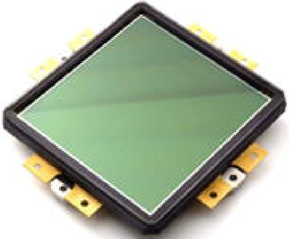
Different platforms and sensors have different geometry and create different types of images:

- frame cameras
- Visible and Infra-Red (VIR) oscillating or push-broom scanners
- Side Looking Antenna Radar (SLAR) or Synthetic Aperture Radar (SAR) sensors

each geometric configuration is “corrected” using different models.

Frame cameras

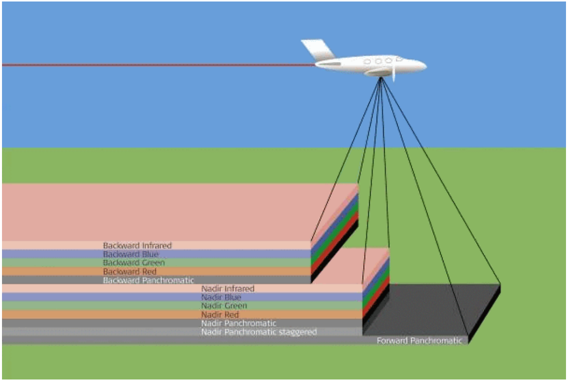
Intergraph DMC digital aerial frame camera (source: Intergraph)



CCD array sensor

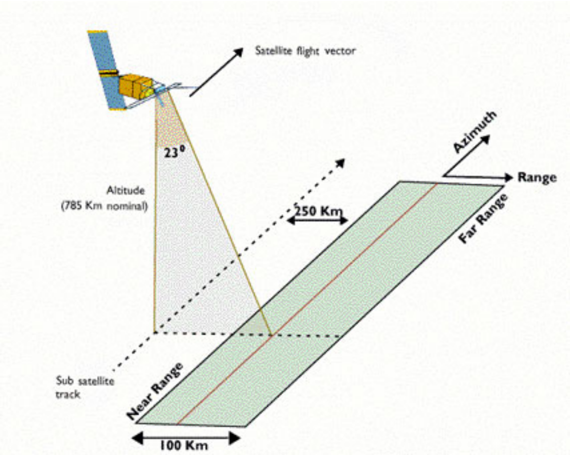
Visible and Infra-Red (VIR) oscillating or push-broom scanners

ADS40 digital aerial push-broom camera (source: Leica Geosystems)



Multiple linear CCD arrays for the Leica ADS40 (source: Leica Geosystems)

side looking antenna radar (SLAR) or synthetic aperture radar (SAR) sensors



SAR system configuration (source: ERS)

Geometric corrections

Geometric corrections are due to:

platforms and sensors - sensor geometry and positioning instruments accuracy (GPS, inertial systems, gyroscopes, ...)

observed objects - objects geometry and atmospheric distortions

cartographic projections - which map the earth surface (ellipsoid) to a plane

Usually all three types of corrections must be applied, in some cases semplifications are possible, for example when a flat terrain is observed.

Some corrections can be considered negligible for low resolution images.

Systematic and accidental effects

Geometric distortions can be divided in:

systematic - predictable (e.g. platform orbit), they are usually corrected by the image provider using determinisitc models

accidental - specific to an image or a group of images (e.g. atmospheric refraction and turbulence, variation of attitude), they must be corrected by the user

Some of the accidental alterations affect all types of sensors, some are sensor specific.

Common and sensor-specific effects

Corrections common to all the sensors are mainly:

- pixel spacing variations due to platform altitude changes and relief
- image (and pixel) shape variation due to attitude changes (roll, pitch and yaw) and Earth's surface curvature

Sensor-specific corrections are:

VIR and SAR
: geometric accuracy depends on the calibration of focal length and the instantaneous field of view (VIR) or range gate delay (SAR)

oblique-viewing system
: are subject to panoramic distortion and Earth curvature and topographic relief changes, which affect the ground pixel sampling along the column.

Empirical and rigorous models

Geometric corrections are performed using:

- 2D/3D empirical models (2D/3D polynomial or 3D rational functions)
  - used when physical models or their parameters are not available
  - do not require a priori knowledge of the system (platform, sensor,...)
- rigorous 2D/3D physical and deterministic models
  - can be performed in one or more steps
  - depend on the system (platform, sensor,...) in use

These models evaluate the position of a pixel on the image corresponding to a point the “corrected” image.
External information is provided through Ground Control Points (GCPs): point of known coordinates in the final ortho-image datum.

Empirical models

Empirical models are based on the use of:

- 2D polynomial functions
- 3D polynomial functions
- rational functions (RFs)

Depending on the model, the number of unknown terms for each component (x,y) grows with the order

Model order	1	2	3
2D polynomial	3	6	10
3D polynomial	4	10	20
RFs	8	20	30

2D polynomial functions

$$P_{2D}(X, Y) = \sum_{i=0}^{m} \sum_{j=0}^{n} a_{ij} X^i Y^j$$

where:

- X, Y are the terrain or cartographic coordinates
- m, n are integer values, usually [0 - 3]
- m + n is the order of the polynomial function, generally three

In general:

- orders above the second do not have physical meaning
- higher orders can lead to over-parametrisation, inducing additional errors
- higher orders require more calculations

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2D polynomial functions - first order

$$x = a_{00} + a_{10}X + a_{01}Y$$
$$y = b_{00} + b_{10}X + b_{01}Y$$

The fist order 2D polynomial (affine) transformation, with 6 terms, allows the correction of:

- a translation in both axes (2 unknowns)
- a rotation (1 unknown)
- scaling in both axes (2 unknowns)
- an obliquity (1 unknown)

2D polynomial functions - second order

$$x = a_{00} + a_{10}X + a_{01}Y + a_{11}XY + a_{20}X^2 + a_{02}Y^2$$
$$y = b_{00} + b_{10}X + b_{01}Y + b_{11}XY + b_{20}X^2 + b_{02}Y^2$$

The second order 2D polynomial transformation, with 12 terms, allows the correction of:

- a translation in both axes (2 unknowns)
- a rotation (1 unknown)
- scaling in both axes (2 unknowns)
- an obliquity (1 unknown)
- torsion in both axes (2 unknowns)
- convexity in both axes (4 unknowns)

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2D polynomial functions

2D polynomial transformations are used only for images with small distortions (nadir-viewing images, corrected images and/or small images over flat terrain).

The results are sensitive to errors in the ground control point (GCP) positioning, therefore GCPs must be numerous and regularly spaced.

These functions are currently used only for low resolution images or for fast preview.

3D polynomial functions

$$P_{3D}(X, Y, Z) = \sum_{i=0}^{m} \sum_{j=0}^{n} \sum_{k=0}^{p} a_{ijk} X^i Y^j Z^k$$

where:

- X, Y and Z are the terrain or cartographic coordinates
- m, n and p are integer values, usually [0 - 3]
- m + n + p is the order of the polynomial function, generally three

3D polynomials:

- take into account relief by using the Z coordinate
- are used only for small images
- need numerous GCPs regularly distributed
- can be used to remove only the effect of relief

3D Rational Functions

$$R_{3D}(X,Y,Z) = \frac{\sum_{i=0}^{m}\sum_{j=0}^{n}\sum_{k=0}^{p} a_{ijk}X^iY^jZ^k}{\sum_{i=0}^{m}\sum_{j=0}^{n}\sum_{k=0}^{p} b_{ijk}X^iY^jZ^k}$$

where:

- X, Y and Z are the terrain or cartographic coordinates
- m, n and p are integer values, usually [0 - 3]
- m + n + p is the order of the polynomial function, generally three

3D Rational Functions:

- can be used to approximate physical models
- are unable to model local distortions (important for VIR or SAR)
- can fail because of null denominator
- can show correlation between the terms of polynomial functions

These problems are solved by splitting the image in sub-images, using RF of variable orders or prepocessing the images.

3D Rational Functions

3D Rational Functions are often used when:

- parameters for rigorous models are not available
- image providers do not deliver satellite/sensor information with the image
- image providers deliver RFs parameters with the image

In the latter case the users can generate ortho-images directly from the images without GCPs (the DEM is still needed). If precise GCPs are available, they can be used for improve the RF parameters estimates.

RFs require a large number of evenly distributed GCPs, especially if the terrain is not flat.

2D/3D physical models

2D/3D physical models describe how the geometry must changes from the image to the ortho-image, therefore they must be taylored for each combination of platform, sensor and sensor geometry.

The most used sensors are:

- frame cameras (photogrammetric cameras), which acquire the whole image instantaneously
- Visible and Infra-Red (VIR) oscillating or push-broom scanners, which use a linear (real or virtual) array of sensor
- Side Looking Antenna Radar (SLAR) or Synthetic Aperture Radar (SAR) sensors

2D/3D physical models

All the three types of correction (due to platforms and sensors, observed objects and cartographic projections) must be modelled, but two strategies are possible:

1. perform each correction separately in a stepwise process
2. perform some or all corrections simoultaneously

While the first approach is usually more clear, since physically meaningful parameters are estimated, the latter can be more effective because many parameters are correlated and have similar effect on the final results.

Collinearity equations

Physical models are base on collinearity equations for instantaneous image or scanline acquisition (photogrammetric cameras, VIR scanner sensors)

$$x = -f \, \frac{r_{11}(X - X_0) + r_{12}(Y - Y_0) + r_{13}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)}$$

$$y = -f \, \frac{r_{21}(X - X_0) + r_{22}(Y - Y_0) + r_{23}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)}$$

where:

- (x, y) are the image coordinates
- (X, Y, Z) are the map coordinates
- (X_0, Y_0, Z_0) are the projection centre coordinates
- $-f$ is the focal length
- $r_i j$ are the 9 elements of the orthogonal 3-rotation matrix

Doppler equations

Doppler and range equations are used for radar images

$$f = 2\frac{(\vec{V}_s - \vec{V}_p) \bullet (\vec{S} - \vec{P})}{\lambda|\vec{S} - \vec{P}|}$$

$$r = |\vec{S} - \vec{P}|$$

where:

- f is the Doppler value
- r is the range distance
- $\vec{S}$ and $\vec{V}_S$ are the sensor position and velocity
- $\vec{P}$ and $\vec{V}_P$ are the target point position and velocity on the ground
- λ is the radar wavelength

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Processing steps

The creation of ortho-images, regardless the use of empirical or physical models, requires:

- image and meta data (for physical models) acquisition
- GCPs acquisition (image and map coordinates, including Z for 3D models) and check
- unknown parameters computation (“orientation” in physical models)
- image rectification (with DEM for 3D models)

Image acquisition

Depending on the image vendor, images are usually available with different:

- levels of pre-processing
- completeness of metadata related to sensor, satellite (ephemerides and attitude) and image
- GCPs or image's corners coordinates

Depending on the image and the available information, a suitable model for ortho-rectification must be chosen.

Ground Control Points I

Ground Control Points are ncessary to compute the models' unkonwns (coefficients for empirical models, orientation parameters for physical models).

The image coordinates (x,y) and the map ("ground") coordinates (X, Y, Z for 3D models) must be known for each GCPs.

In photogrammetry some points ("homologous" points) are used to bind toghether ("relative orientation") different images: in this case only image coordinates are required (but map coordinates are used when available).

Ground Control Points II

The number of GCPs needed depends on the number of unknown parameters, but usually a higher number is used in a least square adjustment procedure.

Advantages of this approach are:

- an estimate of the accuracy of the parameters' values is provided
- it is possible to implement a procedure for the outliers ("bad" points) detection

Ground Control Points III

The number of GCPs used depends on:

- final expected accuracy
- sensor type and its resolution
- image spacing
- GCPs definition and accuracy
- model in use
- survey technique

As a rule of thumb, at least twice the minimum number of GCPs must be collected.

Ground Control Points IV

The accuracy must be coherent with the image resolution.

The accuracy of carthographic coordinates is a function of the map's scale, it can be obtained by multiplying the scale for the graphical error (usually 0.2 mm) of the plotter.
For example for a map at 1:10 000 scale the accuracy is 0.2*10 000 = 2 000mm = 2m.

For GPS/GNSS surveys the accuracy depends mostly on the surveying technique (absolute or relative positioning, cinematic or static survey, etc.), ranging from a few millimeters to some meters.

The height (Z coordinate) can be evaluated from a digital terrain model, once the planimetric (X,Y) coordinates are known.

Model parameters computation I

Geometric model computation is performed using a least square adjustment, which provides estimates of the parameters as well as of their accuracy.

For models with non linear equations (physical models and second or higher order empirical models) approximate values of the parameters must be provided to stat the computation procedure.
The approximate values are set for:

empirical models to zero

physical models to values derived from flight information or from on board positioning systems (GPS, INS, gyroscopes)

The evaluation of the modelling accuracy is given by GCP residuals, a "good" result has RMS residuals in the same order of magnitude than the GCP accuracy.

Model parameters computation II

If some parameters are known from other instruments, it is possible to use their values and their accuracy in the adjustment procedure.

If more than one image has to be processed and the images are ovelapping, it is possible to process all the parameters evaluation process at once in the so called *bundle block adjustment*.

The advantages of this approach are:

- reduction of the number of GCPs (the same point is used more than once)
- a better relative accuracy between the images
- more homogeneous and precise mosaic over large areas

Image rectification I

Image rectification assigns one (for B/W images) or more (for multispectral images) values to each cell of the ortho-rectified image in the map datum.

This operation is performed in two steps:

1. for each cell in the ortho-rectified the coordinates of the corresponding cell in the original image are computed
2. the intensity value for each cell in the ortho-rectified image is evaluated as a function of the values of the cells surrounding the corresponding cell on the image

Image rectification II

The first step is a geometric operation, which uses empirical or physical models.

Different approaches can be used:

- **2D** suitable only for flat terrains and nearly nadiral images
- **3D** a DEM is needed, results depend on DEM resolution and accuracy

The influence of DEM resolution and accuracy depends on the image resolution and the viewing angle.

Image rectification III

The second step is a radiometric operation.

Since in general the coordinates of a cell in the ortho-rectified image do not correspond to the coordinates of the corresponding cell in the original image, a resampling method is applied to the values of the original image cells.

For SAR images, instead of resampling, statistical functions based on the characteristics of the radar are used.

Resampling modifyes the radiometry of the original image, therefore any image analysis tecnique (image classification, pattern recognition, etc.) must be applied **before image ortho-rectification.**

Image rectification IV

It is possible to choose different resampling methods:

nearest neighbour the value(s) of the closest cell are used - fast but causes radiometric degradation and geometric errors of up to half pixel

bilinear interpolation takes into account the four cells surrounding the cell, weighting their values as a function of the cell distance from the computed coordinate values - slower but creates smoother images

deconvolution uses piecewise cubic functions or the $\sin(x)/x$ function - enhances and encreases contrast in the map image

Internal orientation

For frame cameras an additional step is usually performed to evaluate the position of the film (sensor) with respect to the camera and therefore to the platform.

This is called “internal orientation” (opposed to “external orientation”) and is based on the position of *fiducial marks* on the image and uses an affine trasnformation to transfor between image and camera coordinates.

The position of the *fiducial marks* with respect to the camera frame is known from the *Camera calibration certificate*.

Recipe for the ortho-rectification procedure

What you need

- Calibration information - depends on the procedure
- GCPs - the number depends on image, method and terrain
- DEM - the resolution depends on image resolution
- approximate values of the parameters - optional

How to evalutate the result

- check the value of the overall RMS of the parameters evaluation procedure
- check the value of the GCPs coordinates RMS
- use independent check points (similar to GCPs, but not used for parameters evaluation)
- overlay precise maps (vector maps work best) to the ortho-image

Bibliography

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Push-broom scanners image
http://www.amesremote.com/section2.htm
http://www.meted.ucar.edu/npoess/microwave_topics/resources/print.htm

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