The Impact on Topographic Mapping of Developments in Land and Air Survey: 1900-1939

Peter Collier

ABSTRACT: At the beginning of the twentieth century, little of the world outside of Europe, India, and parts of North America had been covered by topographic mapping. By the end of the century there were few areas that were not covered by topographic mapping, if only at small scales. Most of the technological changes that made this extension of map coverage possible were pioneered during the period 1900-1939. This paper reviews the technological developments in land and air survey that took place during that period and relates them to the drive to produce cost-effective mapping for civil and military purposes.

KEYWORDS: Topographic mapping; twentieth century; photogrammetry; land survey; technological developments

Introduction

The development of techniques for data gathering and their impact on topographic mapping can be divided into four phases. The first phase, before World War I, was characterized by numerous experiments using new techniques, often carried out by individuals, but with little direct impact on the making of maps. This phase was also one of considerable cross-national cooperation. During the second phase, World War I, progress was mainly in the development of simple techniques to assist in the rapid production of maps to meet military needs. The third phase, the 1920s, was one of considerable technical development in instrumentation and the first use of aerial photogrammetry, both instrumental and graphical, to make civilian maps. Most of the developments in the 1920s were national, with little attempt at international cooperation. During the fourth phase, the 1930s, a start was made on large-scale production of civil mapping using photogrammetric techniques, which were no longer regarded as experimental. In part, this was the consequence of two important technical developments, the introduction of slotted templets and multiplex. These techniques were also to provide the basis for most post-war medium-scale topographic mapping.

Peter Collier is a principal lecturer in the Department of Geography at the University of Portsmouth, Portsmouth PO1 3HE, U.K. E-mail: <peter.collier@port.ac.uk>.

Topographic Mapping and Techniques: 1900

At the beginning of the twentieth century, while topographic maps of various scales and of variable quality covered most of Western Europe, relatively little of the rest of the World (Figure 1) was covered by topographic mapping, even at small scales (1: 250,000 or smaller). It was this dearth of even small-scale mapping that led to the proposals for the 1:1,000,000-scale International Map of the World (Penck 1893).

Within Europe the range of scales used for basic mapping was a function of the varied histories and responsibilities of the national mapping agencies. At one extreme, the Ordnance Survey in Great Britain had produced topographic mapping for the entire country at 1:10,000 (Seymour 1980). In France, by contrast, the Service Géographique de l'Armée had started working on a new map at 1: 50,000 (Type 1900), which was to replace the old 1:80,000 Carte de France d'État-Major. The new map was based on surveys at 1:10,000 in lowland areas and 1:20,000 in mountain regions. In addition, 1:20,000 'Plans Directeurs' were produced for border areas (Service Géographique de l'Armée 1938).

In Germany, each individual state had its own mapping program. The Hapsburg Monarchy (modern Austria, Hungary, Czech and Slovak Republics, Slovenia, Croatia, and part of Poland) was generally well mapped as a consequence of the activities of the Militärgeographische Institut. The

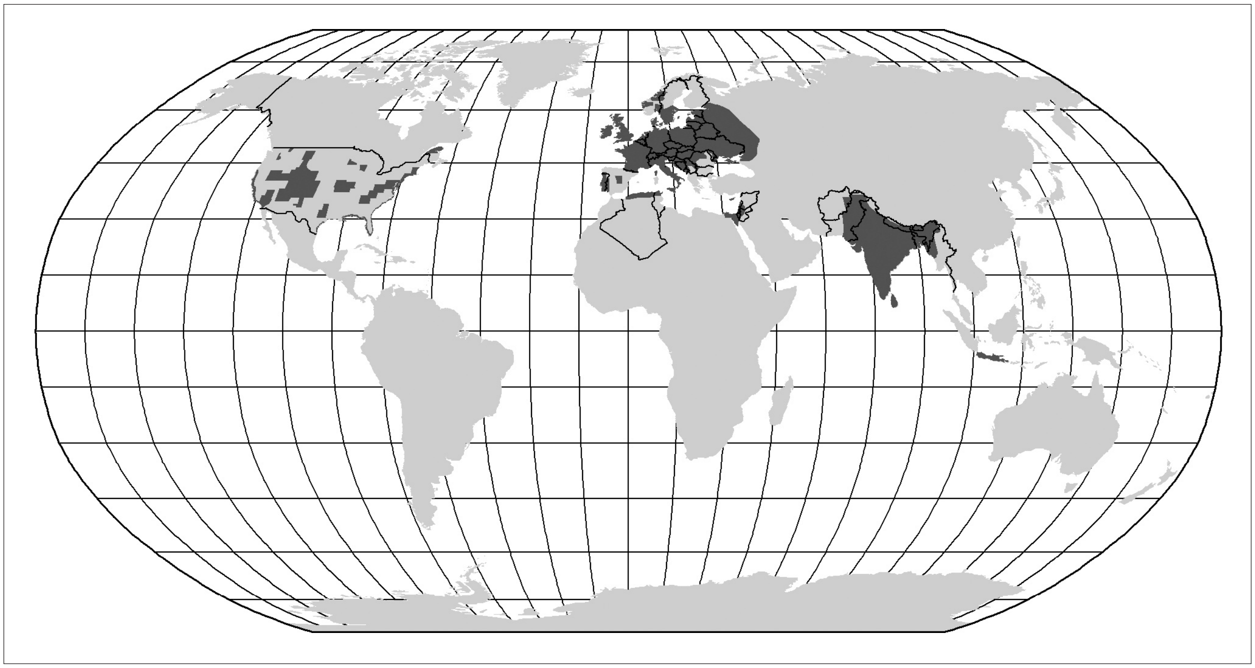

Figure 1. The state of world topographic mapping about 1900 (after Bartholomew 1890; Robinson projection).

whole Empire had been mapped by plane table survey at 1:25,000 between 1869 and 1887, and a new survey, the "Präzisionsaufnahme," had been initiated in 1896 using tacheometry (Kretschmer 1991).

Belgium had been mapped at 1:10,000, and The Netherlands was mapped at 1:25,000. By contrast, the Spanish Instituto Geográfico Estadistic had made relatively slow progress with the 1:50,000 Mapa Topográfico Nacional, which had been started in 1870. Portugal had also started work on 1:50,000 mapping (in 1893), with the first sheet appearing in 1900.

In Scandinavia the picture was mixed, with 1:100,000 maps being produced in Norway (although coverage was far from complete), while in Sweden 1:100,000 was used for the southern parts of the country and 1:200,000 for northern parts. In Denmark, a variety of scales were published for different parts of the country, but in 1891 the scale of 1:100,000 had been adopted as standard.

North America and India were the only other parts of the world that can be said to have had proper mapping programs. Even in North America, the volume of mapping available was relatively small. Mapping at scales of 1:31,680 and 1:24,000 was available in the United States for towns and special projects, while settled rural areas were mapped at a scale of 1:62,500. For the rest of the United States, the largest scales available were 1:125,000 or 1:250,000. In total, topographic mapping covered nearly 26 percent of the continental United States. In Canada, the only topographic maps were at 1:190,080, reduced from 1:31,680 cadastral sheets. The first true topographic maps were not to be produced until 1906.

One of the first tasks undertaken by the East India Company when it acquired control of territory in India was to carry out survey work. Much of the mapping was for fiscal purposes, but administration, control, and defense all required the production of topographic maps. In consequence, the Survey of India can claim to be one of the oldest national mapping agencies. By the end of the nineteenth century most of British India was mapped at various topographic scales.

In the new European colonies of Africa almost no mapping existed. In the British Empire, this led to the setting up of the Colonial Survey Committee in 1905. In the first report of the committee (Colonial Survey Committee 1906, pp. 3-4), the need for mapping was set out in the introduction:

> The purposes for which maps are required in the administration of a country (especially an undeveloped country such as a protectorate in Tropical Africa) are many and varied. Maps are necessary to define the exact limits of national territory, to show the areas and villages under the rule of native chiefs, they are essential for land registration and settlement, for the allotment of mining and forest concessions, and for the organization of internal communications. Of their necessity in war the experiences of the army in South

Africa afford an eloquent testimony, and even the conduct of a "small war" or a police expedition is much simplified by the existence of reliable maps of the scene of operations.

With very few exceptions, the topographic mapping available in 1900 had been produced using ground survey techniques. Although the concept of photogrammetry had been discussed since the late 1850s (Laussedat 1860), very little had actually been achieved. The only extensive mapping undertaken using photographs had been that in Canada by Eduard Deville (1895). Although a number of Europeans had in the 1890s carried out alpine mapping using terrestrial techniques, the equipment necessary to carry out the work cost effectively was not yet available in 1900.

Indeed, the survey techniques being used by land surveyors in 1900 were little different from those used in 1800. Because accurate distance measurements were difficult and expensive to acquire, all control networks used for medium- and large-scale topographic mapping were based on triangulation. Although the discovery of invar (an alloy of steel and nickel with a very low coefficient of expansion with heat) in 1896 was to make accurate distance measurement easier, it was not until the development of electromagnetic distance measurement in the 1950s that alternatives to triangulation became possible. Traversing for lower-order control networks was used in colonial territories, but only if small-scale mapping was to be produced. Traversing was also used for mapping during military operations (Close 1905).

The theodolite had undergone improvements during the nineteenth century. These were largely the result of improvements in the dividing engines used to graduate the horizontal and vertical circles. Consequently, it was possible to make better measurements on instruments with 10-inch circles in 1900 than it had been on instruments with 36-inch circles in 1800. Accurate reading of theodolite angles depended on the use of verniers or micrometers. Vernier instruments were preferred for expeditions and surveys in rough conditions because they were lighter and more robust than the micrometer instruments (Reeves 1933). Edward Reeves was to make a significant improvement in theodolites with the development of the "tangent micrometer," a device which made accurate reading of the circles easier and, perhaps most importantly, could be retrospectively fitted to existing instruments (Close 1905; Reeves 1933). Similar devices were to be incorporated into the designs of theodolites from the major manufacturers. The most significant improvement in the design of theodolites occurred in the twentieth century, when the lead in design passed from Britain to Switzerland and Germany.

Another development adopted by surveyors was the use of the telegraph for the transmission of time signals. This technique became common for the determination of longitude until superseded by the use of radio time signals in the 1920s.

Emerging Technology

At the beginning of the twentieth century, The most important emergent technology was, without doubt, the use of photography for surveying. Although attempts had been made to capture and use aerial photography, the lack of a stable and reliable aerial platform meant that the use of photography was restricted to terrestrial photogrammetry. In 1893, C. B. Adams had proposed a method for plotting by intersection from balloon photographs (U.S. Patent 510758). Although this approach never led to a practicable mapping technique, it provided the conceptual basis for the radial-line techniques in vertical aerial photography. To use terrestrial photography cost effectively in mapmaking, it is necessary to elevate the camera above the surface to be mapped or place it at a sufficient distance from the surface to permit coverage of a large area. In practice, this meant that terrestrial applications were best carried out where there were natural vantage points, such as mountains and high hills.

Terrestrial photogrammetry had first been demonstrated by Aimé Laussedat in 1859 (Blachut and Burkhardt 1989), although he was, at first, limited by the wet plate process. Ignazio Porro in Italy and Dr. A. Meydenbauer in Germany improved upon Laussedat's work. These early attempts all involved the use of graphical techniques to plot the detail and contours from photographs. The process of map creation from photographs was thus slow and laborious, and it tended only to be used where difficult terrain made plane table work impractical. For the photogrammetric approach to become more cost effective, a method of automating the plotting was needed. Work on developing such a method was being actively pursued in a number of countries at the turn of the century.

The Canadian experience had led to a systematic use of terrestrial photography for topographic mapping along the Alaska-Canada boundary by both Canadian and American members of the survey party. John Flemer of the U.S. Coast and Geodetic Survey (USC&GS) was assigned to make a study of European methods, which led to the first

American textbook on photogrammetry (Flemer 1906). Even so, this did not lead to the widespread adoption of photogrammetry within the USC&GS, as photographic techniques could still not compete with the efficiency of existing techniques (Landen 1952). In 1904 the U.S. Geological Survey (USGS), which was also interested in the use of terrestrial photogrammetry, adopted Deville's panoramic camera approach for mapping in Alaska. James Bagley further developed the technique by redesigning the camera and producing a panoramic photo alidade (Bagley 1917).

Photogrammetry to 1914

Until the outbreak of World War I the chief focus of photogrammetry remained terrestrial applications. In 1901, Henry Fourcade described a machine designed to make measurements from stereoscopic photographs, essentially a stereocomparator (Fourcade 1901). At about the same time, Carl Pulfrich (1902) produced and described the Pulfrich Zeiss stereocomparator. During the 1930s there was considerable debate over the precedence in producing a serviceable design for a stereocomparator. Otto von Gruber (1932) gives precedence to Pulfrich by citing his 1902 paper and the 1902 paper by Fourcade, which appeared in *Nature*. But, as noted above, the Fourcade design was first discussed in a paper published in 1901, albeit in a relatively obscure journal. It is not clear whether either designer was aware of the work of the other, even if they both produced very similar designs. This notwithstanding, it is worth noting that von Gruber was also to dismiss Fourcade's claim to precedence over his own work in the design of an instrument that employed the concept of the stereogoniometer. Martin Hotine (1931) makes a strong case in support of Fourcade's precedence in both cases. Both machines could be used to make accurate stereoscopic measurements of points, but because the plan positions and heights of the points were computed individually, maps produced from these measurements required interpolation.

While these early machines demonstrated the possibility of making accurate maps from stereoscopic photographs, the technique was extremely time consuming and only suitable if no other technique was available. Appropriate conditions existed in alpine mapping, where ground survey would have been hazardous or even more time consuming than photogrammetry. Early examples of photogrammetrically derived contours were produced in the Tyrol between 1902 and 1907 by the Austrian survey using the Pulfrich stereocomparator (Kretschmer 1991). Both the Prussian General Staff and, later, the French Service Géographique de l'Armée adopted the Pulfrich stereocomparator for mapping mountainous areas in Pelvoux (Service Géographique de l'Armée 1912; 1938). However there was general recognition that the technique was not cost effective (see the comments of Major Hills following Thompson 1908).

What was needed to make the use of photography cost effective was the ability to produce topographic details and contour lines directly from the photographs rather than by manual interpolation. In 1908, Eduard von Orel produced his autostereograph (von Orel 1910; 1911; 1912; von Gruber 1932; Hotine 1931; Kretschmer 1991), and in the same year, Vivian Thompson published details of his stereoplotter (Thompson 1908; von Gruber 1932; Hotine 1931; Thompson 1974; Petrie 1977; Burnside 1995). Both machines were capable of producing plotted detail lines and contours from terrestrial photographs. The autostereograph was quickly adopted by the Austrian survey for alpine mapping and was subsequently taken up by other national mapping departments. The largest systematic survey carried out with the autostereograph was some 560 km^2 of the Tyrol surveyed in 1911 by the Militärgeographische Institut (Korzer 1924). By contrast, the stereoplotter attracted little interest in its country of origin, Great Britain, but was adopted by the Survey of India for mapping in the Karakorum Range. Because these areas have not subsequently been remapped, the original contours from the stereoplotter are still those used on the published sheets. One plotter was also acquired for survey work in Fiji, where McCaw used it for mapping prior to World War I (Colonial Survey Committee 1911; 1912; 1913).

Both machines were suitable for mapping from terrestrial photographs, as were machines developed from von Orel's autostereograph. (There were no developments from the stereoplotter.) However, because both solutions required coplanar photographs, they could not be readily adapted for use with aerial photography, which is rarely, if ever, coplanar. This fact did not stop many abortive attempts to turn terrestrial photogrammetric plotters into machines capable of handling aerial photographs.

A non-technical development that was to have a significant impact on the development of photogrammetry was the founding of the Austrian Society of Photogrammetry in 1907, followed by the publication in 1908 of the first volume of the *Internationales Archiv für Photogrammetrie*. The International Society for Photogrammetry was founded in Vienna in 1910. Vienna was also the setting for the first International Congress for Photogrammetry in 1913. The Society was to become one of the main vehicles for the dissemination of information on photogrammetry, while the congresses were the main showcases for the latest equipment. Previously the International Geographical Union was the main forum for the dissemination of developments in surveying and photogrammetry, but its importance had continued to decline until after World War II, when it almost completely withdrew from the field.

World War I (1914-1918)

World War I generated an unprecedented demand for maps at scales from 1:200, for detailed trench maps (Chasseaud 1999), to 1:1,000,000 and smaller for strategic planning maps (Heffernan 1996). At the outbreak of war in 1914, the armies of Europe were issued with maps at scales of 1:80,000 or smaller, designed to support a war of rapid movement in which victory would be achieved by bringing to bear an overwhelming force in a decisive battle. Military leaders still believed that offensive operations could be successful despite the precedent of the Russo-Japanese War of 1905, which had degenerated into sieges and large battles of encounter, in which opposing armies fought in the open rather than in prepared positions. Neither side could achieve a decisive blow because of the superiority of defense based on rifles and machine guns.

The strength of the defenses meant that, if there was to be any hope of success in offensive operations, the attacking troops needed accurate maps of the enemy defenses. This included the positions of any artillery, ammunition dumps, and transport infrastructure. All of these features were difficult or impossible to map from the front line. In the case of ammunition dumps and transport, the targets could be many miles behind the front. What the armies of both sides needed was a way of collecting information that could either be added to existing maps or used to produce entirely new maps. Most importantly, as the artillerymen developed ever more accurate targeting, they created a demand for increasingly precise mapping to locate potential targets. As the war progressed, the armies experimented with a closer integration of artillery and infantry operations, such as the rolling barrage (a barrage where the gunner slowly increases the range while infantry advance slowly behind the barrage). Again, this required more precise pointing of guns and locating of targets.

Surveyors were used to fix the position of both guns and targets. The need for secrecy—no point in alerting the enemy that an attack was being prepared—also changed the ways in which the guns "acquired" their targets. Early in the war the normal technique involved the use of "ranging shots." That is, each gun was fired towards a potential target and an observer identified the fall of shot. The observer then told the gunner to either increase or decrease the range, as appropriate, and to traverse left or right until the shot was falling on the target. The problem with this technique was that it revealed that a new gun had been introduced into a stretch of the front. A large number of ranging shots revealed the introduction of a large number of guns and the threat of a forthcoming attack. To overcome this dilemma, the positions of the guns and targets needed to be determined precisely by surveying. From this information artillery boards were prepared to show the positions of the guns as well as the targets. It was then possible to determine the directions in which the guns needed to fire and the range to the target without revealing that new guns had been positioned.

The identification of targets and the accurate positioning of guns led all the nations to adopt the use of grids on their mapping. In the late nineteenth century, John Ardagh had tried to get a grid system adopted by the Survey of India, but without much success (Ardagh 1893). Prior to World War I, therefore, almost no maps carried grids. The exceptions were the "squared" maps used by the French artillery on maneuvers at Chalons in 1911 (Chasseaud 1999). Increased use of indirect fire underscored the need for gridded maps. Unfortunately, grids were adopted on an *ad hoc* basis, which led to considerable confusion. For example, the Germans used three different grid systems with origins at Lille, Rheims, and Paris (Hinks 1919). The British adopted an imperial grid, based on 1000-yard grid squares, even though the entire mapping on the Western Front used metric scales. Despite this uncertain start, it was quickly realized that grids had uses well beyond those of warfare, and they became a standard feature of most post-war topographic mapping.

Military mapping in Europe was largely focused on map revision, whereas that in Palestine, Sinai, and Mesopotamia involved considerable original mapping (Collier 1994; Collier and Inkpen 2001). In the initial stages of the World War I, all the belligerents used existing pre-war mapping supplemented by photographic enlargements. In France, this involved the use of 1:80,000 mapping, subsequently enlarged to 1:40,000. When, however, the deficiencies of the enlargements became evident, they were replaced by new mapping. Only the German survey seems to have continued to use enlargements through to the end of the war (Jack 1920). With the development of positional warfare, 1:40,000 mapping was soon found to be inadequate and was successively complemented by mapping at 1:20,000 and 1:10,000. Where necessary, even larger scales were used (Chasseaud 1999).

Behind the lines, revision and new surveys were carried out using conventional land survey techniques, trigonometrical control surveys, and the plane table to add detail (Jack 1920; Winterbotham 1919a, 1919b; Service Géographique de l'Armée 1938; Albrecht 1969; Chasseaud 1999). For front-line areas and for the enemy's rear areas, the main data source was aerial photography.

The Development of Cameras

Initially, photography for intelligence and map revision involved the acquisition of photography from fairly low flying aircraft using largely improvised camera equipment. With the development of anti-aircraft defenses, however, reconnaissance aircraft were forced to fly higher and higher to avoid being shot down. To compensate, it became necessary to devise cameras with longer and longer focal lengths if the resultant photography was to be of use for analysis and mapping.

The earliest cameras were simple devices that used glass plates and dark slides (devices used to change glass negatives in a camera without exposing the negatives to light). Images were obtained by observers pointing the cameras over the side of the aircraft. The cameras were fitted with simple sighting devices to ensure that the target was actually imaged. Recognition that vertical photographs were much better suited to mapping than the oblique pictures taken with hand-held cameras led to the cameras being fixed to the side of the aircraft. Fairly quickly, magazines were provided so that a series of photographs could be taken by the observer activating a lever to change plates. Even so, changing the magazines still required the observer to lean over the side of the aircraft. Given these difficulties, it seems strange that roll film was not used earlier, especially since panoramic cameras had used it as early as the late nineteenth century. The Germans did not introduce a film camera until 1916 (Albrecht 1969), and the British continued to use plate cameras until the end of the war.

Most of the cameras used for military operations had relatively long focal lengths: the standard British camera in the early part of World War I had a focal length of 8 inches (approximately 200 mm), while the standard German camera had a focal length of 180 mm (Albrecht 1969). By the end of the war, focal lengths of 500 mm were not uncommon—some German cameras had focal lengths as large as 1200 mm (Albrecht 1969). These lenses were designed for reconnaissance rather than mapping, so that each photograph covered only a small area of ground. Cameras needed wide-angle lenses to minimize the amount of control needed for mapping, but none of the high-quality lenses available provided a wide field of view. Multi-lens cameras were developed in the nineteenth century to obtain broader coverage from each exposure station, but these cameras were generally large and cumbersome, and thus unsuited for military operations.

Control for Mapping

Early attempts at using aerial photography for map revision experienced considerable difficulties. As Malcolm MacLeod (1919, pp. 382-83) noted, "though the photographs showed all the principal topographical features in great detail, there was no means of determining their exact scale or the amount of distortion due to the camera not being truly vertical at the moment of exposure of the plate." In the absence of mechanical restitution instruments to overcome these problems, two possible solutions were considered: to develop a device for mechanically determining the altitude and tilt of the camera at the moment of exposure, or to compare the positions of points on the photographs with their known ground coordinates. Although both sides experimented with a mechanical solution, most work involved the latter technique. This placed a heavy demand on access to ground coordinates.

The provision of control points, both in and beyond their own front line, was a major problem for all the combatant nations. Placing markers over control points in frontline areas and then fixing them by observation from the rear was not feasible, as this also enabled the enemy to fix the position of the trenches. A number of strategies were adopted, including the use of periscopic theodolites employed from within the trenches without exposing observers to enemy fire. These theodolites could be used to fix positions within the trenches by resection.

While resection on the plane table was a commonly used technique among topographers, it had not been widely used for instrumental observations because of the relative complexity of the calculations. However, the conditions of trench warfare left few alternatives. Once adopted, resection remained in common use among surveyors. An alternative adopted by the Germans was to fire a flare vertically from the trenches and observe the flare's position from the rear using theodolites (Jack 1920).

Locating control points beyond the front line was even more difficult. Where possible, the position of prominent points would be fixed by intersection. However, in Mesopotamia there were often too few suitable features to intersect. This led to an innovation by Col. C. P. Gunter to fix control points within the Turkish lines using artillery shell bursts. Four observers took simultaneous observations of individual shell bursts, while an observer in an aircraft recorded the position of the explosions on a detailed map of the trenches created from air photographs. On average, out of ten shell bursts, three good intersected points were observed, and the observer would have accurately marked one of these. Points observed in this way were then used to control and adjust the strips of photography used for mapping (Survey of India 1925).

Plotting Detail

Once control had been obtained, it was necessary to interpret and plot the information on photographs. Initially, interpretation was relatively easy as there was little attempt to conceal potential targets from aerial observation. Camouflage only started to be used systematically around 1916 (MacLeod 1919); thereafter, photo-interpretation developed into a specialist skill. Use of camouflage also led to the development of new surveying techniques, such as "flash spotting" and "sound ranging."

Extraction of detail for revision purposes was done by some form of graphic intersection or through the use of optical projection. Despite some use of more rigorous methods involving comparators developed before the war, these instruments, together with the necessary calculations, were slow and not well suited to the urgent needs of the war. The use of automatic plotters, such as the autostereograph, was restricted to terrestrial photography due to the need for coplanar photography. In fact, this technique was used only by the Germans and French in eastern France, where relief was suitable, and by the Austro-Hungarian Army in the Alps. Oskar Albrecht (1969) also refers to the use of terrestrial photogrammetry for artillery assaults on fortresses and the use of photographs taken from tethered balloons.

The belligerent powers employed a variety of graphic techniques. The simplest involved the production of a framework of existing detail on a compilation sheet on which new detail was added from aerial photographs with the help of proportional dividers. Although capable of producing reasonably accurate results, this approach was laborious and slow (MacLeod 1919). The "paper strip" method (Thompson 1966), used for adding small amounts of detail, was equally slow and laborious. The German Army developed a less strenuous technique based on the use of perspective grids. The chief advantage of this technique was that, once the grids had been generated, detail could be transferred by eye from aerial photograph to map. This technique was so successful that it was widely adopted after the war for map revision. Described in most standard textbooks on photogrammetry, the perspective grid approach remained in use until the 1980s, when simple digital techniques rendered it obsolete.

Most of the optical revision techniques relied on the registration of a projected image of the photograph on an existing map or on a framework of control. Once the image was registered, the mapmaker could either transfer the information directly to the map or produce a corrected photographic print for use in revision. Theodor Scheimpflug had shown that an accurate registration could be affected between the projected image and the control data if the projected image was in focus for the entire image area. To satisfy the so-called Scheimpflug condition, the projected planes of the negative, lens, and easel had to meet at a common axis (Scheimpflug 1898; Blachut and Burkhardt 1989). Even if the condition was satisfied there were still errors of registration due to relief displacement. In the instruments used during World War I the Scheimpflug condition was not satisfied, and consequently the results were at best approximate (Blachut and Burkhardt 1989). MacLeod (1919; 1920) describes the use of Camera Lucida and the "enlarging lantern," in both of which the plane of the negative and the plane of the lens were held parallel with only the copy board, which was capable of being tilted. The enlarging lantern could maximize the depth of focus and, hence, the sharpness of the image by reducing the aperture of the lens to the smallest diameter possible. The use of the enlarging lantern to produce semi-rectified prints came to be the preferred technique.

As already noted, while most of the work on the Western Front involved map revision, in non-European theaters the need was for original mapping (Collier 1994; Collier and Inkpen 2001). The first attempts to use aerial photography to construct original mapping took place during the Gallipoli campaign (Dowson 1921). Not very successful, these attempts demonstrated the problems associated with the non-stereoscopic use of aerial photography, as when troops were sent to occupy positions identified monoscopically as trenches or ditches, but which turned out to be shallow scrapes that afforded no shelter from enemy fire. Attempts to create original mapping ceased when modern Turkish maps of the area were captured and revised.

In Egypt, the Turkish threat to the Suez Canal also resulted in experiments in mapping from aerial photography. Like the mapping in Gallipoli, these were largely unsuccessful. The main problem was locating precisely where the photographs had been taken over a largely featureless desert. The bulk of the mapping for the Suez Canal defenses was therefore carried out by triangulation and plane table survey (Maule 1919).

When the Egyptian Expeditionary Force (EEF) advanced across the Sinai Peninsula to engage Turkish forces in Palestine, it moved into territory without up-to-date mapping of an adequate scale. Western Palestine had been mapped for the Palestine Exploration Fund (PEF) in the 1870s (Conder 1878; Conder and Kitchener 1881-83) at a scale of 1:63,360. Although based on triangulation, the detail had been surveyed using compass and cavalry sketching board (Close 1932) and was therefore regarded as insufficiently accurate for modern warfare. British military personnel had surveyed Southern Palestine just before the war, under the cover of a PEF expedition (Woolley and Lawrence 1914). But even here, the scale was too small (1:125,000) for the kind of operations being undertaken. The British army was therefore confronted with the need to map areas beyond its front line for which no adequate base maps were available.

The first successful attempts at mapping from aerial photographs were in the area around Gaza (Gavish and Biger 1983). Here control was provided by the intersection of prominent points behind Turkish lines. Based on these points, a controlled mosaic was created from with vertical aerial photographs, and the mosaic was then used to create the line maps of the planimetry. Although crude by later standards, the map was considered to be a significant improvement on anything then available. This encouraged the surveyors, led by Major W. J. Maule, to embark upon an ambitious plan to create a series of topographic maps at 1: 40,000 for areas of Palestine behind Turkish lines (Maule 1919). Strips of photography were flown roughly parallel to the front line, with additional strips of photography perpendicular to the front flown at intervals to control the strips parallel to the front. Supplementary control was provided by theodolite observations wherever possible. The same basic arrangement pioneered in the mapping of Gaza was followed for the series mapping. However, as the area mapped extended into the hills of Judea (the southern West Bank), it also became necessary to provide some indication of relief. Viewing the photography stereoscopically and form lining achieved this. The nature of the topography, nearly horizontally bedded limestones that eroded into natural terraces, made this task relatively easy. Successful as the mapping was (Thomas 1919), as each new area came under British control, mapping derived from air photos was replaced by mapping made using conventional ground survey techniques.

In a number of ways, the mapping in Mesopotamia can be regarded as the first example of true photogrammetric mapping using aerial photography. Unlike the mapping in Palestine, it was produced as the end product, not as an interim solution to be replaced as soon as ground surveys became possible. And unlike the mapping on the Western Front, it did not involve revision of existing mapping, as no proper maps existed for the area.

Although developments in the use of air photography had been watched "with envy" by the surveyors in Mesopotamia (Survey of India 1925), until early 1916 no airplanes had been available for that theater. Some experience in the use of aerial photography had been gained before the siege of Kut-al-Amarah, but it was the positional fighting around Kut that emphasized the advantages of air survey. Maps were required of areas behind Turkish lines, but the flat landscape meant that surveys could only be extended into no-man's-land. This led to the first real attempt to create maps from aerial photography. As the first map, T.C.4 (T.C. are the initials of Tigris Corps, the original name of the force sent to Mesopotamia) has been discussed at length elsewhere (Collier 1994; Pritchard 1952; Survey of India 1925).

The surveyors working in Mesopotamia experimented with various ways of making maps from aerial photographs, drawing on the experience of surveyors on the Western Front and in Egypt. In the end, though, they developed their own technique, which was well suited to local conditions. Their technique involved creating semi-rectified photographs using an "enlarging lantern" (Gunter 1917) and then mosaicing the photographs using a triangulation scheme. The mosaics were inked up before the bromide prints were bleached out so as to leave just the inked linework. The important point to note is that this technique was used for mapping areas on both sides of the front line and was therefore regarded as the final product. The flat floodplains of the Tigris and Euphrates Rivers lent themselves to mapping using semi-controlled mosaics, as there was an almost complete absence of height to create displacement errors. The mapping of Mesopotamia from aerial photography set a precedent for post-war mapping in India.

Flash Spotting and Sound Ranging

As mentioned earlier, the use of camouflage necessitated the development of techniques for target location, in particular the location of enemy gun positions for counter-battery fire. At the beginning of World War I, guns were aimed by direct observation of targets, and the guns themselves were often positioned in the open to improve their fields of fire. With the increased use of counter battery fire, it became normal for guns to be "dug in," positioned in gun pits, and protected by sandbags. To protect gun positions from enemy air observation, the gun pits were subsequently camouflaged with netting, which thwarted an accurate identification of their positions.

Flash spotting and sound ranging were developed as means of tackling the problem of identifying and locating enemy gun positions. Adopted by all the combatant nations, flash spotting involved intersecting the gun position by observing the flash as the gun was fired. Flash spotting required considerable organization as the observers had to ensure that they were observing the same gun flash, but by carefully noting the times of the observations, it was possible to obtain accurate locations of enemy guns. Most armies established specialist units for this purpose (Innes 1935; Chasseaud 1999; Hinks 1919; Maule 1919).

Sound ranging was a more complex process in which the British and French enjoyed a technological lead over the Germans. General Ludendorff, the German Chief of Staff who issued special instructions that precautions be taken to camouflage the sound of guns, directed the army to secure an example of the British system (quoted in Hinks 1919). Based on a technical solution developed by Lucien Bull at the Institut Marey in Paris, the British system relied on an array of six microphones spread over a 9-kilometer-long baseline situated about 4 km behind the front line. The microphones were connected to a galvanometer at the headquarters. As the sound of a gun reached each microphone in turn, a signal was sent by wire to the galvanometer, where it produced a distinctive trace on photographic film. By measuring the separation of the traces of the gun detected at each microphone, the distance and direction of the gun could be calculated. Complex arrangements with more than two microphones were needed because of uncertainty about the effect of wind speed and other factors on sound waves (see Innes 1935 and Chasseaud 1999 for more technical details).

The German system relied on a forward observer and four other observers along a base of 10 to 15 kilometers. On hearing a gun firing, the forward observer sent a signal by field telephone to the other observers, who, on receiving the signal, started their stopwatches and noted the time interval before they heard the gun. The times were then sent to group headquarters, where the position of the gun was calculated. An alternative, and simpler, method involved an observer noting the time interval between seeing a gun flash and hearing the noise of the gun. The greatest precision possible with these techniques was about $\pm$200 meters.

Non-military Wartime Developments to 1918

While the mapping efforts of the combatant nations were almost entirely directed towards the war effort, cartographers in the United States were actively exploring civilian applications of photogrammetry. The most important development work was carried out at the U.S. Geological Survey, where James Bagley was developing a tri-lens camera and Fred Moffit was developing a "transforming camera" capable of handling the negatives produced by Bagley's camera (Committee on Photographic Surveying 1921).

Developments to 1930

In the period leading up to and including World War I, all the major powers followed broadly similar paths in developing photogrammetry. In most countries, attempts to develop instrumental methods complemented heavy reliance on graphical and optical techniques for producing and revising large-scale maps. After the war, a number of countries took distinctly different paths, with continental European countries generally putting most of their effort into instrumental techniques, while English-speaking countries focused on graphical techniques. Arguably, until about 1930 the approach adopted by the English-speaking countries was the most fruitful, as the instrumental techniques developed in Europe could not compete in cost or efficiency with British and American methods.

After 1930 the relative efficiencies of the two approaches changed markedly. The Americans recognized the changed circumstances more quickly than their British counterparts and began adopting instrumental methods by the mid 1930s. In Britain, and by extension throughout the British Empire, instrumental photogrammetry was still in the experimental phase at the outbreak of World War II in 1939.

The immediate post-war-one period saw a flurry of papers extolling the merits of mapping from aerial photography. At the forefront of the campaign to get the methods accepted in Britain was Capt. H. Hamshaw Thomas (1919; 1920; 1924), who drew heavily on his experiences in the Sinai and Palestine. Much of the effort to promote air survey was conducted in non-specialist journals, such as the *Geographical Journal* (Newcombe 1920), and even in the popular press. MacLeod, who had served in France and had become a firm advocate of air survey methods, also produced a number of papers as well as an important official publication, *Mapping from Air Photographs,* issued by the War Office (MacLeod 1920, but see also MacLeod 1922; 1923a; 1923b).

Britain, more than in any other country, held a conservative attitude towards the new techniques, and this resistance found an influential champion in Harold St. J.L.Winterbotham. A self-proclaimed expert on air survey (see Winterbotham 1929; 1934), Winterbotham did much to impede the adoption of air survey both in Britain and, through his role on the Colonial Survey Committee, in the colonial territories. In contrast, the Dominion territories were free to determine their own policies. Although Canada, a pioneer in photogrammetry, had been joined by India in its use of these techniques before the outbreak of the First World War, other Dominion territories were slower in adopting air survey. Australia took the lead, but local factors either delayed or advanced the adoption of photogrammetry in Dominion territories, which were not compelled to follow the Colonial Survey Committee's recommendation. There is a striking parallel between these largely autonomous territories and the Dutch East Indies, where the survey department was quick to adopt photogrammetry (van Roon 1925) but made no real progress at home in The Netherlands until after World War II.

In the British context, Winterbotham's reservations concerning the cost-effectiveness of air survey methods were probably justified, at least until the development of Reinhard Hugershoff's aerocartograph in 1926 (Blachut and Burkhardt 1989). All the air survey instruments introduced before the aerocartograph were, essentially, terrestrial plotters adapted in some way to cope with non-coplanar photography. This made the instruments difficult and slow to set up, and they usually required two men to carry out orientation and plotting operations. In a well mapped country such as Britain, cumbersome machines could not support map revision as economically as conventional ground survey. Where Winterbotham erred, even in the 1920s, was in extrapolating from the British experience to the colonial territories, where the needs were very different. On the positive side, agitation by Hamshaw Thomas and others as well as the successful application of air survey techniques by the Survey of India led to the setting up of the "Air Survey Committee." Part of the responsibility of this committee was to advise on air survey matters, but it was also responsible for carrying out research.

In the United States, the promotion of air survey techniques was undertaken by Moffit (1920) and other surveyors who had not been directly involved in the war effort but had carried on with their civilian work in government mapping agencies. Part of this promotion was carried out in non-specialist journals, but, unlike in Britain, there was little need to convince the political leadership of the advantages of air survey. By contrast, there was little attempt to promote air survey in France or Germany, other than in technical or professional journals. Almost certainly, this reflects the higher status of engineers and technical experts in those countries compared with Britain. The United States probably fell somewhere between Britain and the continental powers, but more towards the latter.

Survey and mapping activities in Austria suffered a severe setback with the breakup of the Habsburg Empire at the end of World War I. The Militärgeographische Institut was disbanded in 1920 (Kretschmer 1991) and its personnel dispersed amongst the successor states. While this disintegration had clear disadvantages for Austria, survey departments in Poland, Hungary, and Czechoslovakia gained a cadre of trained and experienced personnel able to form the nucleus of new national survey organizations. Despite economic hardship in the wake of the war, Austria had begun in 1928 to supplement existing 1:75,000 topographic mapping; work focused on the mountainous areas using terrestrial photogrammetry.

Graphical Methods

Because of the extensive use of graphical methods during World War I, a large body of trained personnel was available to implement these methods for post-war mapping. But the techniques developed thus far were either non-rigorous (for example, the perspective grid) or suitable only for revising small numbers of features (the paper strip method). What was needed was a rigorous technique that did not require highly skilled workers.

Bagley had sowed the seeds of a rigorous technique during his work with the "Panoramic Photoalidade" (Bagley 1917), but Martin Hotine (1927) provided the theoretical and practical basis for a cost-effective mapping technique. Described as a "Simple Method of Surveying from Air Photographs," Hotine's technique became known as the "Arundel Method" (after Arundel in southern England, where the technique was first used experimentally), or the radial-line technique. Hotine subsequently developed the method of control extension using radial-line methods (Hotine 1929) and laid the foundations for much of the medium-scale photogrammetric mapping carried out in the English-speaking world over the next 40 years. The American development of slotted templets and "radial intersectors" expedited the process of aerotriangulation (see below), but it was Hotine's theoretical work that made these developments possible.

None of the countries using aerial photography for topographic mapping embraced it with greater enthusiasm than India. As noted earlier, the Survey of India had acquired two examples of Thompson's stereo-plotter. Kenneth Mason (1913; 1927) had used the stereo-plotter in 1913 in the Pamirs with considerable success, but the experience of the Survey of India in Mesopotamia during World War I was decisive in promoting air survey techniques in India. In 1920, a series of experiments conducted at Agra demonstrated the utility of air survey methods for mapping flat areas in India (Lewis and Salmond 1920). Air survey proved inefficient for one-inch-to-a-mile mapping—the cost was roughly twice as much as for ground surveys—but it was economical for larger scales. An experiment in urban mapping was carried out but its results were inconclusive.

Among developed countries, the United States was probably the most in need of the advantages that air survey offered post-war mapmakers. For all its great wealth, America was poorly mapped by European standards. Where most European countries were at least mapped at medium scale (roughly 1:100,000 or larger), large tracts of the United States were not mapped even at small scale. It was at just this small-scale range that air survey seemed to offer the greatest advantages.

The work carried out within the USC&GS and USGS prior to and during World War I had prepared both agencies to take advantage of the emerging technology. Starting in 1919, USC&GS used aerial photography for chart revision (Quillian 1919; Mattison 1919) and for wetland surveys (Mattison 1924; Graham 1924-25). Some problems were encountered, but the particular advantages of air survey for mapping wetlands led to the technique becoming the standard procedure (Landen 1952). In carrying out these surveys, the USC&GS used photography supplied by the Navy and the Army Air Corps; it was the Air Corps multi-lens camera that established the cost-effectiveness of air survey (Reading 1927-28). Within the USGS, a quadrangle in Michigan was mapped using a conventional single-lens camera, using air survey for the planimetry only (Thompson 1952). In 1924 a Section of Photographic Mapping was established as part of the Topographic Branch at USGS.

Terrestrial photogrammetric work had been undertaken in Russia as early as 1891 (Koch 1963), but few significant additional developments occurred before 1920. In 1924, the State Technical Office of Aerial Photographic Survey was established. Its first task was the creation of mosaics at 1:10,000 for comparison with plane table surveys. The results were considered sufficiently favorable for mapping at 1:5,000 based on 1:12,000 photography. An ambitious program of aerial photography initiated in 1925 led to the coverage of more than 4,500,000 km^2 by 1940. In 1928, the Central Scientific Research Institute for Geodesy, Photogrammetry and Cartography (ZNIIGAiK) was established to oversee development across the whole field of mapping (Koch 1963).

Instrumental Methods

At the end of World War I, Germany and the Austro-Hungarian Empire had a clear advantage in the development and use of instrumental photogrammetric methods. While Germany continued to enjoy a considerable lead in these techniques, the collapse of the Dual Monarchy and the resultant breakup of the Militärgeographische Institut meant that Austria entered a period of relative decline. Zeiss, which had become the clear leader in the design and manufacture of photogrammetric instruments, not only produced instruments designed by both von Orel and

Pulfrich but employed several leading figures in photogrammetry, including Walter Bauersfeld, Willi Sander, and Otto von Gruber. This ensured that Zeiss was always at or near the forefront of developments in the field.

During the 1920s most efforts were directed toward overcoming the problem inherent in the earlier generation of photogrammetric plotters, namely, the need for the photographs to be coplanar. In 1926, Hugershoff designed an aerocartograph for use with both terrestrial and aerial photography. The instrument, which was manufactured by Heyde Company in Dresden, took advantage of the theoretical developments in orientation theory developed by Max Gasser (1923) and von Grüber (1924). The combination of new orientation procedures and sophisticated design meant that Hugershoff's aerocartograph could be used for plotting and aerotriangulation (Blachut and Burkhardt 1989). Professional rivalry led von Grüber (1932) to dispute the originality of Hugershoff's design, as he was also to do with Heinrich Wild's instruments and the ideas of Fourcade.

Zeiss had produced their stereoplanigraph (the C1) in 1921, based on an earlier design of Bauersfeld. However, it was not until the production of the C4 in 1930 that Zeiss produced an instrument that could handle both terrestrial and aerial photography. Some successful mapping from the earlier models was reported through the 1920s by the Reichsamt für Landesaufnahme, which had a C2 (Seidel 1928), and the Geodetic Institute in Stuttgart, which had a C3 (von Grüber 1932). Most of the mapping was at 1:5,000, but scales as small as 1:20,000 are reported. Even in Germany, systematic mapping programs using photogrammetry were still the exception rather than the rule during the 1920s.

In France, the Service Géographique de l'Armée had been actively experimenting with instrumental photogrammetry before World War I (Bonnet 1920) and had also used the technique for some terrestrial work during the war. France was thus well placed at the end of the war to keep up with the developments elsewhere in Europe. The Service had decided that terrestrial photogrammetry was best suited to 1:20,000 mapping in high mountain areas but considered the equipment too cumbersome and imprecise for reconnaissance surveys (Service Géographique de l'Armée 1912). In 1919, a start was made on mapping in Morocco using panoramic aerial photographs (Service Géographique de l'Armée 1936), but the main drive in France was to develop an autonomous capability in instrumental photogrammetry.

Some equipment had been developed during the war, notably, the "Chambre Claire Varon" and the "Appareil de photorestitution Roussilhe," an instrument for partial rectification of cadastral plans (Blachut and Burkhardt 1989; Service Géographique de l'Armée 1936). The most important development came in 1922 when the first Georges Poivilliers instrument was built (Poivilliers 1922; Blachut and Burkhardt 1989). Poivilliers instruments were to provide the bulk of the photogrammetric capability of the Service, with up to four different types in use at any one time (Institut Géographique National 1947). Other instruments were also used, largely on an experimental basis. In the mid 1920s, the 'stéréorestituteur Boucard' was in use, and in the 1930s, a Gallus Ferber instrument was used experimentally (Service Géographique de l'Armée 1938), with the latter (Blachut and Burkhardt 1989) remaining in service until at least the 1940s (Institut Géographique National 1947).

Italy had been actively engaged in photogrammetry in the nineteenth century with the work of Porro, but as Blachut and Burkhardt (1989) note, the Istituto Geografico Militare showed little interest in the technique until many years after Porro's death in 1875. The resurrection of Italian photogrammetry was largely due to two men: Umberto Nistri, who designed a plotter in 1919 for large-scale plotting, and Ermenegildo Santoni, who produced his first instrument, the autoreductor, in 1921. In 1926, Nistri founded the firm Ottico Meccanica Italiana (OMI) to produce his photogrammetric instruments. Nistri's early instruments all used direct optical projection, while Santoni's instruments all used mechanical projection. The Istituto Geografico Militare was equipped with Santoni instruments, which it used for mapping at 1:25,000 and 1:10,000. The Società Anonima Rilevamenti Aerofotogrammetrici (SARA), on the other hand, used Nistri instruments, largely for topographic mapping outside Italy but also for cadastral mapping within the country.

Photogrammetry had been used in Switzerland for engineering surveys in the nineteenth century, yet there had been no systematic attempt to carry out topographic mapping using the technique. The history of mapping in Switzerland between the two world wars is largely a history of the Wild Heerbrugg Company. Set up in 1921, the company produced its first phototheodolite in 1922 and its first photogrammetric plotter, the A1 stereo-autograph, in 1923. Its first major contribution to surveying came with the production of the T2 theodolite in 1924. The revolutionary design of this instrument—replacing engraved metal circles with glass versions provided more accurate readings and better illumination—led to considerable excitement in scientific and survey circles. By the late 1920s Wild was engaged in serial production of the T2 and T3 theodolites, the P3 phototheodolite, and the A2 autograph, which had replaced the A1. In addition, the C1, C2, and C3 aerial cameras were also in production. In the space of only eight years Wild had become a major player in the survey world, a position enhanced further during the 1930s.

By the late 1920s the Landestopographie in Switzerland had gained considerable experience with Wild instruments for both terrestrial and aerial surveys (Schneider 1929). Topographic maps were produced from terrestrial photography at 1:25,000, while aerial photography was used for 1:10,000 mapping (Schneider 1929; Härry 1971).

In the United States, in addition to using graphical techniques, the USGS started to investigate instrumental methods. In 1921, it obtained a stereoautograph from Germany for evaluation but restricted the use of the instrument to plotting from terrestrial photography and not able to produce maps economically (Thompson 1952). In 1927 the Geological Survey acquired the Hugershoff aerocartograph, the first automatic stereo-plotter used by an American government mapping agency (Thompson 1952). Thomas P. Pendleton laid down guidelines for mapping from aerial photography within the USGS in Bulletin 788-F, *Map Compilation from Aerial Photographs,* issued as part of the *Topographic Instructions of the United States Geological Survey* (Pendleton 1928). Given the rapid developments in radial-line methods (e.g., Hotine 1927), the timing of Pendleton's work was a bit unfortunate as he asserted that radial-line techniques were really only suited for use with multi-lens photography, because the relatively short radial lines that could be drawn on single-lens photographs could not give the best results (Pendleton 1928, p. 409).

In Britain, research work carried out by the Air Survey Committee focused on simple methods, but the Committee did not entirely ignore instrumental techniques. MacLeod's wartime work with rectifiers was developed and, more importantly, the ideas of Fourcade (1926a; 1926b; 1926c; 1926d) on the theory and use of stereogoniometers for photogrammetric plotters were taken up. In 1926 the Committee commissioned the construction of an instrument along the lines proposed by Fourcade, and the instrument was delivered in 1928 (War Office 1935; Hotine 1931).

In India, success with non-instrumental techniques did not distract the Survey from instrumental techniques they had helped pioneer. Mapping officials followed developments taking place in Europe and, in 1926, Mason (1927) carried out a survey in the Shaksgam using a Wild phototheodolite and plotted the results in Switzerland using an autograph in the Topographical Institute at Flums.

Cameras

The tri-lens camera developed by Bagley was used by the USGS in mapping for aeronautical charts. This program was jointly organized with the Corps of Engineers and the Air Service (Committee on Photographic Surveying 1921) and provided valuable experience in civil applications. In 1920, programs with the tri-lens camera were also undertaken in Santo Domingo and Haiti.

The Corps of Engineers became involved in photogrammetric methods in 1920, when Bagley was assigned to cooperate with the Army Air Corps in carrying out tests on aerial photography for topographic mapping. Initially, the trials used Bagley's tri-lens camera, but he went on to develop the five lens T-3A camera, which was to remain the standard mapping camera of the U.S. Army until 1940 (Landen 1952). The War Department issued training regulations for mapping from aerial photography in 1923; however, the techniques discussed in the regulations were largely those refined during World War I.

The 1930s

By the late 1920s photogrammetry had become a cost-effective alternative to some traditional ground surveys. Yet, expensive photogrammetric plotting instruments and labor-intensive graphical plotting meant that photogrammetry still lacked a decisive advantage over ground survey. During the 1930s a number of innovations were to swing the balance decisively in favor of photogrammetric methods.

Progress was slowed if not stopped by the recession that started in 1929. Some measure of the impact can be gauged from job cutbacks at Wild Heerbrugg. In 1930, before the recession had a marked affect on Europe, the workforce stood at 260, but by 1933 the number of jobs had dropped to 125. This was the direct consequence of the decisions taken to retrench mapping projects as well as capital programs. Nearly all the annual reports for the early 1930s mention the financial constraints under which organizations had to work. In the United States some of these problems were offset by appropriations under the Emergency Relief and Construction Act (U.S. Coast and Geodetic Survey 1933). Moreover, the New Deal initiated a wide range of programs in which photogrammetry was to play a major role. By contrast, problems in the colonial territories were, if anything, worse than in Europe and North America. The decline in industrial activity in developed countries led to a collapse in demand for raw materials from the colonies and, as this was the main source of government revenue, they could no longer pay for survey work. Annual reports from most colonial survey departments make reference to a lack of resources to meet the need for mapping. However, by the late 1930s, as a result of rearmament in Europe, governments allocated more money to survey organizations.

Survey organizations were eager to adopt new techniques in routine mapping programs, but the pressures within governments to deal with mass unemployment probably helped to promote the use of labor-intensive methods in survey at the expense of investment in technology. Certainly, organizations such as the Tennessee Valley Authority (TVA), the Agriculture Adjustment Administration, and the Soil Conservation Service in the United States were all heavily dependent on such labor-intensive techniques and did much to develop them as standard mapping methods. Moreover, organizations such as the USGS and the TVA also played a role in the development instrumental methods, such as multiplex. All of this was to be of vital importance to the huge photogrammetric mapping programs that were to emerge during World War II. The scale of these programs would have been inconceivable without the trained body of photogrammetrists developed during the 1930s (Landen 1952).

Within the British colonial territories, the conservative element that had inhibited the development of photogrammetric methods through the 1920s continued to delay adoption of photogrammetry until after World War II—with some illuminating exceptions. Cyprus is the only known example of a local survey department attempting to carry out photogrammetric work. Aerial photography was taken in 1936, but delays in obtaining ground control meant that no use was made of the photography before all normal work was suspended at the outbreak of war. In all the other colonies where photogrammetry was attempted, private survey companies carried out the work. The earliest example of the involvement of private air survey companies had been in 1927, in the mapping of the Anglo-Belgian boundary in the 'Copper Belt' region of Northern Rhodesia (Colonial Survey Committee 1928). Private air survey companies were also active in Uganda, Tanganyika, and Southern Rhodesia, but in all cases this was survey work for specific development projects rather than routine mapping (War Office 1935). There were discussions about the use of photogrammetry in Sierra Leone, where the Aircraft Operating Company of South Africa proposed to revise the 1:62,500 topographic maps for £150,000, including the cost of providing ground control, but the work was never carried out due to financial constraints and the outbreak of World War II. There were also discussions about air survey in Jamaica and the Gold Coast, but nothing came of these projects until after World War II. It is clear from the literature and correspondence of the time that the private air survey companies were lobbying individual colonial governments as well as the British Government to adopt air survey, but the Colonial Survey Committee under Winterbotham was equally forceful in its resistance to change, largely on grounds of cost (see, in particular, Winterbotham 1920; 1921; 1929; 1934; 1936; Hemming 1933).

Increasing recognition that war with Germany was inevitable led to a significant change in the British establishment's attitude towards the use of air survey. In part, this change reflected the retirement of Winterbotham in 1935 and his replacement as Director General of the Ordnance Survey by MacLeod, who was always a warm supporter of air survey. MacLeod had followed Winterbotham, first as Director of Military Surveys and then at the Ordnance Survey, and in each case he played a major role in introducing the use of photogrammetry (Clough 1952).

Advances in Instrumentation

The late 1920s had seen the design and production of the first practical plotting machines for use with aerial photography. The experience provided a foundation for the introduction, during the 1930s, of designs that were to be the mainstays of topographic mapping. The Zeiss C4 had been introduced in 1930 (Burnside 1993). As Thompson (1966) notes, the C4 and the superseding C5 (introduced in 1935 with improved illumination) were, with the Wild A5 (launched in 1937), practically the only universal instruments on the market in the 1930s. Universal instruments designed to

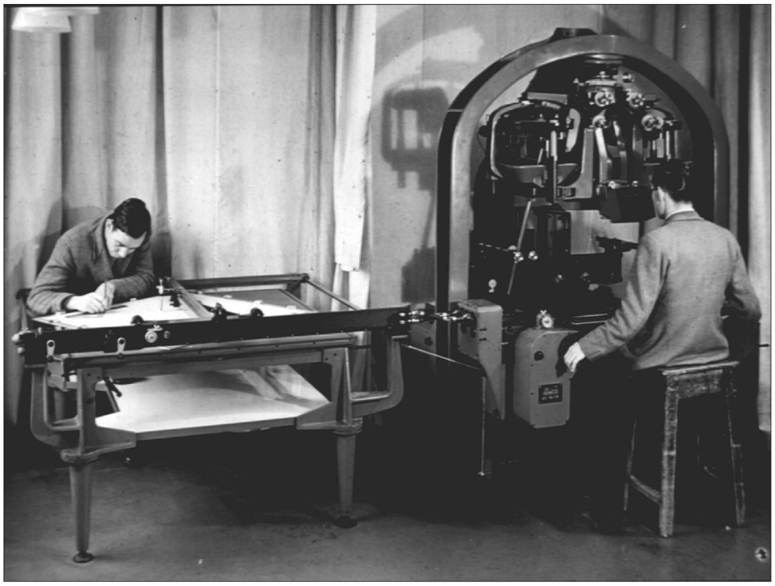

Figure 2. The Wild A5 autograph.

handle all kinds of photography could also be used in aerial triangulation. The Wild A5 (Figure 2) was to be one of the most successful "first order" plotters used for large-scale mapping until it was replaced by another Wild design, the A8, in 1950. In France, improved versions of the Poivilliers were introduced, culminating in the Type C. As each new instrument was designed, it was taken up by the Service Géographique de l'Armée. By the early 1940s the Service had eleven Type B, two "Type B perfectioné," two Type A, and six Type C instruments in routine production, with additional instruments available (Institut Géographique National 1947). Similarly, there were considerable advances in the design of Italian instruments by both Nistri and Santoni. In 1934, the first of the stereosimplex range was introduced for military use (Burnside 1996; Istituto Geografico Militare 1942), but it was never used commercially.

As Thompson (1966) points out, highly complex instruments like the C series from Zeiss, while very accurate, were not suitable for large-scale production of topographic mapping. Needed were relatively simple, low-cost instruments that could be used in mass production of topographic mapping. It is therefore arguable that the most important innovation in instrumentation was the multiplex (Figure 3). Introduced by Zeiss and OMI-Nistri in 1933, the concept was quickly adopted by other instrument manufacturers, including Bausch and Lomb and Williamson (Blachut and Burkhardt 1989). The relative simplicity and low cost of multiplex instruments made them very attractive for medium-scale topographic mapping. They were to open up the era of mass production of topographic maps using photogrammetric methods.

As previously noted, the Tennessee Valley Authority and USGS were involved in the development of multiplex instruments in the United States. The U.S. Army Air Force at Wright Field acquired a few early models for evaluation, and the proven usefulness of the equipment led, in turn, to the USGS acquiring a model in 1935 and evaluating it during 1936. In 1938, USGS and TVA set up an office of multiplex machines built under license by Bausch and Lomb (Pendleton 1938). The basic design was much improved by Bausch and Lomb in cooperation with USGS and TVA. The Corps of Engineers was also an early user of the equipment, and Bausch and Lomb developed an oblique version for the Corps' use. The USC&GS also made some use of the multiplex but remained largely wedded to their multi-lens cameras because of the reduced need for ground control in coastal mapping.

In Britain, despite the resistance to air survey from Winterbotham and other conservatives, there had been a number of attempts to use instrumental techniques, even in the 1920s (War Office 1935, Seymour 1980). In general, these had not been a great success, largely because of cost. The Air Survey Committee, which continued to sponsor research in photogrammetry, commissioned the construction of photogrammetric plotters based on the ideas of Fourcade (Hotine 1931; Burnside 1997). By the time World War II began, a number of prototypes had been constructed but the outbreak of war brought these developments to a halt. The Ordnance Survey had also purchased the new Wild A5 for evaluation. Bombing of Ordnance Survey facilities in 1940 destroyed the prototype machines and also damaged the A5. The A5 was subsequently rebuilt and joined another A5 being used to map potential bomber targets (Seymour 1980).

Advances in Graphical Methods

By the early 1930s radial-line techniques had become widely accepted for providing planimetric mapping from aerial photography. Although it was also possible to plot contour lines using this approach, the need for large amounts of ground control limited its usefulness. The radial-line technique, as developed by Hotine (1927; 1929), suffered from a number of drawbacks. Firstly, it

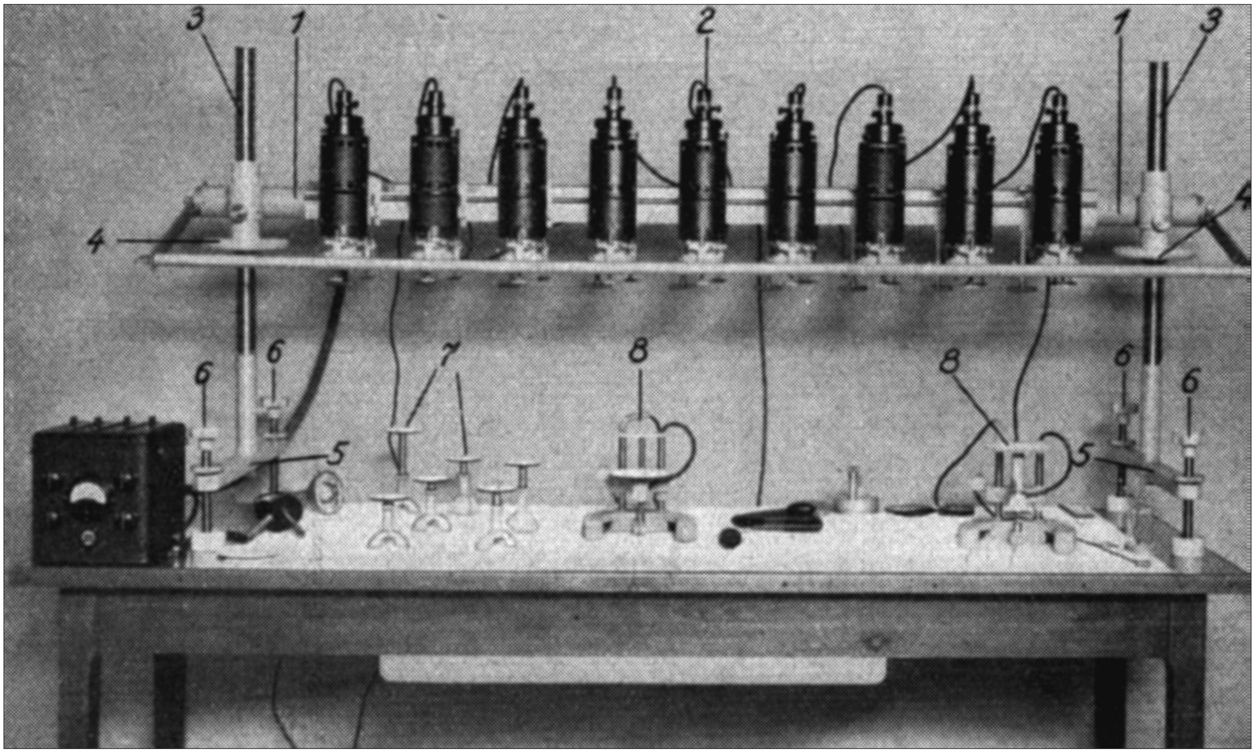

Figure 3. The Zeiss multiplex.

involved a two-stage process to create a minor control plot at a known scale before any plotting could be carried out. Secondly, it could only be used for the production of strips of control. This meant that ground control points were needed for each strip. If a block formation and adjustment process could be developed, it would speed up the process and reduce the need for ground control points. The breakthrough came in 1936, when C.W. Collier of the U.S. Soil Conservation Service developed the slotted-templet method (Kelsh 1940). As David Landen notes, this was "one of the most important inventions in photogrammetry," which made possible the "mass production of photogrammetric maps at low cost and great speed" (1952, p. 884). By the early 1950s, slotted-templet methods were in use in nearly every country involved in map making (Figure 4). Thus, by the end of the 1930s, with the development of the multiplex and the slotted-templet method, all the tools were in place to permit the exponential growth in topographic mapping that was to start during World War II.

Conclusions

At the start of the twentieth century, good-quality topographic mapping existed, with few exceptions, only in parts of Europe, North America, and India. Although adequate mapping for the rest of the world was recognized as a prerequisite for development (Penck 1893), the mapping technology of the day could not meet the need. Photogrammetry offered the possibility of providing detailed surveys for large areas in a cost-effective way, if suitable methods and equipment could be developed. During the first three decades a range of techniques and types of equipment were developed, but they could still not meet the growing needs for mapping. Nonetheless, in the United States and Russia large areas were mapped at medium scales using the new techniques. The important breakthroughs that were to permit intensive cost-effective use of photogrammetry in the rest of the world occurred in the early 1930s with the development of a cheap and efficient plotter, the multiplex, and an efficient radial-line technique based on slotted templets. Although World War II delayed their impact on civilian mapping, both developments were to revolutionize large- and medium-scale topographic cartography.

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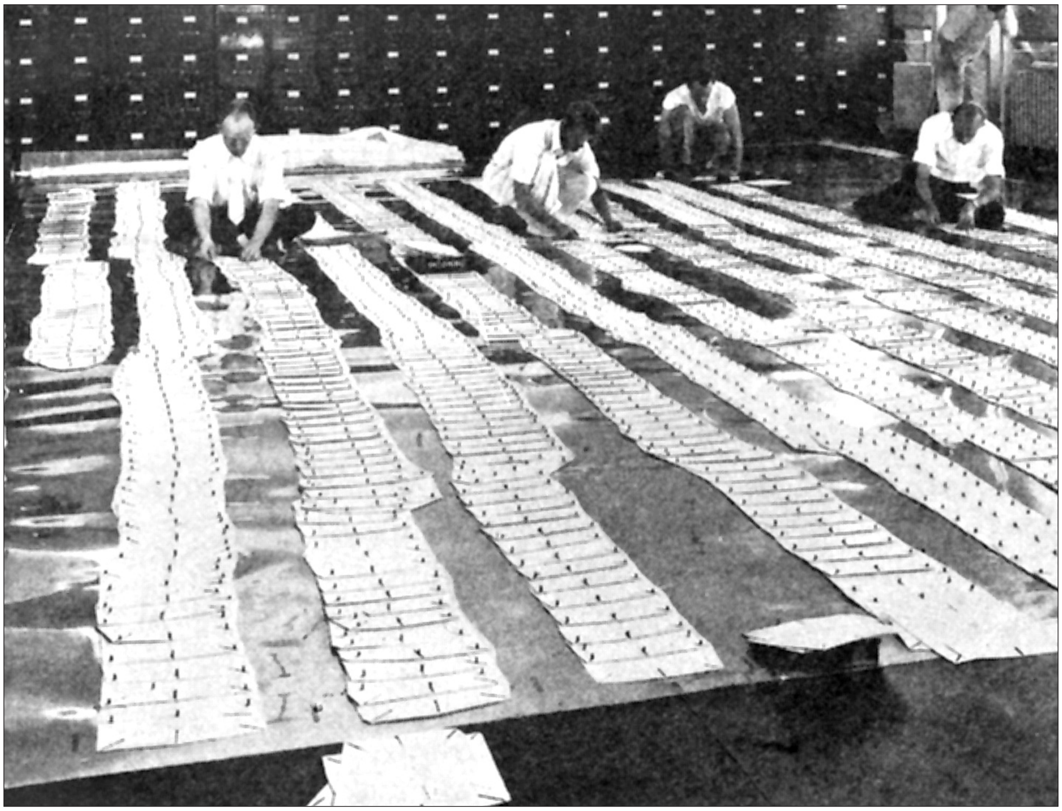

Figure 4. Slotted templets being laid at the Soil Conservation Service, U.S. Department of Agriculture.

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Staff contributing to the Exploratory Essays Initiative

Syracuse University:

Rebecca Carlson
Karen Culcasi
Kate Krezel
Ahmed Saad
Molly Schmelzle

University of Wisconsin—Madison:

Beth Freundlich
Jude Leimer
Teresita Reed
Paul Tierney