Technical note:

Creating geometrically-correct photo-interpretations, photomosaics, and base maps for a project GIS

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Available on-line via `www.itc.nl/personal/rossiter/`

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Contents

1 Overview **3**

2 Materials **4**
2.1 Physical materials 4
2.2 Computer software and datasets 4

3 Procedure **5**
3.1 Interpret the airphotos 5
3.2 Make a digital version of the topographic map 6
3.3 Select a geo-referencing method 8
3.4 Identify tiepoints 9
3.4.1 Tiepoints for the photo 10
3.4.2 Tiepoints for the overlay 11
3.5 Prepare for geo-referencing 11
3.5.1 Extra preparation for orthophoto geo-referencing 11
3.6 Geo-reference 14
3.6.1 Geo-reference the photos from the topographic map 14
3.6.2 Geo-reference overlays from the photos 16
3.7 Digitize the API 17
3.8 Create a thematic map 20
3.9 Resample the photo 20
3.10 Make a photomosaic 21

Appendix **24**

A Computing maximum relief (projective transformation) **24**
A.1 Derivation 24
A.2 Final formula & rule-of-thumb 25
A.3 Small-format photographs 25

B Conversions for scanning **26**
B.1 Required resolution 27
B.2 File sizes 28

C What if some materials are sub-standard? **28**
C.1 A4 scanner 28
C.2 Poor-quality topographic map 28
C.3 Topographic map without overprinted grid 29
C.4 Topographic map with unreliable coordinates 29
C.5 Airphoto without fiducial marks 29

References **30**

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1 Overview

This note is written for those who want to build a GIS of a relatively small project area for purposes of natural resources inventory, monitoring, and management. Examples at ITC are the group project and the individual final assignment for the professional Master degree, and the MSc thesis Hengl [3]. All such GIS's should, if at all possible, include:

— a **base map**, often referred to as a "topographic" map;

— an **airphoto mosaic**;

— **thematic maps**, i.e.
polygon, segment, or point maps from air photo interpretation.

— a **multispectral satellite image** and its products such as false-colour composites;

All of these must be **geo-referenced** and **geometrically-corrected** in a **common coordinate system**. In these notes, we do not deal with the satellite images, but instead emphasize the air photo interpretation (**API**), which we want to convert to an air photo interpretation map (**APIM**). This is most easily accomplished by also producing the digital base map and photomosaic.

Unrectified stereo-pairs of airphotos are invaluable data sources when a detailed 3D view of the landscape is required, for example in soil-landscape mapping according to the geo-pedological approach [10]. These stereo-pairs are manually interpreted as uncorrected, unreferenced **interpretation overlays**[1]. These are not geometrically-correct, i.e. do not have a uniform scale and do not preserve angles, because of the well-known problems of **tilt**, **radial**, and **relief displacement** across the photo, as explained in photogrammetry texts such as [1, §2], [5, §9], and [6, §4]. They also are not geo-referenced, that is, their location with respect to a coordinate system is not known[2]. Finally, most project areas require more than one photograph; therefore the photo-interpretations and photos from adjacent images must be combined to produce maps covering the whole area.

Although the principles explained here can applied with many software packages, these instructions are specific to the ILWIS GIS, version 3 [4, 7], and assume a working knowledge of this program. ILWIS is quite suitable for small to medium-sized GIS's, and is used in many ITC courses to teach the principles of remote sensing and GIS.

These procedures are all covered in other sources, notably the ILWIS Help and various texts and lecture notes. Our purpose in presenting them yet again is to provide a **practical** yet **theoretically-sound** procedure that you can follow **step-by-step** to produce a high-quality product. We have included many hints based on our own and and our colleagues' hard experience.

[1] Single unrectified photos can also be interpreted monoscopically for cultural features such as roads and buildings, and for natural features that can be seen monoscopically such as streams.

[2] Although the flight path and principal points may have been recorded by GPS

2 Materials

2.1 Physical materials

- **Airphotos**, with stereo coverage if needed. Contact prints on high-quality photographic paper are preferable. If you must use a scan or photocopy, use the highest resolution possible to make the scan. A scan of 2400 DPI will give reasonable visual resolution for photo-interpretation; a scan of less than 300 DPI resolution will be difficult to interpret.

- Stable **mylar** for making interpretation overlays.

- An A3 (42×29.7 cm) or larger **scanner**; note that the smaller dimension must hold a standard 23×23 cm airphoto plus enough margin to see the fiducial marks. An A4 (29.7×21 cm) scanner is just a bit too small (see C.1 if this is all you have).

- A **topographic map** of the area, with **overprinted metric grid** and **known coordinate system**. This will be converted to digital form (§3.2). Use as stable a product as possible! The ideal are mylar separates, second best are unfolded prints on stable paper.

- A precise **metric ruler** (steel preferred), to measure the fiducial marks for the orthophoto transformation (§3.3). Not needed for projective or direct linear transformations.

2.2 Computer software and datasets

- The ILWIS computer program [4, 7]. You should know how to find the details of operations in the on-line Help.

- A **coordinate system object** defined in ILWIS, covering the study area with a defined projection and datum, corresponding to that of the topographic map.

- In areas with significant relief (§3.3), a raster **digital elevation model** (DEM) covering the whole area, in the common coordinate system. It doesn't have to be too precise for this purpose, since only the elevations are used, not relief parameters such as slope gradient; it can cover a larger area. The question of how to create a DEM requires its own technical note. The ILWIS Help has extensive information on this. In connection with the present procedure, the important point is that any reasonable DEM will produce acceptable results; requirements for terrain modelling are much more strict. If you have a DEM in a different coordinate system, you will have to re-sample it to the common coordinate system. The georeference (grid size and orientation) does **not** have to match other raster maps for the purposes of this note. In the DEM's *properties*, make sure the *Interpolate* check box is on (checked).

3 Procedure

The steps you will follow are:

1. Interpret the airphotos (§3.1)
2. Make a digital version of the topographic map (§3.2)
3. Select a geo-referencing method (§3.3)
4. Identify tiepoints (§3.4)
5. Prepare for geo-referencing (§3.5)
6. Geo-reference (§3.6), first the photos from the topographic map, and then the overlays from the photos
7. Digitize the API (§3.7)
8. Create a thematic map from the overlays (§3.8)
9. Resample the photo to make it a map (§3.9)
10. Make a photomosaic map (§3.10)

It is **extremely important** to evaluate the quality of a step, before going on to the next one! Remember, 'garbage in, garbage out' applies to each step of the process. Remember, always **keep a log** of everything you do, with system output. That way you can later write a meaningful **metadata description** of the datasets you are creating.

3.1 Interpret the airphotos

In this step, you create the information content of the final map, by making an airphoto interpretation (API) (Fig. 2).

1. **Register a stable mylar overlay** to the airphoto (Fig. 1) by tracing the main road and stream network; this provides a number of well-defined photo points, namely road and stream junctions, spread over the photo, and aids in making sure the overlay is exactly registered on the photo.
2. **Interpret the photos** over (almost) the entire area of a central photo, using different adjacent images for stereo-coverage. Use a pen or pencil width of at least 0.3 mm, to show up well on the scan. It is **not** necessary to restrict yourself to the central area of a photo; it is more efficient to interpret larger areas of fewer photos, using different adjacent photos to provide stereo coverage. The result is a mylar overlay with landscape lines (Fig. 2). This is the step where you are **creating information** so remember, "garbage in, garbage out"! If you have a poor-quality photo-interpretation, you will have a poor-quality map, no matter how good its geometry. Make sure the outside of the study area is closed (bounding box); there is no need to draw lines to separate photos.

3.2 Make a digital version of the topographic map

The topographic map is the highest-quality geometry available for your project, so you should take care to make a very accurate conversion to digital form.

1. Scan the topographic map at a high enough resolution to provide accurate locations, typically 300DPI, which gives a resolution of $\approx$ 0.1mm per pixel. Note that the highest-possible plotting accuracy of a paper map produced by computer methods is 0.1mm [8, §3.1.3]; 300 DPI is about 15% finer resolution than this. If the map was produced by analogue methods, a 100 DPI scan is sufficient to preserve location accuracy, although it will not look good. If you want to preserve the appearance of the map at large magnifications, you will need to use a higher scan resolution; see Appendix B for how to determine this. If the scanner is smaller than the map, you will have to scan in sections of the map separately, and georeference each one independently, as if they were separate maps.

2. Make sure the scan is in the **uncompressed TIF** (Tagged Imaged Format) format; this should be an option your scanner software, or you may need to use a graphics conversion utility.

3. Import the scanned map into ILWIS, from TIF to raster. This will automatically create a raster map with the same number of rows & columns as the TIF, with coordinate system "unknown".

4. Create a new georeference (`create grf`). In the form that appears:

   (a) Select the GeoRef method "Tiepoints"

   (b) Select the project's coordinate system mentioned in 'Materials' (§2).

   (c) Select as the **background map** the raster file you want to georeference, i.e. the scanned topo map.

   The georeference editor will open, with the topographic map displayed as the background. There is a lot of help available from ILWIS here (topic "Georeference Tiepoints editor: Functionality"), if you get confused.

5. There is an option in the toolbar for the type of transformation; by default it is **affine**; this is correct for a geometrically-correct (but not geo-referenced) image such as a scanned topographic map. It only requires three tiepoints, but at least six should be entered to be able to check accuracy. The affine transformation can adjust scale independently in two axes and can also correct for rotation. These are the only two distortions introduced by a good scanner. The distortions due to the projection are corrected by the definition of the coordinate system. However, the scanner may introduce barrel distortions, because the curvature of the lens is not completely corrected at the edges. To correct for this, you can choose the **full second order** transformation; it requires six tiepoints, but at least ten should be entered to be able to check accuracy.

Figure 1: A single airphoto (AP) used to create the ortho-photo map. The camera and aircraft information are shown in the left margin of the photo.

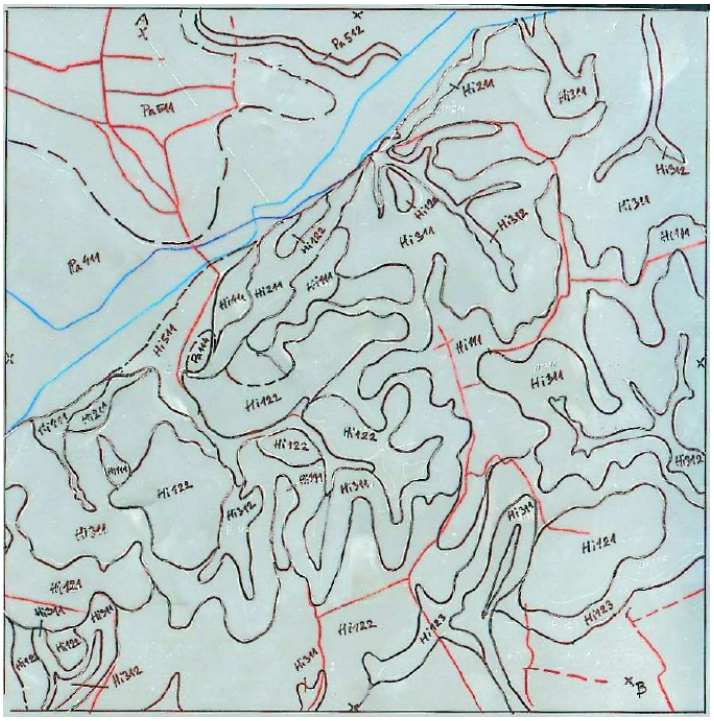


Figure 2: Photo-iterpretation drawn on the transparent overlay.

6. Use the tiepoint editor to digitize the tiepoints as **grid intersections** near the *edges of the map*, and enter their real-world coordinates, which are known from the grid lines. Zoom in to find the exact centre of the intersection. In a typical case, the grid line as drawn on the map is 0.3 mm wide, which is about 4 pixels at a 300 DPI scan; find the centre pixel of the intersection. The topo map in Fig. 3 shows the corner of a digital topographic map, with the coordinates clearly shown.

7. After you have entered the minimum number of tiepoints, you will see geographic coordinates for each new point, i.e. the scanned topographic map is geo-referenced. As you add the extra tiepoints, you will see a realistic measure of the accuracy of the transformation.

8. You should evaluate the accuracy of the geo-referencing both visually and numerically. To evaluate **visually**, add the grid lines as an annotation to the displayed map, in a contrasting colour (e.g. yellow). They should be all exactly in the centre of the grid lines as drawn on the map. To evaluate **numerically**, examine the `DRow` and `DCol` fields for each point. These should be quite small. They should be equivalent to the maximum location accuracy or less at map scale, i.e. 0.1 mm if the map was produced by fully-automated means or 0.25 mm if by analogue means. If the scan was at 300 DPI, this is within one to four pixels.

3.3 Select a geo-referencing method

In this step, you decide on the type of geo-referencing you will perform: There are three possibilities:

Projective Corrects **tilt** and **radial** displacement only; **suitable for relatively flat or monotonically-sloping areas only**; does not require a DEM or fiducial marks. Should not be used if there is significant relief displacement. It is often suitable for small-format photos (taken by a standard small-format "35 mm" camera) even if there is significant relief, because the radial distances are small on the 24×36 mm negative. See Appendix A for how to compute the maximum allowable relief displacement; a quick rule of thumb for a map that meets map accuracy standards, from a standard photogrammetric air-photo, is to divide the photo scale number by 10,000 and then multiply by 2.5. For example, the maximum allowable relief displacement on a 1 : 20 000 photo is roughly $(20,000/10,000) \cdot 2.5 = 5$ m. This also can correct **tilt in the landscape** (as well as tilt in the aircraft), i.e. a tilted plain that goes only in one direction.

Direct linear Corrects **tilt**, **radial**, and **relief** displacement; requires a DEM; does not use fiducial marks. Use if you can't find the fiducial marks or don't know the camera focal length. In our experience, this gives almost equal results to orthophoto if tiepoints are accurate.

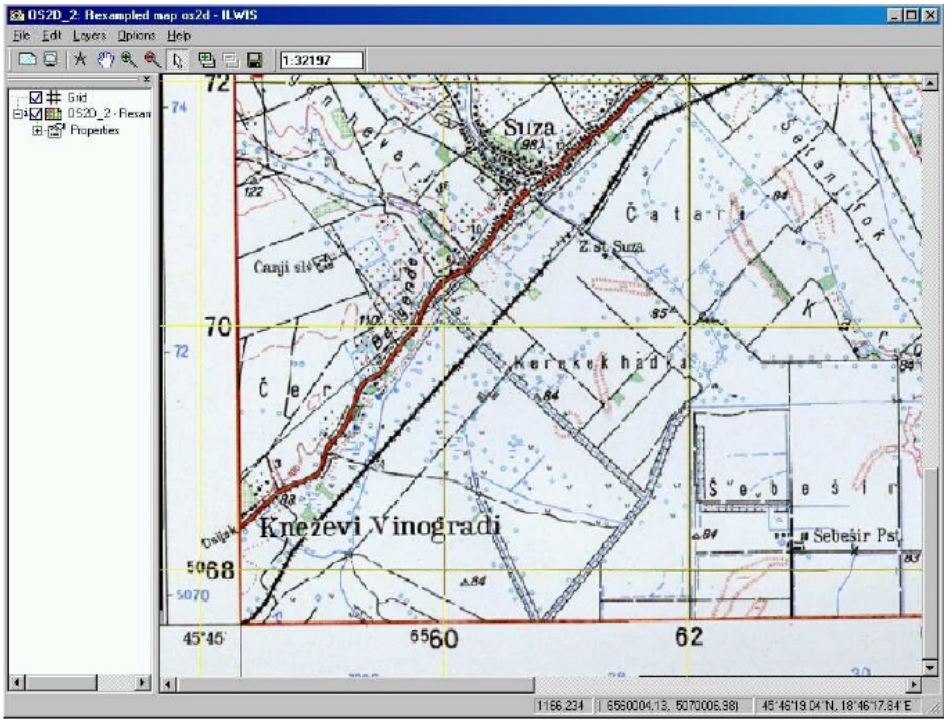


Figure 3: Detail of a 1:1 50000 topographic map, showing the marginal coordinates. The grid intersection at the lower left, below the label "Kneževi Vinogradi", has coordinates `(6 560 000E, 5 068 000N)` in the local coordinate system used for this map.

Orthophoto Corrects **tilt**, **radial**, and **relief** displacement; requires a DEM, fiducial marks, and the camera's focal length. The camera geometry provides a stable reference frame for the tiepoints, so this should give the highest accuracy.

Affine, second-order and other linear transformations can not correct for radial displacement, so they should not be used for airphotos. For your interest: the technical difference between georeference "orthophoto" and "direct linear" lies in the fact that, for the orthophoto, there is a so-called **inner orientation** that can be calculated by ILWIS from the camera geometry. This establishes the relations on the photo plane as they existed in the aircraft when the photo was taken; then from the tiepoints, ILWIS can calculate where the camera must have been, and the angle of the photo plane, in relation to the ground. This allows a very precise reconstruction of the original land surface. In the **direct linear** georeference, there is no inner orientation, so the principal point is unknown. That is, we don't know what point of the photo was directly under the camera. So everything must be calculated from the tiepoints.

3.4 Identify tiepoints

In this step, you identify the points which will be used to geo-reference the photos and overlays in the following steps. This is usually easiest in two steps:

1. Tiepoints on the topographic map to geo-reference the photos
2. Tiepoints on the photos to geo-reference the overlay

The reason for this is that there is much more detail on the photos than on the topographic map, so that you have a wide choice of good tiepoints to mark on the overlay. These may be points which are not clear on the topographic map. Also, they can be marked with much higher precision on the photo than on the topographic map.

3.4.1 Tiepoints for the photo

1. On each photo, find at eight to twelve **tiepoints**, well-distributed (especially towards the corner), which you can see also on a topographic base map. Be careful to find points that you are fairly sure have not moved, in case the sources are of different dates. Streams change the courses, roads are rebuilt, etc. Fig. 4 shows a well-defined tiepoint (here, a rural church) that is clearly visible on both the photo and topographic map (Fig. 5). It is very important that the points be **well-distributed** on the photo in the `(X, Y)` direction. Do not select points that are close together; they will bias the fit: any error of measurement will be magnified. In the case of the direct linear transformation (§3.3), the tiepoints must also be well spread in the `Z` (height) direction; they should also not be not coplanar, i.e. on a (tilted) plane. See the ILWIS Help topic "ILWIS objects Georeference Direct Linear" for details.
2. Open the digital topographic map, zoom in to locate each tiepoint, and then read their coordinates `(E,N)` off the screen. This does not have to be so precise, since you will locate them exactly during the actual geo-referencing. Make a **list** of the tiepoints on each photo, with their number, approximate coordinates, and a sketch and description of what they represent (e.g. 'middle of road junction', 'center of road bridge over canal'), so you can find them again on the photo.

3.4.2 Tiepoints for the overlay

1. On each photo, find at eight to twelve **tiepoints**, well-distributed (especially towards the corner). Any clear point will do. You do not have to use points from the topographic map. The same cautions about point distribution as mentioned just above apply here as well.

2. Register the overlay to the photo, and mark the tiepoints very precisely on the overlay, with a small circle and a number, so you can find them again on the digital photo. Make a **list** of the tiepoints on each overlay, with their number and a sketch and description of what they represent.

3.5 Prepare for geo-referencing

In this step, you prepare materials to be digitally geo-referenced.

1. Scan the photos at the resolution you want to display in your final photo-mosaic, typically 300 DPI or higher, with the fiducial marks if you intend to use the orthophoto transformation (see Appendix B to compute the required resolution). Use an A3 or larger scanner, to cover the entire 25×25 cm area. Store them in the project directory as **uncompressed** TIF (Tagged Imaged Format) files. Either set the scanner to produce uncompressed files, or convert the format in an image processing software. ILWIS can not import compressed files. There is a tradeoff between resolution and size: doubling the scan resolution quadruples the file size, and at a certain point it becomes impractical.

2. Scan the overlays; this can be at a a coarser resolution than for the photo, since you will just need to screen digitize over the displayed scanned overlay; also, you should have drawn the interpretation lines with a line at least 0.3 mm wide. So, 0.2 mm to 0.25 mm resolution (150 or 100 DPI) is fine.

3. Import the photos and overlays into ILWIS as explained in §3.2.

3.5.1 Extra preparation for orthophoto geo-referencing

In case you have selected "orthophoto" as your geo-referencing method, you must do some more preparation:

1. For each **photo** find out the **principal distance** (focal length) of the camera; it is ≈ 152 mm for a standard photogrammetric camera used in aircraft. The exact distance is calibrated in the factory and is often included in the margin of the photograph.

2. Find and mark the **fiducial marks** on the photo. These are tiny dots (pinprick size) within a larger dark area, either at the corners or in the middle of the edges of the photo. They may be hard to see; you may need to use the magnifying stereoscope.

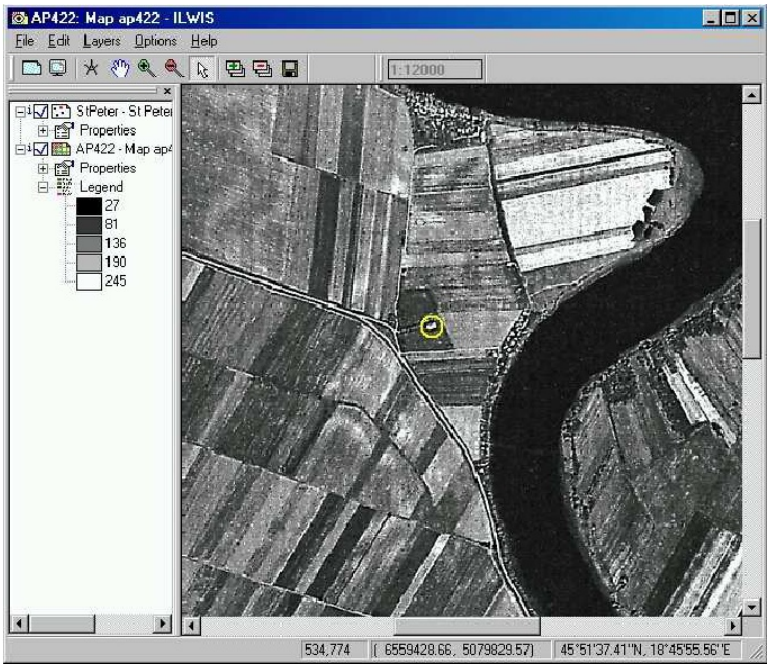


Figure 4: A well-defined tiepoint (here, St Peter's Church) that is clearly visible on both the photo and topographic map (Fig. 5). A small yellow circle has been drawn around the church on the photo. Notice that the road near the church has been upgraded (smoother curve) since the map was made; however, it is more difficult to move a church!

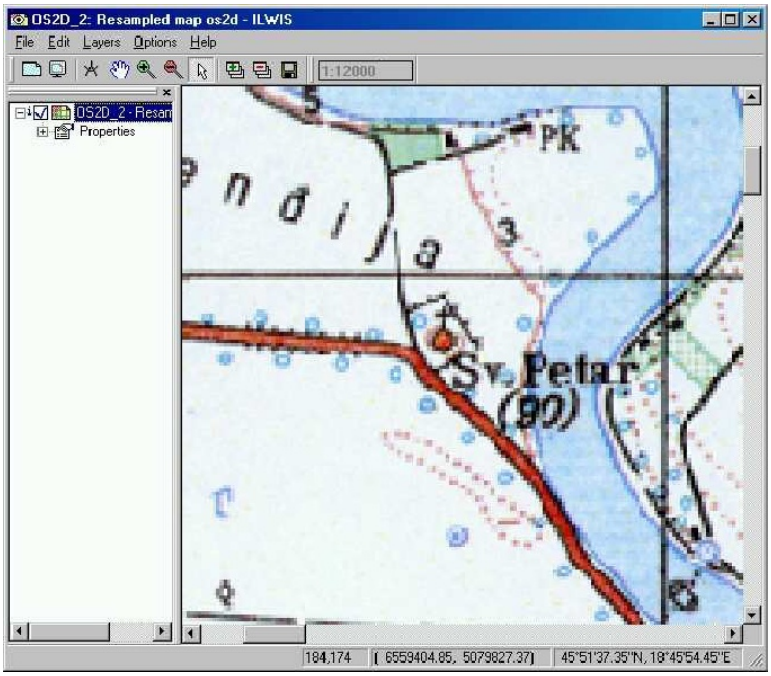


Figure 5: Tiepoint (St Peter's Church) as visible on the topo map.

3. Find the **principal point** on the photo, by connecting the opposite fiducial marks by straight lines, and marking their intersection. This point was directly under the camera when the photo was taken.

4. **Measure the distances** `(X,Y)` from the principal point to the fiducial marks, in **actual photo mm**, considering the principal point (in the centre of the photo) as `(0,0)`. Therefore, X coordinates to the left of the point, and Y coordinates below it, are negative. Use as high-quality a ruler as you can find, preferably a stable steel ruler, and try to measure to 0.1 mm and even estimate to 0.01 mm (maybe using the magnifying stereoscope). An example for fiducial marks on the four sides, reading clockwise from the right margin, is: `(0.0, 111.0), (-111.0, 0.0), (0.0, -111.0), (111.0, 0.0)` (see Fig. 6).

5. For each **overlay** register the overlay as in §3.1, and, on the overlay, mark the **fiducial marks** that you just identified on the photo.

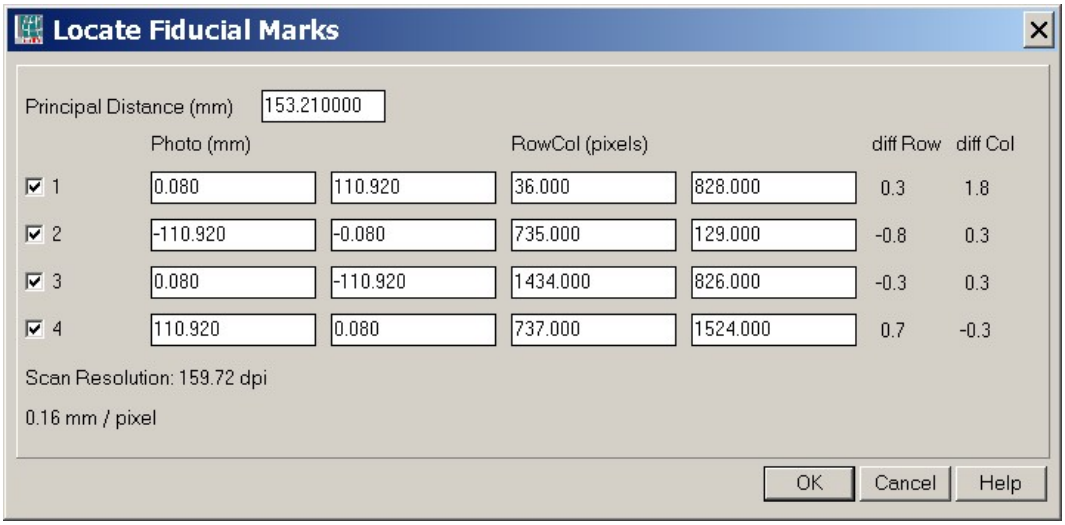


Figure 6: Specifying the fiducial marks in ILWIS; from the number of pixels in the image and the actual photo size in mm, the program was able to calculate the scan resolution.

3.6 Geo-reference

In this step, you specify the relation between ground coordinates and the raster images (scanned photos and overlays), thereby geo-referencing them. You have to follow this step for each photo and each overlay, one at a time. As explained in §3.4, it is more difficult to geo-reference the photo from the topographic map than the overlay from the photo, because of the finer detail of the photo. So, you will do this in two steps:

1. Geo-reference the photos from the topographic map (§3.6.1)
2. Geo-reference the overlays from the photos (§3.6.2)

Make sure the first step has given good results before proceeding! Otherwise your thematic map will be useless.

3.6.1 Geo-reference the photos from the topographic map

For **each** photo **separately**:

1. Create a **new georeference** (`create grf`). In the form that appears:
   (a) Select the appropriate GeoRef method: "Tiepoints" for the projective, "Direct linear", or "Orthophoto".
   (b) Select the project's **coordinate system** mentioned in 'Materials' (§2).
   (c) Select the **background map**, i.e. the raster file of the photo you want to georeference.
2. In case you have selected "direct linear" or "orthophoto", specify the raster DEM.
3. In case you have selected "orthophoto", you will also be asked to specify the **photo geometry**: camera principal distance, and the fiducial marks. Enter them in order, clicking on the photo to specify their row and column in the raster image, and entering their photo coordinates in the dialog box. The ILWIS screen for this is shown in Fig. 6. The georeference editor will then open, with the background map displayed.
4. In case you have selected "tiepoints", you will notice there is an option in the toolbar for the type of transformation; by default it is "affine"; change it to "projective".
5. On the displayed photo, add the grid lines in a fairly dense net (e.g. 1000 m). They will not be shown at first, because there are not enough points to establish a georeference.
6. Open the topographic map in another window.
7. Use the tiepoint editor, click on a tiepoint on the photo, switch to the topographic map, click on the same point on the topographic map, switch back to the photo, and accept the point.

8. Once you have enough points, you will see geographic coordinates for each new point and the pixel size in real-world units, as well as the grid lines. The image is now geo-referenced; however, this may not yet be the best transformation, and it can even be very bad, because some points may be in error. This can be for several reasons:

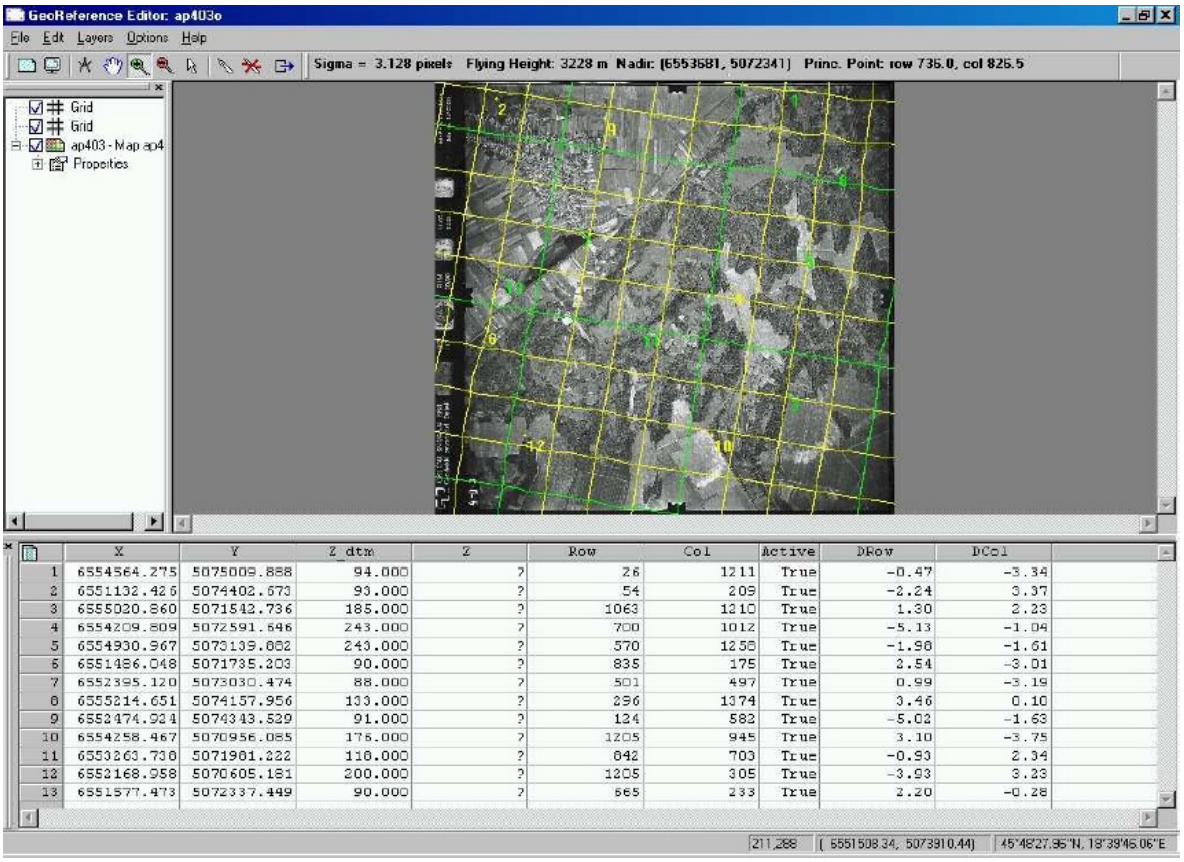
   - because you didn't read their coordinates correctly,
   - because you didn't identify them correctly on the photo, or even
   - because they are incorrectly drawn on the map.

   Once you have entered all the points, look at the `DRow` and `DCol` fields; they give the error of each point in pixels. Convert these to map mm, using the scan resolution, to see if they are acceptable. Depending on the map accuracy standard, this should be on the order of 0.25 mm (analogue) or 0.1 mm (digital). For example, if the original scan was at 300 DPI, these correspond to 3 and 1 pixels, respectively. If some points are much worse than others, try disabling them by marking them "False" and see if the overall error decreases. Go back to the original sources to see if you made a mistake. This step can take quite some time. Fig. 7 shows the ILWIS georeference editor in action. Pay close attention to the displayed grid. Lines should be generally parallel E–W and N–S, and perpendicular at the intersections. Squares at the center should be a bit larger than those at the corners (because the center was closer to the camera, so more photo area is used to represent the same ground area) and on higher areas. The grid will be distorted as it crosses hills and valleys: it is displaced away from the principal point in valleys (because these were farther from the camera) and towards it on hills, with the displacement increasing with relief and towards the corners. The relief effect is magnified by the radial effect, so that hills and vales are most obvious near the corners (Fig. 8). If you see converging grid lines, or a pattern that looks like a tilted plain, you have made a serious error in marking one or more tie points, so that the scale in one part of the photo is seriously distorted, thereby affecting the transformation (Fig. 9). Do **not** delete points just to make the geo-reference better! As a scientist, you require **evidence** to delete a point. For example, you may infer that a point has moved (stream after a flood, or a re-built road), or than you mis-identified it, or even that the original map was in error. Establish a hierarchy of reliability[3].

9. When you have entered all the points, and discarded or adjusted any that are in error, close the editor; now the image is geo-referenced and associated with the new georeference you just created.

Note that the photo has not changed its geometry: it still has the same pixels in the same rows and columns, and it still has variable scale across it (i.e. the pixels represent different ground areas). However, with the information we have specified about the tiepoints, ILWIS can calculate, for each pixel, its true location. So the grid lines which follow a fixed `E` or `N` appear distorted on the uncorrected image, and the length of a grid line between intersections

[3]Hint: If you have a bad geo-reference, try making all the points False and then turning them on one by one, in order of reliability.



	X	Y	Z dtm	Z	Row	Col	Active	DRow	DCol
1	6554564.275	5075009.888	94.000	?	26	1211	True	-0.47	-3.34
2	6551132.426	5074402.673	93.000	?	54	209	True	-2.24	3.37
3	6555020.860	5071543.736	185.000	?	1063	1210	True	1.30	2.23
4	6554209.809	5072591.646	243.000	?	700	1012	True	-5.13	-1.04
5	6554930.967	5073139.882	243.000	?	570	1256	True	-1.98	-1.61
6	6551486.048	5071735.203	90.000	?	835	175	True	2.54	-3.01
7	6552395.120	5073030.474	88.000	?	501	497	True	0.99	-3.19
8	6555214.651	5074157.956	133.000	?	296	1374	True	3.46	0.10
9	6552474.924	5074343.529	91.000	?	124	582	True	-5.02	-1.63
10	6554258.467	5070956.085	176.000	?	1205	945	True	3.10	-3.75
11	6553263.738	5071901.222	118.000	?	842	703	True	-0.93	2.34
12	6552168.958	5070605.181	200.000	?	1205	305	True	-3.93	3.23
13	6551577.473	5072337.449	90.000	?	665	233	True	2.20	-0.28

Figure 7: The ILWIS georeference editor, while specifying the orthophoto transformation. The program was able to calculate the camera position when the photo was taken (flying height and nadir, i.e. the principal point, which was directly under the camera). Note how the grid lines follow the radial and relief displacements.

are different. In fact it's the other way around: the grid lines are straight and with a true scale, and the photo is distorted. Once the image is resampled into a north-oriented map (§3.9, below), the grid lines will be straight and areas in the photo will be distorted.

3.6.2 Geo-reference overlays from the photos

This follows the same procedure, but should not present any problems of point selection, since they are so clear on the photo. For each overlay:

1. Create a new geo-reference, with the same type as you used for the corresponding photo.

2. On the displayed overlay, add the grid lines in a fairly dense net (e.g. 1000 m). They will not be shown at first, because there are not enough points to establish a georeference.

3. Open the corresponding photo (already geo-referenced) in another window.

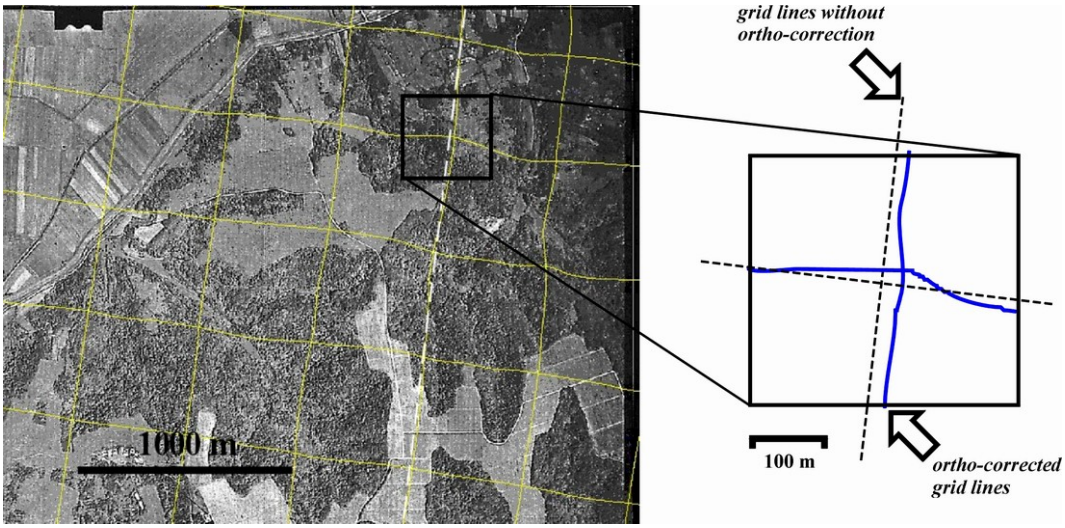


Figure 8: Detail of the relief and radial displacements which are corrected by the ortho-photo transformation. These are shown by overlaying north-oriented straight grid lines on the unrectified but geo-referenced photo.

4. Use the tiepoint editor, click on a tiepoint on the overlay, switch to the photo map, click on the same point on the photo, switch back to the overlay, and accept the point.

5. Once you have enough points, you will see geographic coordinates for each new point and the pixel size in real-world units, as well as the grid lines. Once you have entered all the points, look at the `DRow` and `DCol` fields; they give the error of each point in pixels. Convert these to map mm, using the scan resolution, to see if they are acceptable. Since we are dealing with a hand-drawn overlay, we use the map accuracy standard of 0.25 mm. If the original scan was at 150 DPI (typical for an overlay), this corresponds to 1.5 pixels. There should really be no problems with this step; any significant error means that you did not place the tiepoints precisely enough on the overlay: maybe you did not register the mylar correctly?

6. When you have entered all the points, and verified the accuracy of the transformation, close the editor; now the image is geo-referenced and associated with the new georeference you just created.

Now both photos and overlays are geo-referenced, and should agree with the base topographic map: you finally have the beginnings of a GIS database!

3.7 Digitize the API

Now that you have a geo-referenced overlay, you can create a thematic polygon map. First you will digitize the segments (this step), and then you will create the labels and polygon topology (next step). The ILWIS Help text refers to this process of on-screen digitizing over a geo-referenced but uncorrected image (here, the overlay) as **monoplotting**.

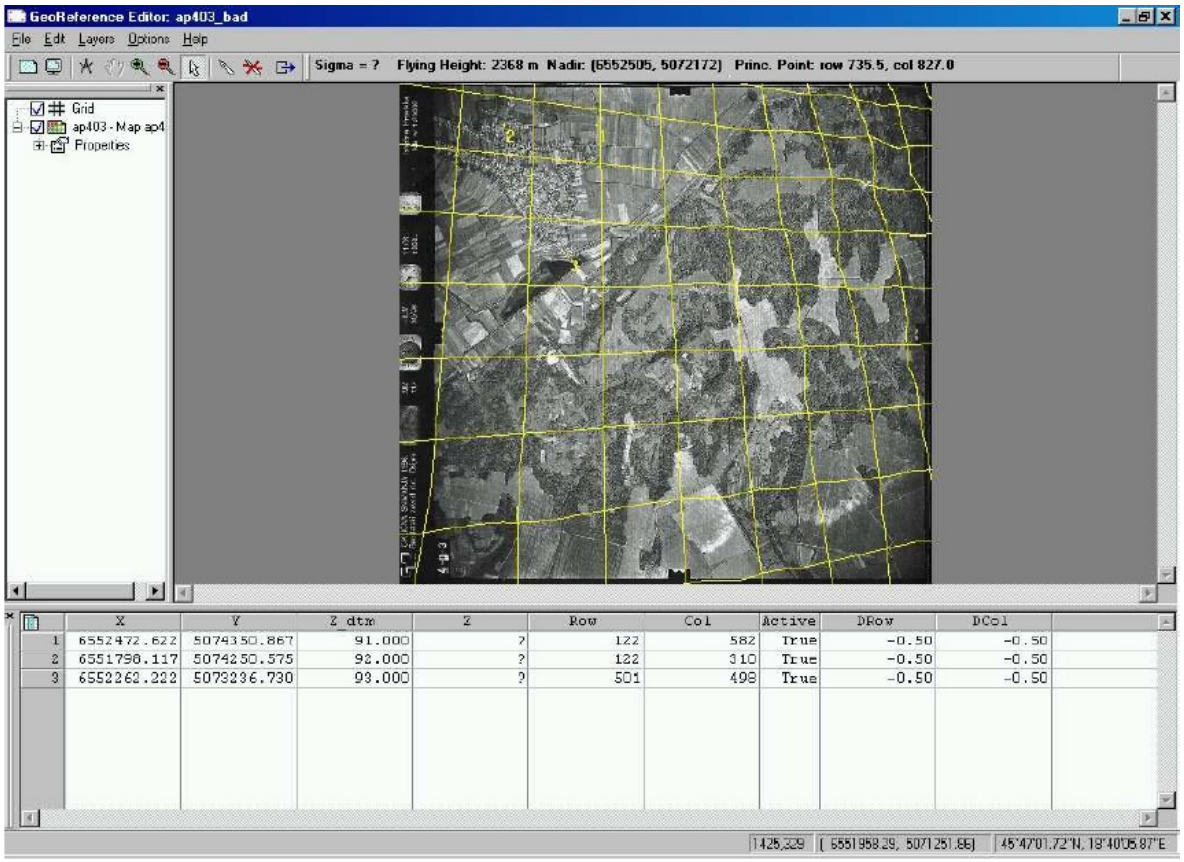


Figure 9: The ILWIS georeference editor, for the orthophoto transformation, with an incorrect geo-reference. The co-ordinates for the three tiepoints points are too close together; this increases the scale for that part of the photo and gives the effect of tilt.

1. Create a **new segment file** using the project's coordinate system mentioned in 'Materials' (§2).

2. Open the segment editor; display any one of the scanned overlay as the background image.

3. Set the snap tolerance (under `File | Customize ...`) to match the precision of the overlay. This tolerance must be entered in ground coordinates, usually meters. Since your drawing accuracy when making the overlay could not have been higher than 0.25 mm, convert this to meters and enter the value. For example, at 1:1 50000 this is 12.5 m.

4. **Trace the segments** from the overlay, using **on-screen digitizing**. The line codes are not important unless you want to show the origin of the line or its fuzziness (another subject ...). In the normal case, use one class for all segments.

5. When one overlay is complete, choose **another** overlay as background image. You will

see the segments from the first overlay, and an empty space under the present overlay[4].

6. **Trace the segments** from this overlay, using **on-screen digitizing**. When you approach existing segments from adjacent overlays, adjust them manually so that they snap together. The geometry should be very close if you have correctly geo-referenced each overlay.

7. Repeat this process for each overlay.

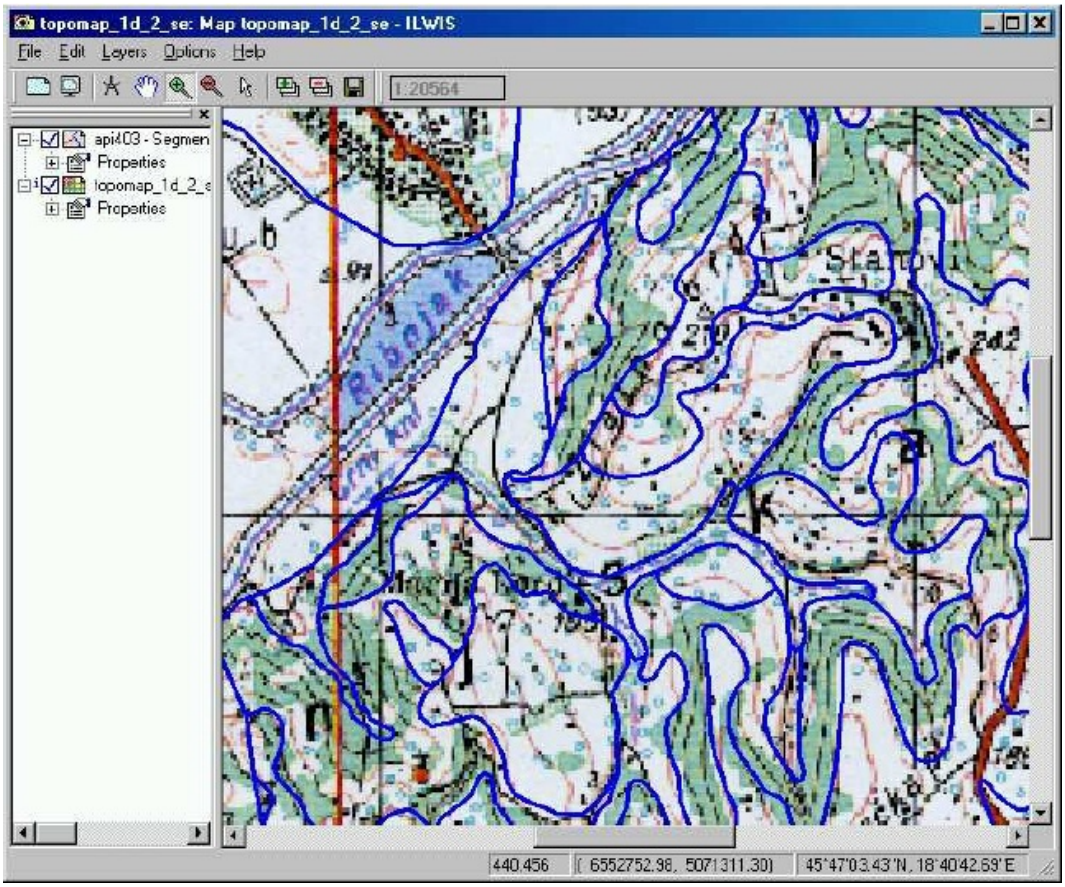


Figure 10: Digitized soil boundaries shown on the topographic map. Note how well they follow the landscape.

Now you are in the position to check that your geo-reference is in fact correct:

- Display the topographic map, and overlay the digitized segments. Check the segments that should correspond to features on the topographic map, e.g. boundaries of water bodies, edges of terraces or valleys, etc. In addition, the general form of the soil

[4]You can close and re-open the segment editor at any time during this process; make sure to specify the **same** segment file.

boundaries often follows the landscape (e.g. hilltops, steep hillsides) and can be checked against the relief as shown by the contour lines. Fig. 10 shows the topographic map, with the digitized segments overlaid. Note how how well they follow the landscape: for example, small vales in the hilland (seen from the pattern of the contour lines, and the streams) are centred in the corresponding photo-interpretation unit. This depends on a correct photo-interpretation and then all the geo-referencing steps in this technical note. If these do not correspond, it means that you have incorrectly geo-referenced either the photo or the overlay.

You now have a single geometrically-correct, geo-referenced file with the polygon boundaries from all the overlays. There is no further use for the digital overlays.

3.8 Create a thematic map

Now you can create the labels and polygon topology. This can be done as follows:

1. In case there are any 'open' polygons on the outside, close them with a bounding line.
2. In the segment editor, check the segments for dead ends and other errors (`File | Check segments`)
3. Create a **new point file** with a **new domain** which contains the legend categories, for example, soil-landscape map units.
4. On-screen digitize a **label point** for each polygon, using the segment map as background; give each point its correct label from the domain you just created (e.g., soil-landscape code).
5. **Polygonize** the segment map, using the point file as labels (option `Label Points` in the Polygonize command).

Fig. 11 shows the results of on-screen digitizing and Fig. 12 the final polygon map. Now you have a geometrically-correct, geo-referenced polygon map from your photo-interpretation, i.e. you have a **thematic map** for your GIS.

3.9 Resample the photo

You can convert your set of geo-referenced photos into geometrically-correct, true-scale, north-oriented maps by resampling. Follow this procedure for **each** photo; in the next step we will mosaic the resulting maps:

1. Create a **new georeference** "georeference corners" for the new map.
2. Select the project's coordinate system mentioned in 'Materials' (§2).
3. Specify a pixel size and limiting coordinates (bounding box). You can find the coordinates from the limits of the geo-referenced photo. If you want the photo to have the

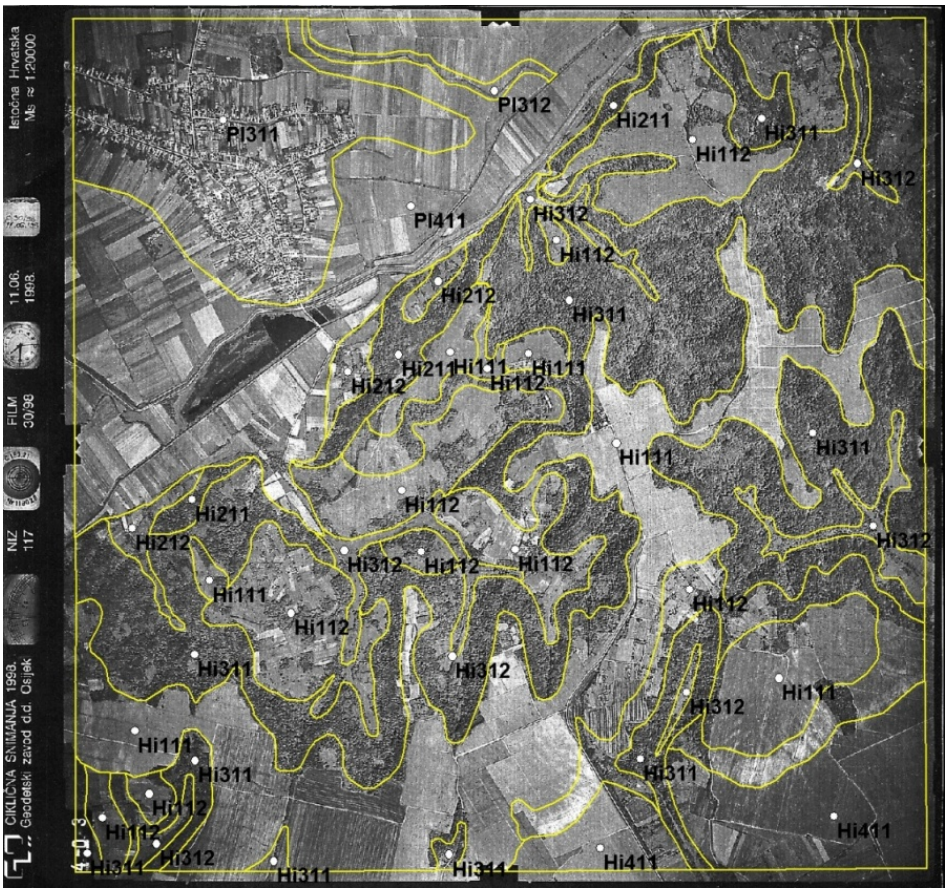


Figure 11: Creating a thematic map - digitized segments separating polygons, with label points.

same resolution as the original, you must determine the pixel size in the geo-referenced image, or you can calculate it approximately from the scan resolution and reported approximate photo scale (see Appendix B).

4. Select operation `resample`; the input map is the georeferenced photo, the output is a new file, and the georeference is the one you just created.

5. The resulting resampled photo is a north-oriented map. You will notice that it no longer is square (radial displacement is corrected; see Fig. 13), and if you used "direct linear" or "orthophoto", the effect of relief, especially near the corners is obvious. If you overlay the grid lines, they will be straight and have a true scale.

3.10 Make a photomosaic

You can now make a geometrically-correct, geo-referenced photomosaic from the several resampled photos. You may be limited by the capacity of your computer; especially if the

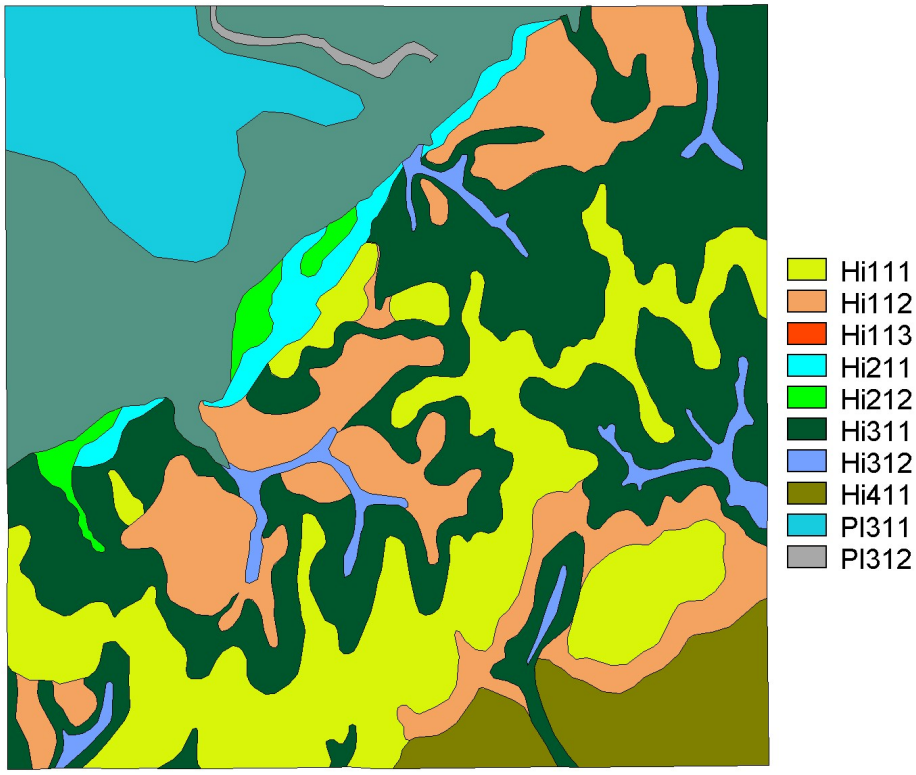


Figure 12: Resulting polygon map with legend.

photos were scanned with high resolution, you may have to create several photomosaics, each covering a part of your study area. If you have access to a workstation with more specialised image processing software (e.g. ERDAS or Geomatica), you may find it easier to export the individual photos to this software, perform the mosaicking and eventual trimming there, and import to ILWIS.)

1. Use operation "Glue Raster Maps" (`glueras`) to create one mosaic from the several photos. ILWIS limits you to a maximum of four photos at a time, so you may have to build up the final map in pieces.

2. Use operation "SubMap of Raster Map" (`subras`) to trim the mosaic to the desired size, e.g. if the study area only covers part of the mosaic. You can also use this to make the photomosaic correspond exactly to the boundaries of topographic map sheets. In this case, you must specify the boundaries as exact coordinates. If the map series has corners in geographic coordinates, convert these to metric coordinates using the interactive calculator provided by operation "Transform Coordinates" (`transform`).

Now you have a geometrically-correct, geo-referenced photomosaic of your study area, i.e. you have another **map** for your GIS.

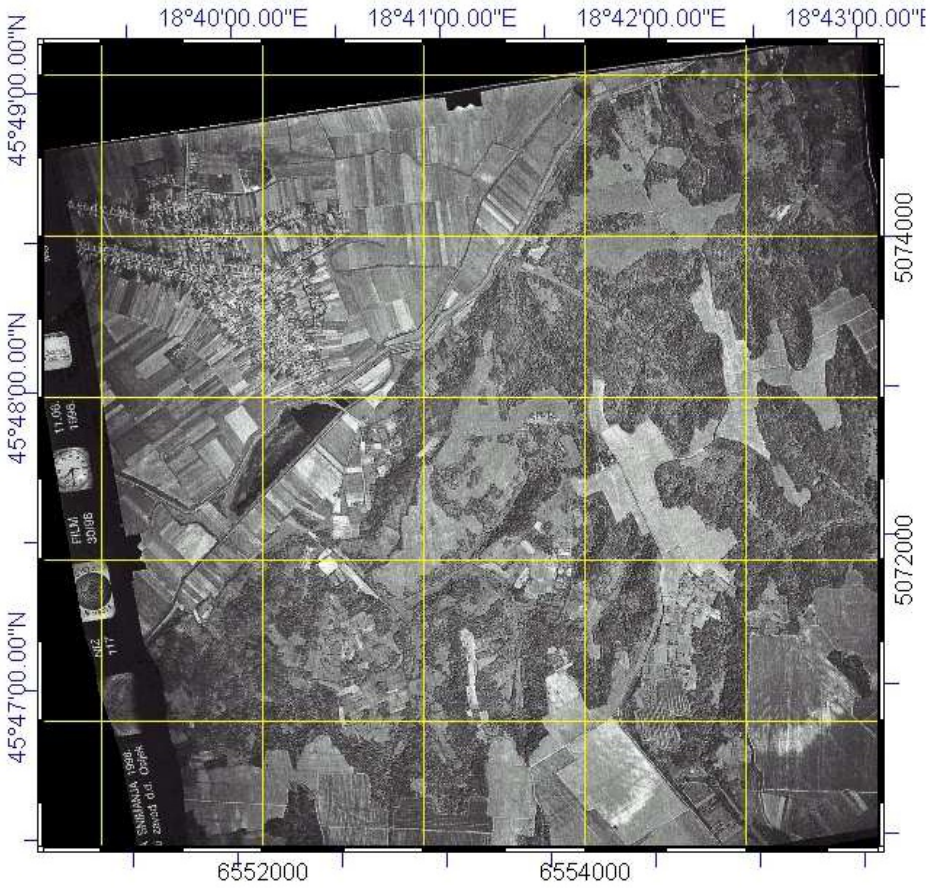


Figure 13: The resampled airphoto, as a map. Note that the grid lines are now exactly vertical and horizontal (so the top of the map is grid North) and they are equally-spaced; the photo has been locally distorted according to the ortho-correction.

Appendix

A Computing maximum relief (projective transformation)

See Equation 7 for a quick rule-of-thumb that covers the common case; read the derivation if you are interested in what is really going on.

A.1 Derivation

The basic relation[5] is Equation (1), which expresses the relief displacement δ in meters as:

$$\delta \quad = \quad r \cdot (h/H) \tag{1}$$

where r is the distance of the object from the centre of the photo, h is the height of the object above some datum, and H is the flying height above that same datum, all in meters. We want to turn this equation around to determine h, the maximum allowable relief, given a specified maximum allowable displacement δ'. First, however, we can calculate r and H.

Maximum radial distance The maximum radial distance r on a typical 23×23 cm airphoto is:

$$(23/2) \cdot \sqrt{2} \quad \approx \quad 16.25 \text{ cm} \tag{2}$$

on the negative. To convert to ground meters, multiply by $(s/100)$, where s is the **scale number**, i.e. the denominator of the **scale ratio**. For example, on a 1 : 20 000 photo, the scale number is 20 000, so the maximum radial distance is $\approx 16.25 \cdot 200 = 3,250$ m $= 3.25$ km. We use the **maximum** distance to ensure that the **entire** photo meets accuracy standards. If the outer edges of the photo will not be used (e.g. in mosaicking if they will be covered by other photos, and if you will not be interpreting in these areas), you should replace the $(23/2) \cdot \sqrt{2}$ above with the actual maximum distance, in mm.

Nominal scale To determine the nominal scale number s of the photo, simply measure between some known points on both the photo (distance d_p, in mm) and topographic map (distance d_m, in m) and compute the ratio:

$$s \quad = \quad \frac{d_m \cdot 1,000}{d_p} \tag{3}$$

The photo does not have uniform scale, so different measurements will give slightly different results. This is not important for the following calculation.

Maximum acceptable relief Having the maximum radial distance r, we can then compute the maximum acceptable relief h from the maximum acceptable distortion δ' and the flying height H:

$$\begin{aligned} (h/H) &= \delta'/r \\ h &= H \cdot (\delta'/r) \end{aligned} \tag{4}$$

[5] derived in [1, Eqn. 2.5], [5, Eqn. 9.1], and [6, Eqn. 4.7], among many others.

Note that both h and H are computed from the same datum; if it is taken as zero at the centre of the photo, the flying height H is then above ground level at nadir, and the relief h is relative to th ground level.

Flying height We can compute the flying height H from the nominal scale number s and the focal length of the camera f:

$$H = f \cdot s \tag{5}$$

For example, if f is the usual 152 mm and s is 20 000, we calculate $H = 152 \cdot 20000 = 3.04 \times 10^6$ mm $= 3040$ m

Maximum allowable displacement The maximum allowable displacement can be related to map accuracy standards: most of the well-defined points should be plotted to within 0.25 mm on the map; this is converted to map scale by multiplying by the scale number, e.g. if the scale is 1:20 000, the maximum displacement is 5 m. So, if we specify δ' as, for example, 5 m, we obtain, by Equation (4), $h = 3040 \text{ m} \cdot (5/3250) = 4.674$ m. This is very small, implying that to reach map accuracy standards at the corners of a photo, the local relief must be very low. If the accuracy standards are relaxed, or the map scale is smaller, the acceptable local relief will be greater.

A.2 Final formula & rule-of-thumb

We can derive a **combined formula** (Equation 6) using just the focal length f mm, map accuracy standard a mm, and map scale number s:

$$\begin{aligned} h &= \frac{(f \cdot (s/1000)) \cdot (a \cdot (s/1000))}{23/2 \cdot \sqrt{2} \cdot (s/100)} \\ &= \frac{s}{10\ 000} \cdot 0.0615 \cdot f \cdot a \end{aligned} \tag{6}$$

Using the same example as above, with $f = 152$ mm, $a = 0.25$ mm, and $s = 20\ 000$ we compute $h = 4.674 \approx 5$ m. All of this can be distilled down to a simple rule-of-thumb for the default $a = 0.25$, $f = 152$, and photo size $= (23 \text{ cm})^2$:

$$h \approx \frac{s}{10\ 000} \cdot 2.5 \tag{7}$$

A.3 Small-format photographs

These are taken with a standard "35 mm" camera from a low-flying aircraft, and are a low-cost alternative to photogrammetric missions. The negative size is 2.4×3.6 cm, so the maximum radial distance on the photo, equivalent to Equation 2, is:

$$\sqrt{(2.4/2)^2 + (3.6/2)^2)} = 2.16\bar{3} \text{ cm} \tag{8}$$

They are usually taken with a camera focal length $f \approx 50$ mm. A typical flying height of 1000 m with this lens results in a scale (from Equation 5) of

$$50 \text{ mm}/(1000 \text{ m} \cdot 1000 \text{ mm m}^{-1}) = 1 : 20\,000$$

The equivalent to Equation 6 is:

$$\begin{aligned} h &= \frac{(f \cdot (s/1000)) \cdot (a \cdot (s/1000))}{\sqrt{(2.4/2)^2 + (3.6/2)^2)} \cdot (s/100)} \\ &= \frac{s}{10\ 000} \cdot 0.46225 \cdot f \cdot a \end{aligned} \tag{9}$$

Taking $f = 50$ mm, $a = 0.25$ mm, and $s = 20\ 000$ we compute $h = 11.55625 \approx 12$ m, i.e. about double the allowable relief in the large-format photo, but of course in a much smaller area (for a 1:20 000 photo, 480×720 m = 34.56 ha). This is why small-format photos can often be rectified with a projective transformation. All of this can be distilled down to a simple rule-of-thumb for the default $a = 0.25$ and $f = 50$:

$$h \approx \frac{s}{10\ 000} \cdot 5.8 \tag{10}$$

If the flying height is lower or the camera has a longer focal length, the the photo covers less ground area, i.e. scale is larger, and the permissible vertical relief is also larger.

B Conversions for scanning

Conversion for scans, from dots per inch (DPI) to pixels:

$$\begin{aligned} 100\ \text{DPI} &\rightarrow 100\ \text{pixels in}^{-1} \\ &= 100\ \text{pixels}\ 25.4\ \text{mm}^{-1} \\ &= 3.937\ \text{pixels mm}^{-1} \\ &= 0.254\ \text{mm pixel}^{-1} \end{aligned} \tag{11}$$

Common scan resolutions are:

$$\begin{aligned} 100\ \text{DPI} &\rightarrow .254\ \text{mm pixel}^{-1} \\ 150\ \text{DPI} &\rightarrow .169\bar{3}\ \text{mm pixel}^{-1} \\ 300\ \text{DPI} &\rightarrow .084\bar{6}\ \text{mm pixel}^{-1} \\ 600\ \text{DPI} &\rightarrow .042\bar{3}\ \text{mm pixel}^{-1} \\ 1200\ \text{DPI} &\rightarrow .0211\bar{6}\ \text{mm pixel}^{-1} \\ 2400\ \text{DPI} &\rightarrow .010583\bar{3}\ \text{mm pixel}^{-1} \end{aligned} \tag{12}$$

These can be multipled by the map scale number (in thousands) to obtain ground meters per pixel. For example, if a photo's nominal scale is 1:24 000, and it is scanned at 1200 DPI, one scan pixel is $.0211\bar{6}$ mm $\times$ 50 mm m^{-1} = $1.0583\bar{3}$m $\approx$ 1m

Another way to think about this is the number of pixels per mm:

$$\begin{aligned} 100 \text{ DPI} &\rightarrow \approx 3.94 \text{ pixels mm}^{-1} \\ 150 \text{ DPI} &\rightarrow \approx 5.91 \text{ pixels mm}^{-1} \\ 300 \text{ DPI} &\rightarrow \approx 11.81 \text{ pixels mm}^{-1} \\ 600 \text{ DPI} &\rightarrow \approx 23.62 \text{ pixels mm}^{-1} \\ 1200 \text{ DPI} &\rightarrow \approx 47.24 \text{ pixels mm}^{-1} \\ 2400 \text{ DPI} &\rightarrow \approx 94.49 \text{ pixels mm}^{-1} \end{aligned} \tag{13}$$

So to preserve a resolution of, say, 0.1 mm would require a scan of 300 DPI; for fine detail on a topographic map we may want a resolution of 0.01 mm, which requires 2400 DPI. A simple rule-of-thumb to memorize is that 300 DPI corresponds to a pixel size somewhat smaller than 0.1 mm.

B.1 Required resolution

There are two requirements: **visualisation** and **location**. The first requirement is æsthetic: you scan at the resolution necessary to preserve the appearance of the original. If it is high-quality, such as a contact photo print or an original paper map, very high resolutions are needed. The resolution of silver halide grains in a contact print on high quality photographic paper is extremely high. For a paper map with high-quality paper and printing processess, it is also very high (think of trying to reproduce a bank note ...).

If the original was produced at a lower resolution (e.g. by printing on a 600 DPI laser printer), this is the maximum scan resolution; any more is wasted. However, you may not require such good resolution for **your** visualisation purposes. Unless you are going to print at high resolution, it doesn't make sense to scan at any higher resolution than your final output, allowing of course for any digital enlargement. For example, if you will print at 300 DPI and you will enlarge by a factor of 2, you would need to scan at 600 DPI. The second requirement depends on the accuracy with which you need to locate points on the digital product. This is limited by the map scale, both of the source (what is being scanned) and your final GIS products.

The required location accuracy can not be higher than the **working scale** of your project, which is typically determined by the accuracy of your base map or GPS receiver, depending on how you are doing the geo-referencing. In the first case, the limit is set by the map accuracy standards [2, § 1], [8, §3.1.3], which for medium- and small-scale maps is 0.25 mm on the map if produced by analogue methods and 0.1 mm if produced by fully-automated methods. The 0.25 mm limit can be converted to the scan resolution with the inverse of Eqn. (11), where we see that this is almost exactly equal to 100 DPI In other words, **a map that conforms to manual accuracy standards should be scanned at 100 DPI for purposes of location**. The corresponding figure for fully-automated maps is 300 DPI. These resolutions may not be visually-pleasing, in which case a higher resolution may be used.

Note that 0.25 mm on the map corresponds to 12.5m on the ground for a 1 : 50 000 map, and to 5m for a 1 : 20 000 map; the corresponding figures of 0.1 mm on the map are 5m and

2m. This implies that location accuracy from printed maps are not particularly high; values such as those for the 0.25 mm accuracy can be obtained with most single-receiver field GPS; for the 0.1 mm accuracy differential GPS must be used.

B.2 File sizes

Using large scan resolutions leads to file sizes that may not be practical. To determine the storage requirement, multiply one dimension, in mm, by the number of pixels mm^{-1}; this gives the number of row or columns. Multiply the dimensions to determine the number of pixels, and finally by the number of bytes per pixel to determine total storage requirement. For example, a standard 23×23 cm photo at 300 DPI requires approximately:

$$\begin{aligned} 23\text{ cm} \times 10\text{ mm cm}^{-1} \times 11.81\text{ pixels mm}^{-1} &= 2,716\text{ rows} \\ 2,716\text{ rows} \times 2,716\text{ columns} &= 7,376,656\text{ pixels} \\ &\approx 7.035\text{ Mb} \end{aligned}$$

For 600 DPI this is quadrupled to ≈ 28.14 Mb, which is quite large even for today's (2001 c.e.) Windows-based workstation. At 150 DPI this is reduced to a much more manageable ≈ 1.76 Mb.

C What if some materials are sub-standard?

It may be that not all the materials listed in §2 are as they should be. In this section we give some hints for the most common cases.

C.1 A4 scanner

If you can only find an A4 (29.7×21 cm) scanner, you will not be able to fit a standard 23×23 cm airphoto plus margins for the fiducial marks, in one dimension. The best you can do is scan the central 21 cm in one dimension, and use the direct linear transformation. The marginal areas that you could not scan must be included in scans of adjacent photos, for the final photo-mosaic. Do not interpret in these areas.

C.2 Poor-quality topographic map

Unfortunately, sometimes one has to work with ripped, worn-out, multiply-folded base maps, which may even be copies on unstable paper, rather than original prints. In such cases, it is impossible to geo-reference a scan, since the scale will be far from uniform across the map. If the map has an over-printed grid, the solution is to **measure the coordinates** `(E,N)` of the control points in a **local area** of the map, using a precise **metric ruler** (steel preferred). Since the distortion in a small area of the map is relatively small, the coordinates should be adequate. Especially with photocopies, but also with poor-quality originals, play close attention to the **true scale**, which may not match the nominal scale. Use the metric ruler to establish the true scale in the local area, by measuring the mm between grid lines of known

distance. You should be able to read with a good steel millimeter ruler to 0.25 mm (map accuracy standard), i.e. 12.5m for 1:50 000 scale maps (since 1 mm = 50m). In practice, this means you should divide a 1 mm unit into 4 and read to the nearest 0.25 mm. For example, if the overprint grid is 1×1 km, as is typical, and the actual distance between grid lines, measured on the paper map with the metric ruler, is 37.6 mm (3.76 cm), the true scale is $1 \times 10^6/37.6 \approx 1:26\,596$.

If the nominal scale (printed on the map) is 1:25 000, we would expect this distance to be 40 mm (4 cm). This shows that the copying process has shrunk the map by $(40 - 37.6)/40 = 6\%$, which is not uncommon. Then, when measuring on the map, you must convert the map mm to ground m with the **actual scale**. Using the example above, if you read 12.25 mm to the right from the grid line for `325000 E`, the coordinate is $325\,000 + (12.25 \times 26.596) \approx$ `325315 E` (to the nearest meter).

C.3 Topographic map without overprinted grid

In some countries (e.g. India) maps are printed without a grid; however, these usually have known coordinates in (latitude and longitude) at the corners of each topographic sheet, because the map series is usually divided according to the geographic grid. The solution here is to geo-reference in the **geographic** coordinate system, with the appropriate projection, and then **transform coordinates** to a chosen metric grid, e.g. the local UTM zone in a specific datum. The specific situation of India, as well as the general technique, is dealt with in [9].

C.4 Topographic map with unreliable coordinates

In some countries, e.g. ex-Soviet Union and satellites, the grid is deliberately distorted, and even the corners of the topographic sheet are not reliable. In this case, the only good solution is to find the tiepoints in the field with a GPS, using the same coordinate system. You can use these same tiepoints to geo-reference the scanned topographic map.

C.5 Airphoto without fiducial marks

As explained in §3.3 ("Selecting a geo-referencing method"), if the photo has no fiducial marks, you should use the direct linear transformation if there is significant relief, otherwise the projective transformation.

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