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7.1 Introduction

Photogrammetry and remote sensing are two indirect methods of obtaining both quantitative and qualitative data about the Earth's surface or other features of interest. Since some debate exists regarding the demarcation between the two subjects, the following broad distinction will be used throughout this chapter. Photogrammetry will be considered to be concerned with the scientific methods of obtaining reliable measurements from ground or airborne imagery (primarily photographic) in order to produce a precise representation (graphical or digital) of the feature of interest. Remote sensing, in contrast, will be defined as encompassing those methods of detecting variations in radiant energy from the Earth's surface using airborne or satellite sensors. Interpretation (either visually or using computer techniques) of these recorded patterns is used to create thematic maps. The aim of this chapter will therefore be to: (1) provide an introduction to the fundamental principles of photogrammetry and remote sensing; (2) review the current state of development of instrumentation in both fields; and (3) examine the application of both techniques to problems in civil engineering.

7.2 Principles of photogrammetry

Since measurements may be taken from both air and ground images (normally photographs) two separate branches of the discipline are generally recognized: aerial and close range (or terrestrial) photogrammetry.

Aerial photogrammetry is a well-established technique in civil engineering for the production of topographic maps. Aerial photographs produced for such purposes can be obtained either with the optical axis of the camera pointing, nominally, vertically downwards so producing vertical aerial photographs or, with the axis intentionally tilted, to produce oblique aerial photographs. The former are almost exclusively used nowadays for photogrammetric purposes, although the latter have received a revival in recent years with the advent of analytical techniques. Vertical aerial photographs are normally acquired to achieve a 60% forward and a 20 to 25% lateral overlap in coverage. This enables a stereoscopic view of the terrain to be obtained and also a stereoscopic 'model' to be produced. The latter forms the basis of almost all of the photogrammetric instruments and techniques discussed in section 7.3.

Close-range, terrestrial or, to use a less attractive but commonly used alternative, nonoptophotograph photogrammetry, is concerned with photographs taken on, or near the ground, rather than from an aerial platform. This branch of photogrammetry has developed considerably in the past 20 yr or so and has been applied to many problems in civil engineering. A selected number of these applications are presented in section 7.4.

A further distinction which is becoming used increasingly as a means of classification, both in aerial and close-range photogrammetry (CRP), is that between the analogue and analytical approaches to the subject. Apart from a few exceptions, until relatively recently photogrammetric instruments and techniques consisted of optical and mechanical analogue systems which were used for the production of a graphical end product (map, plan, elevation, section, etc.). However, the emphasis in photogrammetry is now moving towards analytical systems which use rigorous mathematical models to simulate the problem under investigation. By using these mathematical models in conjunction with modern computers, new photogrammetric instruments have evolved which offer significant advantages over their analogue counterparts in terms of speed of operation, accuracy and flexibility. Furthermore, the output products of these computer-based systems consist not only of graphical products, but also of other information sources such as digital terrain models.

7.2.1 Geometry of a single photograph

A photograph differs fundamentally in geometric terms from a map (unless the terrain is flat and the photograph vertical). Image displacement causes scale variations over the format due to the alteration in the position of points, compared with their corresponding map positions, as a result of the effects of ground relief and tilt of the photograph at the moment of exposure. The geometrical influence of both factors is illustrated by Figure 7.1 which shows that a tall tower is not imaged as a single point, as it would be on a map, but rather as a displaced line t-t' and t'-t on the vertical and tilted photographs respectively. In this case, the displacement is greatest on the vertical photograph. A similar displacement will exist for all points above the datum level e.g. point X. It is also evident that the tilted and vertical photographs are coincident at point i, the isocentre, and that tilt displacement radiates from this point. This radial nature of the displacements can be used to devise a simple method of plotting from a pair of photographs.

![Figure 7.1 Relief and tilt image displacements on a vertical and near-vertical aerial photograph](image)

The effect of image displacement on scale can be seen in Figures 7.2 and 7.3 which illustrate the separate results of tilt and variation in ground relief. It can be seen that, unlike a map which has a constant scale, the combined effects of relief and tilt produce a photograph which will be of constantly changing scale.

![Figure 7.2 Scale changes on a vertical aerial photograph caused by variations in the elevation of the ground](image)
scale, although an average nominal value for the scale can be calculated (often referred to as the contact scale).

7.2.2 Stereoscopy and parallax

Stereoscopic viewing and the measurement of the perceived stereomodel is fundamental to photogrammetry and thus of great importance. If two photographs taken from different viewpoints of the same area are viewed simultaneously, the difference in position of a common image point on the two photographs results in a discrepancy in image coordinates and this leads to the concept of $x$-parallax and $y$-parallax.

All points appearing on successive overlapping photographs exhibit $x$-parallax in the direction of flight and this is the principal reason why a stereomodel exists. It can be seen from Figure 7.4 that the combined movement of point A across the focal plane of both photographs relative to the central axis is greater than for point B, thus point A is defined as exhibiting a greater absolute $x$-parallax than B. It is also evident from the diagram that the absolute $x$-parallax of a point is related to the height of that point and that it increases with increasing height. This simple concept forms the basis of the methods used to derive heights from aerial photographs. Section 7.3.3 outlines one such technique.

In contrast, $y$-parallax is not related to height variations. It is produced if there is a difference in orientation of the two photographs at the time of exposure. The effect of $y$-parallax on a stereomodel can be eliminated by reproducing the original camera orientations to ensure that corresponding rays from the two photographs will intersect. Such a process is termed the ‘relative orientation’ phase in setting up a stereoplotter.

7.2.3 Analytical photogrammetry

Many photogrammetric operations which were previously carried out by graphical or analogue methods are now being performed digitally using analytical instruments and computational techniques. Since most analytical methods involve some form of coordinate transformation, it is first necessary to examine the coordinate reference systems which are used. On the plane of the photograph, the reference system known as the ‘image space’ system is defined with respect to the principal point and the fiducial marks, as shown in Figure 7.5. It may also be important to take into account any variation in position which exists between the fiducial centre (the intersection of the fiducial marks) and the principal point (where the perpendicular line from the lens intersects the focal plane). This is defined by a camera calibration procedure. On the ground, positions are usually referred to a cartesian coordinate system, e.g. the National Grid. This is illustrated by Figure 7.6 in which $X_c$, $Y_c$ and $Z_c$ represent the ‘object space’ coordinates of the camera exposure station.

An appreciation of the two basic assumptions which are used in order to define positions is also essential. Firstly, the line in space joining a point in the object space - the perspective centre of the camera lens and the position of the point on the photograph - is assumed to be a straight line, i.e. line $p-C$ in Figure 7.6. In analogue stereoplotters, this assumption is imposed by optical projection or mechanical ‘space rods’.

Analytically, it is expressed by means of the collinearity equations for a single photograph:

$$x = -f \frac{M_{11}(X - X_c) + M_{12}(Y - Y_c) + M_{13}(Z - Z_c)}{M_{31}(X - X_c) + M_{32}(Y - Y_c) + M_{33}(Z - Z_c)}$$  \hspace{1cm} (7.1)
7.3 Photogrammetric instrumentation

7.3.1 Cameras

Most photogrammetric measurements are recorded from photography produced by a high-quality camera specifically designed for photogrammetric purposes. The main feature which distinguishes this type of camera from others is that the internal geometrical characteristics are known precisely. Thus, data relating to the lens distortion, focal length and principal point location are established, and monitored periodically by a camera calibration procedure.

Both aerial and close-range cameras are used for data acquisition. Aerial mapping cameras are normally classified on the basis of the angular field of view of the lens, a parameter which relates directly to both the focal length \((f)\) and the format size of the camera. The focal length of an aerial camera is defined as the distance from the optical centre of the lens to the image plane. For the general case of a \(230 \times 230\) mm format, the classification shown in Table 7.1 can be produced. Normal angle (NA) photography is only occasionally used and it can be seen from Figure 7.8 that the principal advantage of the super wide

<table>
<thead>
<tr>
<th>Camera type</th>
<th>Approximate angular field of view (^\circ)</th>
<th>Approximate focal length (mm)</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super wide angle</td>
<td>120</td>
<td>90</td>
<td>Zeiss (Ober.) RMK A 8.5/23</td>
</tr>
<tr>
<td>(SWA)</td>
<td></td>
<td></td>
<td>Wild RC-10 (Super Aviogon lens)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zeiss (Jena) MRB 9/2323</td>
</tr>
<tr>
<td>Wide angle</td>
<td>90</td>
<td>150</td>
<td>Zeiss (Ober.) RMK A 15/23</td>
</tr>
<tr>
<td>(WA)</td>
<td></td>
<td></td>
<td>Wild RC-8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wild RC-10 (Universal Aviogon lens)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zeiss (Jena) MRB 15/2323</td>
</tr>
<tr>
<td>Normal angle</td>
<td>60</td>
<td>300</td>
<td>Zeiss (Ober.) RMK A 30/23</td>
</tr>
<tr>
<td>(NA)</td>
<td></td>
<td></td>
<td>Wild RC-10 (Normal Aviogon lens)</td>
</tr>
</tbody>
</table>

Table 7.1 Classification of aerial mapping cameras

A further analytical technique which is used by photogrammetrists is that defined by the coplanarity equations. Coplanarity equations can be established for a pair of photographs and they may be used to reconstruct the orientation of the cameras at the moment of exposure, i.e. an analytical method of relative orientation. In order to satisfy the condition, the two exposure stations \(C_1\) and \(C_2\), the object point \(R\) and its corresponding image points \(r_1\) and \(r_2\) are assumed to all lie in a common plane, known as the epipolar plane (Figure 7.7).
angle (SWA) lens is its greater ground coverage for a given flying height. This is particularly important since it not only reduces the number of photographs required to cover an area, but also reduces the number of control points which are required for controlling the mapping. However, because SWA photography is more susceptible to the production of 'dead ground' (loss of detail because of the screening effect of features), a compromise solution is normally adopted by using a camera which enables wide angle (WA) photography to be produced.

Three distinct types of close range or terrestrial photogrammetric camera are currently available: (1) metric; (2) stereometric; and (3) nonmetric. The metric camera models include those in which a camera and a theodolite form one integrated unit, the classical phototheodolite, and those where the camera is a separate unit from the theodolite. The latter case tends to be more common and the UMK10/1318 is a typical example (Figure 7.9). Details of the characteristics of several cameras of this type are listed in Table 7.2.

The second design, the stereometric system, consists of two matched camera units mounted on each end of a base bar, typically 0.4 to 3 m long. The camera axes are set at right angles to the bar and since the relative position and orientation of the cameras at the instant of exposure are known, the subsequent analysis phase is considerably simplified. The Zeiss (Oberkochen) range of cameras illustrated by Figure 7.10 are representative of this design. Further details of other cameras of this type are listed in Table 7.3.

A nonmetric camera is one which was not designed specifically for photogrammetry. Although such cameras offer advantages in terms of size and cost, their use is limited, unless analytical techniques are used to compensate for the unstable interior geometry of the camera. A varied selection of nonmetric cameras has been used for photogrammetric purposes including...
medium-priced 'amateur' cameras, such as the Olympus OM-2, Canon TX, Minolta XG-7 and Rolleiflex SL66, as well as the more expensive 'professional' cameras such as the Linhof Technica and the Hasselblad 500EL.

7.3.2 Single-photograph-based instruments

In certain circumstances it may be appropriate to attempt to derive metric plan information from a single photograph. Reasonable results can be obtained provided that relatively flat ground has been imaged on an almost tilt-free photograph.

The camera lucida principle, whereby images of an existing map and the corresponding photograph are superimposed, has been adopted to produce a simple mapping instrument such as the Zeiss (Jena) Sketchmaster and the Bausch and Laumb Zoom Transfer Scope. Adjustments can be made either mechanically or optically in order to remove the effect of minor tilt distortions and to make a correction for small variations in scale between map and photograph. This type of instrument is of particular value for map revision. When detail shown on both photograph and map has been aligned, new details imaged on the photograph can be traced on to the map.

It is also possible to apply a digital approach to measurement on a single photograph using a monocomparator. This instrument essentially consists of a travelling microscope moving

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Nominal focal length (mm)</th>
<th>Principal distance (F = fixed, V = variable)</th>
<th>Format (mm)</th>
<th>Minimum range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild</td>
<td>P30</td>
<td>165</td>
<td>F</td>
<td>100 x 150</td>
<td>20</td>
</tr>
<tr>
<td>Wild</td>
<td>P31</td>
<td>45, 100, 200</td>
<td>F, V, V</td>
<td>100 x 150</td>
<td>7, 1.4, 8</td>
</tr>
<tr>
<td>Wild</td>
<td>P32</td>
<td>64</td>
<td>F</td>
<td>65 x 90</td>
<td>3.3</td>
</tr>
<tr>
<td>Officine Galileo</td>
<td>Verostat</td>
<td>100</td>
<td>V</td>
<td>90 x 120</td>
<td>2</td>
</tr>
<tr>
<td>Zeiss (Jena)</td>
<td>UMK 10/1318</td>
<td>100</td>
<td>V</td>
<td>130 x 180</td>
<td>1.4</td>
</tr>
<tr>
<td>Zeiss (Ober.)</td>
<td>TMK 6</td>
<td>60</td>
<td>V</td>
<td>90 x 120</td>
<td>5</td>
</tr>
</tbody>
</table>


Table 7.2 Summary of main features of a selection of close-range photogrammetric cameras

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Nominal principal distance (mm)</th>
<th>Principal distance (F = fixed, V = variable)</th>
<th>Format (mm)</th>
<th>Focusing range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild</td>
<td>C40</td>
<td>64</td>
<td>F</td>
<td>65 x 90</td>
<td>1.5 - 7.0</td>
</tr>
<tr>
<td>Wild</td>
<td>C120</td>
<td>64</td>
<td>F</td>
<td>65 x 90</td>
<td>2.7 - 8.0</td>
</tr>
<tr>
<td>Officine Galileo Veroplast</td>
<td>100</td>
<td>V</td>
<td>90 x 120</td>
<td>2 - 12.0</td>
<td></td>
</tr>
<tr>
<td>Zeiss (Jena)</td>
<td>SMK 5.5/0808</td>
<td>56</td>
<td>F</td>
<td>80 x 80</td>
<td>5 - 12.0</td>
</tr>
<tr>
<td>Zeiss (Ober.)</td>
<td>SMK 120</td>
<td>60</td>
<td>F</td>
<td>90 x 120</td>
<td>5 - 12.0</td>
</tr>
</tbody>
</table>


Figure 7.10 Zeiss (Oberkochen) SMK 120 and SMK 40 stereometric camera

Table 7.3 Summary of main features of stereometric close-range photogrammetric cameras
along orthogonal axes in order to determine image coordinates. Various refinements to the basic principle have been made; the Surveying and Scientific Instruments PI-1a, for example, employs a miniature CCTV observation system and provides digital readout with the MDR 1S/3 display, whilst the Zeiss PSK-1 instrument uses optical scales based on Moiré fringes. With the aid of a microcomputer and suitable software, a plot can be produced from such equipment.

7.3.3 Approximate solution stereoscopic instruments

When reconnaissance mapping or revision of existing maps from new photography is being carried out, it is often more cost effective to use a simple, approximate stereoscopic instrument rather than a sophisticated and expensive rigorous stereoplotter.

Several manufacturers produce stereoscopic versions of the monoscopic instruments which are based on the camera lucida principle, e.g. the Cartographic Engineering Stereosketch and the Bausch and Laumb Stereo Zoom Transfer Scope. The image of the stereoscopic view of an overlap is superimposed on the map image and photographic plan detail can be traced; no facilities are provided for height measurement. The Cartographic Engineering Radial Line Plotter (Figure 7.11) is a simple, lightweight instrument which can be used for small-scale planimetric mapping. The instrument design is based on the radial line assumption which states that angles measured at the principal point are true if the photographic tilt and variation in ground relief are below some limiting value (normally 3° and 10% of the flying height). Other approximate instruments include the Zeiss (Oberkochen) G2 Stereocord and the Officine Galileo Stereomicrometer.

A parallax bar (Figure 7.12) is a portable device for obtaining measurements of differences in $x$ parallax which can be used to calculate differences in height. Spot heights at changes of slope can hence be obtained and contours interpolated. The eye observes the measuring mark on the glass plates through a stereoscope. When adjusted to the correct $x$ separation the two marks appear to fuse into a single point which may appear to ‘float’ above the level of the terrain. In order to make some correction for possible photographic tilt and variation in flying height for the stereopair, a minimum of five control points of known ground height are required for the overlap; ideally eight to ten points will be used. Each of the control points is observed in turn and the micrometer screw is turned to remove $x$ parallax and, hence, bring the floating mark to ground level.

Any $y$ parallax can be eliminated by adjusting the right-hand stage plate in the $y$ direction. The micrometer readings are recorded for all the control points. In order to calculate spot heights, the mean flying height must be determined from scaled measurements on the photographs and the absolute parallax of one point must be determined using a travelling microscope. A computer program is then normally used to calculate crude

---

**Figure 7.11** Radial line plotter. (Courtesy: Cartographic Engineering)

**Figure 7.12** Parallax bar.
heights from Equation (7.3) and to obtain corrected spot heights from Equation (7.4). If redundant control has been provided, residuals will be available and the heighting accuracy can be investigated.

\[ h_B = h_A - \frac{(H - h_A)\Delta p_{AB}}{p_A - \Delta p_{AB}} \]  

(7.3)

where \( h_A \) = height of A (a reference point of known height), \( h_B \) = crude height of point B (point of required height), \( \Delta p_{AB} \) = difference in parallax bar readings between A and B (care must be taken with sign) and \( p_A \) = parallax of A.

\[ h_B = h_B + a_0 + a_1x + a_2y + a_3xy + a_4x^2 \]  

(7.4)

where \( h_B \) = corrected height of point B and \( x, y \) are image coordinates of B, and \( a_0, \ldots, a_4 \) are coefficients, constant for a given overlap. This method of height correction was first proposed by Thompson and was subsequently modified by Methley. Contours may be interpolated between spot heights, continuous reference being made to the stereomodel as they are drawn.

### 7.3.4 Rigorous solution stereoscopic instruments

#### 7.3.4.1 Analogue stereoplotters

Analogue stereoplotters create and measure an exact three-dimensional model of the ground. Direct optical projection in the form of Multiplex equipment was the earliest method of realizing this objective. The Zeiss (Ober.) DP 2 stereoplotter (Figure 7.13) is a modern version of Multiplex equipment. Plotters such as these, which employ direct optical projection, have the disadvantage of relatively poor viewing conditions and an inflexible plotting scale, usually approximately double the photograph scale. However, their uncomplicated operation and minimum of maintenance make them very suitable for medium-scale mapping and map revision, although in recent years they have tended to be superseded by mechanical and analytical instruments.

Mechanical rods replace light rays when a rigorous model is formed in instruments employing mechanical projection (Figure 7.14). Full-sized diapositives are placed in projector heads which can be tilted; a stereoview is obtained through a binocular eyepiece linked to viewing microscopes fitted to each projector. The movement of each microscope is communicated via a tie rod to a sleeve at the top of a space rod which pivots about a gimbal joint representing the projection centre. The two space rods take up the attitude of the space rays from the ground point to the camera stations; they normally intersect in a model point which is connected to a plotting pencil by gears. The principal distance of the taking camera is represented by the separation of the sleeve on the space rod which represents the image point and the gimbal joint; this distance can easily be varied so that mechanical projection plotters can accommodate photography taken with a wide variety of cameras. Considerable flexibility of plotting scales (up to 6 times the photographic scale) is provided by altering the gears linking the model point to the plotting point (Table 7.4).

![Figure 7.13 Zeiss (Oberkochen) DP-2 stereoplotter. (Courtesy: Zeiss (Oberkochen))]
photogrammetric stereoplotter has emerged: the analytical stereoplotter. With this type of instrument a mathematical model replaces the space rods and other mechanical linkages which are found in more conventional analogue stereoplotters. An instrument which is representative of this design is the Officine Galileo Digicart. This instrument consists of a stereoviewing system, linear encoders to digitally record the position of the carriages on which the photographs are mounted, a minicomputer to process the data, and a plotting table. Unlike a conventional analogue instrument where manual elimination of y-parallax is performed initially over the entire model, with this design any parallax existing within the model is continuously eliminated by a feedback loop which ensures that corrections are transmitted to the optics in real time (50 times a second) to provide a model free from parallax. Figure 7.16 illustrates the principle of operation.

The advent of analytical techniques has had a considerable influence on the practical application of photogrammetry to engineering problems. In particular, analytical techniques offer the following advantages over conventional analogue techniques:

(1) Higher accuracy of measurement can be achieved than was previously possible (up to ±3 μm at photoscale with suitable care).
(2) Photography taken with differing format sizes and focal lengths can be used. In certain cases, provided suitable
precautions are taken to eliminate any systematic errors such as lens distortion, nonmetric cameras can be used.

(3) The setting up of any stereomodel presents little difficulty; most models can be set up in 10 to 15 min by an experienced operator, thus leaving more time for the actual measuring phase.

(4) Photography can be obtained in the field without too great a concern about the orientation of the camera. This can save a great deal of time (as much as 50% over the conventional approach). Where access is difficult, and vertical or normal case geometry is impeded, oblique photography may be taken. Such an approach would have been precluded using traditional methods.

(5) Data are captured in ground coordinates and stored on positives on glass stage plates. For analogue instruments, either fixed (as is the case for direct optical projection instruments), register glass must be aligned. Unless the principal distance is set up the model correctly.

7.3.4.3 Orientation of stereoplotters
Whatever type of equipment is used, before drawing can commence three stages of orientation must be carried out in order to set up the model correctly.

Inner orientation consists of the careful setting of the diapositives on glass stage plates. For analogue instruments, either the principal point or the fiducial marks on both diapositive and register glass must be aligned. Unless the principal distance is fixed (as is the case for direct optical projection instruments), this must be set to the value obtained from the camera calibration certificate. If an analytical plotter is used, the reference marker is taken to each fiducial mark in turn and the coordinates are recorded; the camera principal distance is entered into the computer as are any known lens distortion characteristics.

Relative orientation is next carried out in order to produce a true undistorted model. It does not require any reference to ground control and is achieved in analogue instruments by removing $y$ parallax for clear points of detail selected at five standard positions. The entire model should then be clear of $y$ parallax. For analytical models, $y$ parallax is measured at five or more positions to enable the computer to deduce the movement of the servomotors subsequently required to view a parallax-free model.

Absolute orientation is required in order to scale the model and level it to ground datum. Scaling is basically accomplished by comparing a model distance with a known ground distance and adjusting the machine base in analogue instruments to achieve the required model scale. For heighting, the model and ground heights of a minimum of three points are compared and the model is rotated about the machine $X$ and $Y$ axes until differences in height agree. The machine datum will then be parallel to ground datum and its exact level can be determined. True ground heights can then be read directly from the instrument height scale. Analytically, photo coordinates and corresponding ground coordinates of three or more control points are compared in order to enable the required transformation coefficients to be computed.

The machine is now set up and plotting can commence. For plan detail, the operator moves the floating mark to follow image detail, keeping it in contact with the model surface by constantly adjusting its height. In correspondence, the plotting pencil traces out the detail on the map sheet. In order to plot a contour, the floating mark is kept at the required constant height and is moved in contact with the model surface so that the contour line is drawn on the plot. A similar procedure is followed for the analytical plotter as far as the movement of the floating mark by the operator is concerned, but computer-assisted plotting offers additional options such as defining the end points of a straight line and instructing the pencil to join them.

The machine plot will only contain information that can be obtained directly from the stereopair and field completion is required to add ground detail which might be obscured on the photographs, e.g. within woodland or below the eaves of houses, and also to assist annotation of, for example, place names and road classifications.

7.3.4.4 Orthophoto systems
An orthoprojector is used to generate a photograph that is the geometrical equivalent of a map by a process of differential rectification. An exact model is set up in a stereoplotter, the effects of tilt being removed by the standard procedures of relative and absolute orientation. The operator scans the model systematically with the floating mark, adjusting the effective height of the mark continuously so that it remains on the surface of the ground. The orthoprojector operates in the darkroom conditions and holds a duplicate of one of the photographs of the stereopair. The tilt of the corresponding plotter projector, and the linear motion and height movement of the floating mark are transmitted either mechanically (Zeiss (Oberkochens) DP Ortho-3), optically (Wild PPO-8) or analytically (Zeiss (Oberkochen) Orthocomp Z-2) to the orthoprojector which allows exposure through a small slit on to light-sensitive paper. Thus a corrected print of the overlap area, known as an orthophoto-graph, is gradually built up as the slit moves in sympathy with the floating mark, the effects of height difference being removed by the continuous adjustment of the orthoprojector. Cartographic enhancement may be added to the print (e.g. contour lines, grid lines and place names), resulting in an orthophoto-map.

7.4 The use of photogrammetry in civil engineering

7.4.1 Aerial photogrammetry

7.4.1.1 Topographic mapping

The use of aerial survey is generally considered to be the standard method of producing a topographic map or plan at scales smaller than 1:500. For scales greater than 1:500, ground survey would almost invariably be used.

The basic sequence of operations required for the production of a topographic map is shown by the flow diagram in Figure 7.17. The major air survey companies will have the equipment and manpower to carry out all the stages indicated but smaller concerns might, for example, subcontract the photography. It is very important that the exact requirements for the survey output should be known at the outset and that detailed discussion should take place between the civil engineer and the air survey company in order to identify any specific problems which might arise in connection with a particular project.

Flight planning. Before a survey flight can commence, a flight plan must be prepared detailing all the information required by the pilot, navigator and camera operator.

Aerial photographs which are to be used for mapping purposes must be taken in a regular sequence along parallel lines of flight. Navigation is usually visual by identifying landmarks shown on the map, mosaic or satellite image on which the
A standard Specification for vertical aerial photography has been prepared by the Royal Institution of Chartered Surveyors in collaboration with the British Air Survey Association. This specification is used by air survey companies throughout the world as a contract document for providing black-and-white aerial photography. The specification includes the air camera and its calibration, photographic coverage and operation, flying conditions, the type of aerial film, processing and drying conditions, the resultant products to be supplied, and documentation and annotation.

**Aerial triangulation.** The object of aerial triangulation is to establish a network of control points with known ground coordinates which are required before a map can be plotted from aerial photographs. In order to perform absolute orientation when setting up a model in a stereoplottter, the minimum theoretical control required for each model is 2 points with known plan coordinates and 3 points with known heights (in practice, 3 plan points and 4 height points are usually considered to be the minimum). Thus, a large project would require the provision of an extensive amount of control; it would be very expensive and time-consuming if this had to be carried out exclusively by field survey methods. Aerial triangulation also has the advantage that it is easy to provide more than the bare minimum of control and it will usually be possible to obtain points in very convenient positions for their subsequent use in a stereoplottter.

Analogue methods of aerial triangulation have evolved steadily with the development of analogue stereoplotters. The method of aerial triangulation by independent models (AIM) is now used almost universally with modern analogue instruments. Since the technique requires model coordinates to be measured in an analogue plotter, a substantial amount of computation is required to obtain ground coordinates and it could therefore be described as a semi-analytical method.

Whereas model coordinates measured in an analogue plotter form the basic data for the calculation of aerial triangulation by independent models, x, y coordinates measured either in a mono- or stereocomparator provide the raw data for the fully analytical methods. Much less observation time is required than with the equivalent analogue methods, but much greater emphasis is, however, placed on the data processing phase, both for the location of gross and systematic errors and for the computation of the coordinates. As outlined in section 7.2.3, it is possible to establish the mathematical equations of the bundle of rays from the optical centre of the camera lens to all image points observed on a given photograph by using the collinearity method. The combination of all the bundles of rays for the entire block can be used to carry out absolute and relative orientation simultaneously. The calculated ground coordinates obtained by this method are adjusted to a best mean fit by least squares. It is clearly advantageous if both the necessary hardware and software are available to consider the block as an entity rather than to adjust a strip and then connect adjacent strips in a separate operation.

Having carried out aerial triangulation, each stereomodel is subsequently set up in turn using the orientation procedures mentioned in section 7.3.4.3. Plotting can then commence, so creating a topographic map or the operator may measure spot heights to form a digital terrain model.

**7.4.1.2 Production of digital terrain models**

The term digital terrain model (DTM) was originally coined in 1958 by Miller and La Flamme. Since then, the subject has developed considerably and is currently an area of widespread activity in surveying, geology and geophysics, civil and mining engineering and other disciplines in the earth sciences.

Although a variety of different techniques exist for the creation of DTMs in general, the distinction can be made between those which make use of height data which have been collected in a regular grid and those based on a network of randomly located height points. The former, simpler, approach is generally adopted when photogrammetric equipment is being used for the generation of the DTM. While the square grid is the
most common form, rectangular-, hexagonal- and triangular-based grids are also used.

Although the regular grid is the simplest technique to adopt it has one serious limitation: the distribution of data points is not related to the characteristics of the terrain. If the data point sampling is conducted on the basis of a regular grid, then the density must be high enough to portray accurately the smallest terrain features present in the area being modelled. If this is done, then the density of data collected will be too high in most areas of the model, in which case there will be an embarrassing and unnecessary data redundancy in these areas.

One solution to this problem is to use progressive sampling and its development, composite sampling. Instead of all points in a dense grid being measured, the density of the sampling is varied in different parts of the grid, being matched to the local roughness of the terrain surface. This approach has been widely implemented on a variety of grid-based terrain modelling packages such as HIF1, Intergraph DTMN. A comprehensive review of the use of such terrain modelling packages in surveying and civil engineering can be found in Petrie and Kennie.

7.4.1.3 Monitoring

Aerial photogrammetry has been used extensively in the past as a means of monitoring changing conditions such as the depletion of coal stocks or the degree of coastal erosion occurring over a period of years. In more recent years, its use has also developed for monitoring the deformation of natural or man-made features.

Fraser and Fraser and Gruendig describe the planning and subsequent execution of a photogrammetric survey of the Frank landslide/rockslide region of Turtle Mountain in Alberta, Canada. A rockslide occurred in this area over 80 yr ago when more than 30 million m³ of rock moved down the east face of the mountain covering an area 3 km² at a depth of 14 m. Since 1933, crack monitoring surveys of the area have been undertaken to determine the stability of the rock wedge forming the southern peak of the mountain. These surveys have been supplemented in recent years by an in situ monitoring program using crack motion detectors. Whilst these devices are capable of very high accuracy (± 0.1 mm/yr), they can only, realistically, be deployed over a very small area. Also, if hazardous movements are detected it may be considered unsafe to continue recording measurements. Aerial photogrammetry, by covering large areas in a noncontact manner, can overcome these limitations. Therefore, it was considered appropriate to evaluate the potential of photogrammetry for this project. Fraser established that the optimum flight plan consisted of obtaining large-scale (1:2000) multiple photographs (10 to 15) of the area containing the thirty monitoring target points. Photography was obtained using a Wild RC8 camera (focal length 152 mm) on two occasions approximately 1 yr apart. A subsequent analysis of the results indicated that statistically significant deformations had occurred at eight of the thirty points, the maximum movement being 63 mm.

7.4.2 Close-range photogrammetry (CRP)

Whereas it is possible to identify a standard procedure for mapping from aerial photographs, each project which requires the use of close-range photographs will tend to be regarded as unique due to the wide variation in circumstances which can arise for both taking the photographs and the subsequent analysis. For example, the positioning of the cameras for photography needs to be adapted to the particular demands of an individual task and may vary from a simulated aerial case with parallel, near vertical axes, through inclined and convergent axes to parallel horizontal axes. At the measurement stage, use of either analogue or analytical equipment may be specified according to the type of camera and whether a graphical or a numerical output is demanded.

Although some air survey companies also have a department which specializes in CRP, as do a few land survey organizations and universities, much of this type of work could be carried out by engineering firms themselves, perhaps within a research and development department as, for example, at Rolls Royce. It is even more vital for CRP than for aerial photogrammetry that the engineer should be very closely associated with all stages of the work so that he can ensure that his exact requirements are met.

7.4.2.1 Monitoring

Deformation of structures. Close-range photogrammetry has been used widely in the field of structural engineering. The ability of the technique to record both the shape of a structure at one moment and the deformations which occur between two epochs have been exploited. Notable in the first case is the extensive work which has been carried out in architectural photogrammetry. In the latter case, comprehensive applications reviews have been written by Atkinson and Cheffins and Chisholm. A review of the various methods which can be adopted has been prepared by Cooper. Cooper identifies four main methods including those which make use of a single camera (time parallax), controlled stereomodels, resection/intersection, and bundle adjustment. The latter is considered to be the most general case and most suitable for high-accuracy applications.

The range of large engineering structures which have been investigated by photogrammetric methods includes cooling towers, box girder bridges, elevation of St Paul's Cathedral, tower cranes, offshore platforms, and ships. In addition, photogrammetry has been used for the measurement and dimensional control of smaller structures such as microwave antennae, robots, and large compressors (see Welsh for further details). Increasingly, the emphasis is being placed on the development of a real-time photogrammetric system using video technology and solid-state cameras. Wong and Wei-Hsin outline the development of such a system.

Earth and rockfill dam monitoring. The use of CRP for monitoring earth and rockfill dams has been discussed by Moore and Brandenberger, among others. In the case of Moore, the author describes the use of a Wild P30 phototheodolite for monitoring the three-dimensional displacements of the Llyn Brianne rockfill dam, in mid Wales, during several stages of construction. The predicted displacements were in the range of ± 0.5 to 1.0 m, and whilst high absolute positional accuracy was deemed to be important, it was considered that the definition of the direction of movement was of equal importance. By using a Wild A7 stereoplotter, measurements were taken at over 80 targets, at differing levels of fill. The results indicated a range of displacements, from 0.1 to 0.6 m (with a standard error of ± 0.05 m).

Retaining wall monitoring. The use of a modified KA-2 aerial camera (focal length 610 mm, format 23 x 23 cm) to monitor the deflection of a gabion wall is described by Veress, Jackson and Hatsopoulos. The wall, situated near Seattle, Washington State, was over 400 m long and varied in height from 2 to 18 m. The gabions were constructed of 1-m steel mesh rockfilled cubes. Photographs were obtained from fixed control points up
to 1000 m from the wall. Over 100 target points were observed with an analytical plotter and ground coordinates computed. The wall was measured on eleven occasions. The authors suggest that CRP used in conjunction with an internal monitoring system such as an inclinometer would be an ideal system for monitoring new structures.

7.4.2.2 Slope/rock stability studies

One of the earliest reports of rockface mapping is given in Cheffins and Rushton. This paper describes the procedures used to produce 1:50-scale contoured elevations of the north face of Edinburgh Castle Rock. The elevations were required by a team of engineering geologists who were carrying out rock bolting and grouting as stabilizing measures to reduce the chance of rock falls from the face. The survey was carried out by taking four pairs of overlapping photographs from a baseline approximately parallel to the face. The photographs were obtained using a Wild RC5A aerial camera mounted on a hydraulic platform. The elevations with 0.25-m contours were subsequently used, in conjunction with ultrasonic data about the joint structure, to plan the positions of the necessary boreholes for rock bolting.

Moore discusses the use of a phototheodolite for mapping vertical faces, in this case in clay pits. The problem under investigation involved the determination of information about the continuity and spacing of major joints in the clay face. Photogrammetric techniques enabled a three-dimensional model of the spatial disposition of the joints to be constructed. Other references which mention the use of photogrammetry for slope and rockface stability monitoring include Torlegard and Dauphin and Robertson et al.

Landslides are a commonly occurring hazard in road design and construction. Heath, Parsley and Dowling describe the use of a Wild P32 camera to obtain photographs of areas susceptible to landslipping in Columbia and Nepal. The photographs were observed using a Zeiss Topocart and Wild A40 Terrestrial Stereoplotter, and 1:200- to 1:10 000-scale contoured plots were produced. The plans were subsequently used to design remedial and preventative measures associated with the landslip areas. They also enabled a classification of landslide characteristics to be produced.

Kennie and McKay discuss the use of CRP to monitor the erosion of chalk cliffs around a road tunnel in East Sussex. Control stations were enumerated at both the top and base of the cliffs, ensuring that a minimum of six control points were visible within each stereomodel. The stations were surveyed by EDM and theodolite and targets positioned over the monuments for precise viewing and control pointing in the stereo model. Photography was taken with a Zeiss UMK 10/1318 camera using glass negatives for greater stability.

Due to the angle of slope of the cliff face from the camera a wide variation in photoscale resulted in this case, from 1:400 to 1:900. For each of the four faces under investigation, the control network was rotated about two points on top of the cliff thus forming a datum line parallel to the face itself. The shape of the cliff was then defined by contours at 0.25-m intervals of depth – i.e. as differences in the horizontal distance from this datum plane - rather than as more conventionally vertical elevations above a height datum. The accuracy of points shown on both the map and sections was within ±5 cm of true ground position.

7.4.2.3 Tunnel profiling

Recent developments associated with the use of photogrammetry for producing tunnel profiles are described by Anderson and Stevens. Anderson and Stevens outline the development and use of a ‘mono-photogrammetric’ tunnel profile measuring system. The two main elements of the system are a high-intensity light plane generator, which illuminates the section to be profiled, and a camera which records the line of light which is generated. By digitizing the line, applying corrections for lens distortion, and scaling the photographs, an accuracy of ±10 mm is claimed. Furthermore, if the quoted progress rate of 100 sections per hour can be achieved in practice, the system would appear to be a highly cost-effective solution.

7.4.2.4 Laboratory-based applications

Close-range photogrammetry has also been applied to measurement problems in the laboratory; for example, Andrews and Butterfield, Wong and Vonderhoh, and Davidson have used the motion or ‘false parallax’ technique to measure the planar displacement fields associated with soil models. In the first two cases cited, the technique involved taking repeat photographs, from a single camera position, of a glass-sided tank which contained the soil under investigation. Photographs were taken using a nonmetric 35 mm camera before and after the sand within the tank was subjected to movement by a moving wall or wedge situated in the tank. By examination of enlargements of the photographs in an analogue stereoplotter, the relative positions of features could be measured and displacement contour diagrams produced. Analysis of these diagrams enabled the displacement component along the sand bed to be determined to within 5 μm. The latter two authors, in contrast, used analytical techniques to investigate the movement of soil particles around a model tunnel and soil penetration probe respectively.

7.5 Principles of remote sensing

The interpretation of aerial photography has for many years proved to be a valuable source of data for civil engineers. Until the early 1960s civilian ‘remote sensing’ was concerned primarily with the interpretation of such imagery. Since then, however, developments in orbiting satellites, sensor technology and computing have led to the creation of a discipline which now impinges on many areas in science and engineering. Although still in an embryonic state, particularly in the field of image processing, it has already proved to be a cost-effective method of investigating engineering phenomena of both large aerial extent, e.g. surface drainage, and those which are more localized, e.g. landslides, unstable land, etc.

7.5.1 The electromagnetic spectrum

Electromagnetic (EM) energy is all energy which travels in a periodic harmonic manner at the velocity of light. Electromagnetic energy is normally considered to consist of a continuum of wavelengths referred to as the EM spectrum (Figure 7.18).

It can be seen from Figure 7.18 that several regions of the EM spectrum are of particular importance in remote sensing. For example, the visible and reflected infra-red regions of the spectrum are important since they enable reflected solar radiation to be measured. In contrast, at longer wavelengths in the infra-red (8 to 14 μm waveband) the sensing of emitted thermal energy is of more significance. Measurements within the visible and infra-red (reflected and emitted) regions are considered to be passive in nature since the radiation being recorded occurs naturally. As the wavelength increases to the order of several millimetres it becomes more convenient actively to generate EM radiation of this wavelength and record the reflected radiation from the terrain. Thus, a typical active system would be side-
looking airborne radar (SLAR). It should be noted that instruments also exist for the measurement of passive microwave emission. However, since the emitted EM energy at this wavelength is very small, microwave radiometers are much less common than SLAR instruments.

Depending on the nature of the radiation being measured, it is possible to record the reflected or emitted energy by using either a lens and photographic emulsion or by using a linescanner and crystal detector. The geometrical distinction between the two approaches is illustrated in Figure 7.19. The primary advantage of using a linescanner approach is that it is possible to record radiation of wavelengths greater than about 0.9 μm. It is also possible to measure the variations in radiation within narrow spectral regions and to record directly these variations in digital form.

Mention should also be made here of the distinction between the terms 'photograph' and 'image'. A 'photograph' is an image which has been detected by photographic techniques and recorded on photographic film. In contrast, an 'image' is a more general term used to describe any pictorial representation of detected radiation data. Therefore, although scanner data may be used to create a photographic product, this result is normally referred to as an 'image' since the original detection mechanism involved the use of crystal detectors creating electrical signals, rather than a lens focused on to photographic film.

7.5.2 Classification of remote sensing systems

Remote sensing systems can be classified using various criteria, such as sensor sensitivity range, mode of recording (photographic or scanning), mode of operation (active or passive) or type of sensor platform (aircraft or satellite). Table 7.5 provides a framework for the classification of data acquisition systems in remote sensing by using the latter two criteria; it also provides some common examples of each category.

### Table 7.5 Classification of data acquisition systems

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Satellite</th>
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<tbody>
<tr>
<td>Passive systems</td>
<td>Passive systems</td>
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<tr>
<td>Wild RC-10 camera</td>
<td>Spacelab metric camera</td>
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<tr>
<td>Daedalus 1268 MSS</td>
<td>NASA large-format camera</td>
</tr>
<tr>
<td>Daedalus 1230 Thermal Scanner</td>
<td>Landsat MSS, RBV, TM SPOT</td>
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<tr>
<td>Barr and Stroud IR18 TVFS</td>
<td>MOMS</td>
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<tr>
<td>Active systems</td>
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<td>Goodyear GEMS</td>
<td>Seastar</td>
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<td>Westinghouse SLAR SAR 580</td>
<td>SIR A/B</td>
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<td>ERS-1</td>
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<td></td>
<td>Radarsat</td>
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7.6 Data acquisition

Data can be acquired for remote sensing from a variety of aerial platforms, although fixed-wing aircraft and unmanned orbiting satellites are the most common. Both have specific and complementary advantages. Aircraft, for example, enable small localized phenomena to be investigated at high levels of resolution, whereas satellites enable wide synoptic views of the terrain to be obtained, often on a repeatable basis, but at much lower resolution.

7.6.1 Airborne systems

7.6.1.1 Photography

Vertical panchromatic aerial photography taken with a high-