Chapter 5

ALIGNMENT AND REFERENCING OF MAPS AND AERIAL PHOTOGRAPHS

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Introduction

Documentation of survivor locations as well as sample collection sites for dosimetry-related measurements requires reference to suitable maps. The maps traditionally used at RERF for these purposes are the U.S. Army maps that date from circa 1945 (see Chapter 1). In later years, some use has been made of Japanese city plan maps, which are much newer (1979 in Hiroshima and 1981 in Nagasaki) and of larger scale (1:2,500 vs. 1:12,500 for the U.S. Army maps). Even before the publication of DS86, efforts were made to reconcile the locations of buildings and other features of interest on these two sets of maps. Beyond the simple desire to compare two different sources of map information, it was thought that a better standard of accuracy for technical reasons could be achieved with the use of the newer maps. The U.S. Army maps were compiled under wartime conditions from an assortment of older Japanese maps and other sources, including aerial photographs of limited quality, using the best methods available at the time. The newer Japanese maps had the benefit of 34 years of improvement in cartographic methods and were made with extensive new survey information. Because of their larger scale, they are also more detailed than the U.S. Army maps.

The newer city plan maps offer an excellent new template for map work at RERF. Although they are accurate and detailed, they are old enough to contain depictions of most of the buildings from which samples were taken for the current dosimetry reassessment effort, as most of those samples were collected after 1979. Furthermore, as discussed below, the newer city plan maps can be aligned very well with wartime aerial photographs, suggesting that many major features such as river channels and major thoroughfares have not changed location since the time of the bombing. The newer maps with their map grid coordinates offer an excellent frame of reference for situating work that can now be done to georeference the neighborhood drawings pertaining to survivor shielding histories and the aerial photographs from which they were originally traced. This process has the added benefit of relating the locations of interest to the current street plan and other present-day map features of the two cities.

There are still newer maps available, which are published in digital media and can be used directly in computer-based Geographical Information Systems (GIS). However, these maps lack many of the important buildings that are central to this work in Hiroshima, as those buildings were demolished in the years since 1979 (see, for example, Table 8), and they reflect other changes due to construction during that period. As the 1979 and 1981 maps are very accurate, the incremental improvement in accuracy that the newest maps could offer in contrast is a small one, on the same order as the irreducible errors associated with the GIS due to such sources as the limits of image resolution and other sources discussed below in the section entitled "Capabilities of the GIS in Contrast to Manual Methods."

It remains true that some sample locations of interest to the dosimetry reassessment are documented only on the U.S. Army map, because the building or other map feature in question had completely disappeared by the time that the 1979 and 1981 Japanese city plan maps were made. On the other hand, some sample locations of interest are documented only on the newer Japanese city plan maps, because the buildings or other map features of interest were still in existence when the newer maps were made, but were not shown on the U.S. Army maps due to its limited detail and limited sources of information. Thus, there is no way to perform adequate determinations of distance from the hypocenters for all sample locations exclusively on one set of maps or the other, and establishing some relationship between the maps is a basic necessity.

A major focus of concern has been to determine the locations on the newer maps of hypocenters for the atomic bombs that were determined on the U.S. Army maps, based on the premise that samples depicted on only one map could then have their distances from the hypocenter determined using that map. However, as noted above and addressed in detail below, there were also *a priori* reasons to believe that one or both maps contained inaccuracies in their depiction of the relative locations of buildings and other map features of interest, a concern that arose from attempts to align the two maps in each city. The real problem of interest is larger in scope, as it amounts to determining as well as possible *all* of the discrepancies in depicted locations of features (roads, rivers, bridges, buildings, etc.) on the two sets of maps, investigating the nature of such discrepancies, and determining their implications. The goal is not just to determine the locations of the hypocenters on the newer maps, but to explore relationships among the inferred distances from the hypocenters to locations of various features, and to make judgments on the overall accuracy of each map.

Aerial photographs that were taken shortly before and after the atomic bombings provide a very important adjunct to the current work. Most importantly, the GIS can be used to put all of the applicable maps and aerial photographs into a common frame of reference, allowing them to be superimposed in various ways to determine the spatial relationships involved (Verbyla and Chang 1997). The work reported here suggests several key points:

- The newer Japanese city plan maps, as one might expect, are more accurate and detailed than the U.S. Army maps, and should provide a better basis for determining distance from the hypocenter to sample locations, as well as for other purposes such as establishing a set of locations in properly georeferenced coordinates that can be used for later reference. Such data can also be more readily referred to other geographical coordinate systems on which other maps or sources of geographical information might be based.
- The U.S. Army maps can be aligned with the newer Japanese city plan maps better than was previously supposed, although in the case of Hiroshima the best fit requires a slight (1.3%) stretching of the U.S. Army map in the east-west direction.

- The alignment of the U.S. Army maps to the newer Japanese city plan maps establishes a correspondence that is very useful for applications involving locations that are depicted or defined on one map and not on the other.
- The U.S. Army maps contain some inaccuracies in the depiction of various features, but there are only a few limited indications in the locations surveyed for this work that entire areas of a city are shifted substantially relative to other areas. It appears appropriate to consider each depicted feature on the U.S. Army map as having random errors in its X and Y coordinates that are not significantly correlated with the errors in the hypocenter coordinates.
- This work suggests a hypocenter location transferred to the newer Japanese city plan map in Hiroshima that differs from previous work by about 13 to 15 m. The difference appears to be due to the influence on earlier work of misleading impressions created by the misplacement, by about 10 to 12 m on the U.S. Army map, of a few key features near the hypocenter location. This does not appear to be the case in Nagasaki.

Fundamental Concepts of Cartography and the GIS

Features depicted on a map using GIS are typically referenced to a coordinate system that establishes their locations on the surface of the earth, so that they can be related to locations depicted on other maps and to other sources of geographical information. Much map work is done in geographical coordinates such as degrees of longitude and latitude for a specified model of the earth’s surface (*datum*). Some work with large-scale maps is done with plane rectangular coordinates that represent a Cartesian coordinate system of appropriate scale in the plane of the map’s projection. Both the U.S. Army maps and the newer Japanese city plan maps have plane rectangular coordinate systems. In the past, the plane rectangular coordinates of the U.S. Army maps have been used extensively in defining the locations of hypocenters, samples, and survivors.

Georeferencing

Georeferencing is the specification of a set of coordinates, such as decimal degrees longitude and latitude, for some item of geographical information. In the case of an image raster consisting of a scanned map or aerial photograph, which are the principal objects of interest in this work, the georeferencing process results in a small numerical file that assigns a set of coordinates to every picture element (pixel) in the image. A good discussion of georeferencing and related affine transformations is given in Verbyla and Chang (1997) beginning on page 158. A discussion of affine transformations and their documentation in the “world file” created by ArcGIS for a georeferenced map image file is available on the internet in the ESRI Online Support Center (Roberts 2000).

The work reported here was done using a first-order affine transformation that can be represented as

$$X = A + Bi + Cj \qquad (1)$$

and

$$Y = D + Ei + Fj \qquad (2)$$

where X and Y are the plane rectangular or geographical coordinates (e.g., in this work, the longitude and latitude), i and j are the column and row occupied by the pixel in the image raster, and A through F are coefficients to be fitted.

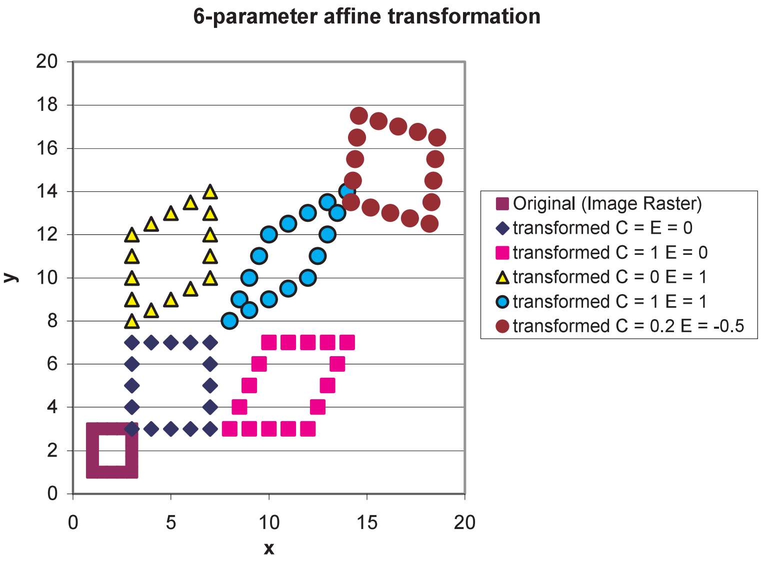

Figure 1. *Examples of the effect of various cross-term coefficients on a first-order affine transformation.*

The first-order transformation allows the image to be located (i.e., coefficients A and D in the transformation are by definition the coordinates of the upper, leftmost pixel in the image raster), scaled in both dimensions (mainly coefficients B and F unless the image raster is substantially rotated with respect to the coordinate system), and rotated, skewed or warped in certain limited ways as defined by the cross-terms (coefficients C and E). Figure 1 shows simple examples of the sorts of changes in shape allowed by the first-order affine transformation. The application of a pure rotation involves multiplying the coefficients B, C, E and F by the sines and cosines of the angle of rotation as illustrated by the transformation in equation (3) of the section entitled “The Work of Hubbell” below.

Georeferencing is done by a procedure that utilizes the graphical user interface of GIS to link individual *control points* on the image raster with corresponding markers situated at coordinates that are considered to be correct for them. The software determines the coefficients A through F that minimize the sum of squared distances between the control points in the image raster and their corresponding markers. That is, three such control points suffice to define a unique solution, and additional control points create an overdetermined system of equations that is optimized by a least-squares type minimization of the sum of the squared distances between, respectively,

1) the coordinates assigned to the pixel addresses of the control points on the image raster by the affine transformation using a particular set of coefficient values, and
2) the defined coordinates specified for those control points and used to place the markers to which the corresponding control points are linked. (See additional discussion below under the section entitled “Outline of the GIS-based Method Used for this Work.”)

Second- and third-order transformations are available in the GIS software that was used for this work, but the software documentation suggests they should be used with caution, and suggests that first-order transformations should suffice for most applications (see pages 404-405 of *Using*

ArcMap, Minami 2000). In addition, two specific considerations may militate strongly against using higher-order transformations in this work.

- One is that the locations of the hypocenters on the U.S. Army maps were determined using complicated sets of triangulations from various features on the maps, which were done on the untransformed maps. If a higher-order transformation is used on the U.S. Army maps, the transformation is no longer affine, and it would generally not be true that the geometry of the triangulations is preserved in the transformed location of the hypocenter. This important point is discussed further in the section entitled "Geometrical Considerations Relating to the Position of the Hypocenter" below. It is not practical at present to re-do the hypocenter determinations (i.e., the work summarized in Hubbell et al. 1969 and Kerr and Solomon 1976) on a transformed version of the U.S. Army map that would be obtained from such a higher-order transformation, due to the extensive amount of work involved. Furthermore, such an exercise would be compromised by the fact that many of the features used as landmarks in the original work had disappeared by 1979 and are not shown on the newer Japanese city plan maps, so that their location on the higher-order-transformed U.S. Army map could not be checked directly against the newer map.
- Another more general consideration in the present work is that control points for georeferencing of the U.S. Army map are concentrated more in certain areas of the map than others. The uneven spatial distribution of available control points is much more troubling in the case of fitting a higher-order transformation than in the first-order case.

Datum, Geographical Coordinates, and Map Coordinate Systems

Every map has a *datum* that defines its assumptions about the overall or average shape and dimensions of the earth's surface (i.e., averaging out altitude variations associated with mountains, etc.), along with the other specifications (angular unit of measure, prime meridian) that suffice to define a coordinate system in *geographical coordinates* such as longitude and latitude. For this purpose cartographers assume the earth's surface to be a surface of rotation obtained by rotating a 2-dimensional cross-sectional shape about an axis. The assumed cross-sectional shape typically consists of something such as an ellipse, rotated about its minor axis, producing the oblate spheroidal shape somewhat flattened at the poles that is characteristic of the earth. That is, the earth would be modeled as an *ellipsoid* with a semi-major (longer) axis in the plane of the equator and a semi-minor (shorter) axis in a plane containing its axis of rotation.

Therefore, a major factor to be considered in using longitude and latitude is that they are not unique—*the specification of the longitude and latitude of a given point on a map depends upon the assumed datum on which the map was based* (Figure 2).

The *datum* on which the U.S. Army maps are based is not certain. The historical context suggests that, at least in terms of the ellipsoid used, they may have been based on a Clarke ellipsoid dating from circa 1866 that was the basis for the North American Datum of 1927 (NAD1927), a very widely used *datum* in the U.S. in the time period when the U.S. Army maps were made. Research has been undertaken to determine what *datum* was used, but results have not yet been obtained as of this writing. Other considerations, however, render this point moot, because a map alignment based solely on a geodetic relationship between the *datum* of the U.S. Army maps and the *datum* of the newer city plan maps is not feasible, as discussed in the section entitled "Geodetic Considerations" below. The U.S. Army maps have a grid (plane rectangular coordinate) system based on 1,000-yard squares, and the conversion from map grid coordinates to longitude and latitude as defined by the makers of the U.S. Army map is implicit in that tic marks for each minute of longitude and latitude are shown on the map in addition to the grid lines. However, exact equations for the transformation have not been available for this work.

The newer Japanese city maps are based on a 1,000-meter plane rectangular grid taken from the nationwide Japanese land survey system. They do not have cross-hair type tic marks for longitude and latitude, although the Nagasaki new city maps have separate tic marks for longitude on the horizontal margins and latitude on the vertical margins of each tile. However, formulae for converting the map grid coordinates to longitude and latitude are available, based on the equations that are given on the website of the Japanese Geographical Survey Institute (GSI). Until the year 2001, these equations were based on the Tokyo *datum*, which uses a Bessel ellipsoid determined in 1842. The parameters of the Bessel ellipsoid are given in Table 1. The equations necessary to make this transformation are given in the publication “World Geodesic System and Coordinate Transformation” (in Japanese) by the Japan Survey Association (Tobita 2002). These equations were coded into a spreadsheet and checked to verify their agreement with a calculational program available on the website of the Japanese Geographical Survey Institute (Geographical Survey Institute 2002).

In addition, the longitude and latitude of a geographical survey benchmark on the roof of the Chugoku Electric Co. building was calculated from map coordinates on the newer Japanese city plan map of Hiroshima and was found to be consistent with that listed on the GSI website to within less than 2 m.

To make an initial comparison using the geographical information system (GIS), the Japanese city map for Hiroshima was georeferenced in the geographical coordinates (longitude and latitude) of the Tokyo *datum*, using the GSI formulae, as described in more detail below. Then the U.S. Army map was georeferenced using its longitude/latitude tic marks, i.e., treating those longitude and latitude values as though they were specified for the Tokyo *datum*. For control points that are shown as features on both maps, it was noted that there was a variable discrepancy that appeared to contain a regular, systematic shift of about 65 to 70 m in a roughly north-south direction as shown in Figure 3. It seems likely that this systematic portion of the discrepancy is primarily due to the difference between the geodetic assumptions about *datum* that were used in making the two maps. Additional technical matters pertaining to this discrepancy are discussed in detail in the section “Geodetic Considerations” below.

As the considerations just described relate to georeferencing the maps with respect to a geographical coordinate system, i.e., globally defining their location on the earth’s surface, the details are not strictly necessary for the sort of local map alignment work that is the crux of this

Table 1. Earth constants for the Tokyo datum

Parameter of Bessel ellipsoid	Value
Semimajor axis a	6377397.155 m
Semiminor axis b	6356078.963 m
flattening f	0.003342773
F	299.152813
E	0.081696831
e'	0.081970841

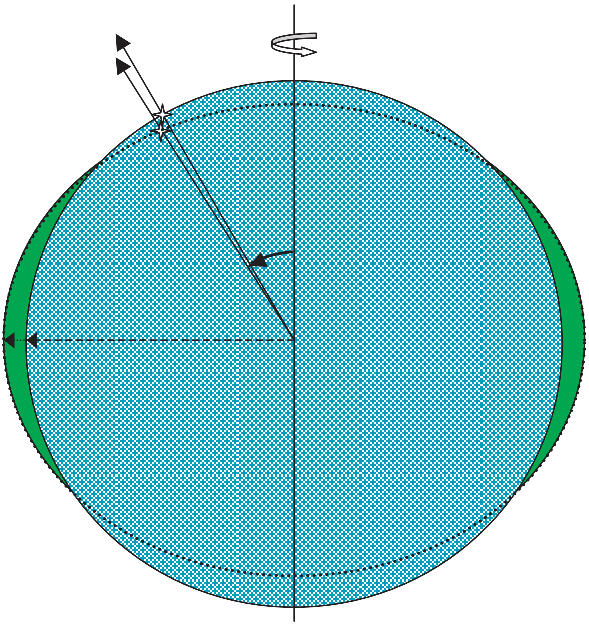

Figure 2. *Different assumptions about the size and shape of the earth's cross section as defined in the datum of a map may result in different assignments of geographical coordinates (i.e., longitude and latitude) for the same depicted location.*

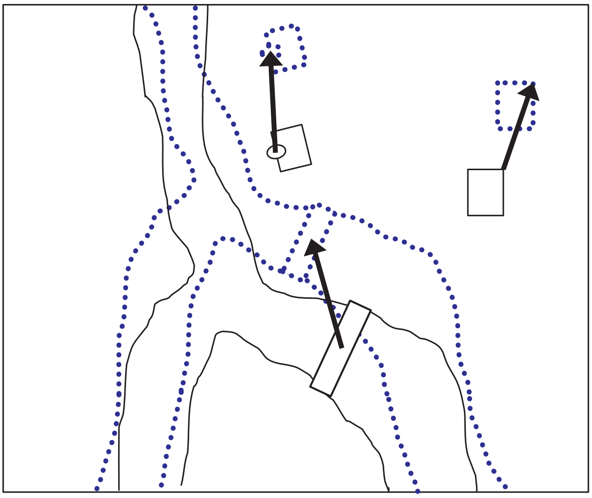

Figure 3. *When the maps of Hiroshima are georeferenced in the GIS according to their stated reference values (viz., by using their longitude and latitude tic marks in the geographical coordinate system based on the Tokyo datum), there is a variable discrepancy in their depicted locations of common features vs. the newer city plan maps, which contains a relatively large systematic component.*

chapter. However, it is important that these matters be documented for reference purposes. Doing the work in a local frame of reference without relating it to geographical coordinates would appear to make it less useful with respect to easily extending or generalizing it. For example, proper reference to geographical coordinates facilitates updating by incorporating new information from independent sources such as Global Positioning System (GPS) receivers, geographic survey markers, satellite imagery, and so forth. Furthermore, there are technical matters of interest that depend on geographical coordinates, as discussed below, such as the question just mentioned of whether it is possible to produce a true nominal alignment of the maps based strictly on the mapmakers' assumptions and their specification of the geographical coordinates of features depicted on the maps.

Map Projections and the Inherent Errors Associated with the Use of Plane Rectangular Coordinates

It is a fundamental fact of cartography that maps differ in their depiction of areas they cover, depending on what projection they use. Every map has a *projection* that defines the geometrical relationship between the earth's curved surface and a flat (planar) surface onto which it is projected to allow a scaled depiction on paper constituting the 2-dimensional map. The U.S. Army maps are based on a series of conic projections called the *world polyconic grid*, which the *Army Dictionary* (U.S. Army 1998) defines as a "Military grid system in which a grid network is applied to polyconic projections of zones of the earth's surface covering nine degrees of longitude with one degree of overlap between zones, and extending to 72 degrees north and south latitude." In a conic projection the surface of the projection is tangent to (touching) the earth's surface along one *parallel* (line of equal latitude) for the simple type or two parallels for the secant type, as shown in Figure 4.

The newer Japanese city maps, on the other hand, are based on a Gauss-Krueger system of projections, which cover zones six degrees wide in longitude, similar to the Universal Transverse Mercator series of projections. These are cylindrical projections in which the axis of the cylinder is perpendicular to the earth's axis (hence transverse) and the surface of the projection is tangent to the earth's surface along one *meridian* (line of equal longitude) for the simple type or two lines parallel to the central meridian for the secant type, also shown in Figure 4.

By geometrical definition the distance on the curved surface of the earth and in the plane of projection is equal along a line of tangency, but not at other locations. Thus the nominal quoted value of scale for a map (e.g., 1:2,500 for the newer city plan maps) applies exactly only for distances between points lying on a line of tangency. For other points, the scale is not equal to the exact nominal value. There is some small, inherent inaccuracy in the plane rectangular coordinates of both the U.S. Army maps and the newer city plan maps, which is an accepted approximation in using such large-scale maps (Verbyla and Chang 1997). That is, the plane rectangular coordinates are exact uniform Cartesian coordinates in the plane of the map projection, but the geometry of the map projection does not generally preserve a constant relationship between the distance between two points on the earth's curved surface and the linear distance between those points in the plane of the map projection.

Fortunately, the scale of the maps used here is so large that differences due to projections are small enough to have very little effect. Some idea of this inaccuracy can be obtained from simple considerations of spherical geometry. The area of interest for dosimetry-related measurements in either city is no larger in latitudinal (north-south) extent than about 5 km, or about 5 km × (90° latitude/10,000 km) = 0.045° of arc. For two locations separated by a circumferential distance of 5 km on a sphere with radius $r = 20{,}000\ \text{km}/\pi = 6{,}366$ km, the chord distance of $2r \times \sin(0.0225°) \cong 4.99999987$ km differs from the circumferential distance by less than 1 mm. Another example is that, considering a simple spherical datum for purposes of illustration, for a north-south span of 5 km centered on the Hiroshima hypocenter, the difference in meters of distance per degree of longitude (distance along a parallel on the spherical surface) between the southernmost and northernmost points of interest is proportional to $\cos(34.390711° - 0.0225°)$ vs. $\cos(34.390711° + 0.0225°)$, or about 0.054%. Thus, the idealized spherical (or ellipsoidal, or other geoidal) surface of the earth departs very little from planarity over the distances of interest. These relationships are depicted in Figure 5.

Because the Gauss-Krueger system of the Japan land survey system employs transverse cylindrical projections, the scale varies with longitude. The secant type is used, and the scale factor (ratio of the scale at a given location to that at the lines of tangency) is slightly less than one at longitudes inside the lines of tangency and slightly more than one outside the lines, which are parallel to the central meridian at equal distances to the east and west. The six-degree zones are designed to the criterion that the scale factor should not differ from unity by more than one part in 10,000 at the boundary of each six-degree zone. The two lines of tangency where the scale factor is exactly unity are 90 km east and west of the central meridian, at the latitude of the origin of the plane rectangular coordinates for the zone in question. The actual errors implicit in the plane rectangular coordinate system of the newer city plan maps can be evaluated by using the exact map projection equations given on the GSI website (described in the section “Datum, Geographical Coordinates, and Map Coordinate Systems” above). The first derivatives of distance on the projected map per unit angle in the corresponding geographical coordinates were evaluated in meters per degree of longitude and meters per degree of latitude at three corners of a tile of the newer city plan maps, by using simple finite-difference approximations. The results are given in Table 2. These inaccuracies translate into possible errors not exceeding about 2 meters, for the longest distances that might be measured in the area of interest to dosimetry.

The 1,000-yard grid lines on the U.S. Army map were checked by determining the pixel addresses of their intersections in the scanned map image raster, and it was confirmed that they approximate straight lines at right angles to a tolerance of less than one part per thousand. The exact scale factors could not be computed because the information was not readily available for implementing the projection equations of the map. This is not a problem in the present situation, because the basic method that was chosen for this work, as described in detail in the following sections, is to use a method that does *not* depend on the nominal geographical coordinates of longitude and latitude associated with the U.S. Army map’s plane rectangular coordinates to fit the U.S. Army maps to the newer city plan maps. This defines the coordinates and the locations depicted on the U.S. Army maps in the coordinate systems of the newer city plan maps.

The inherent errors of the plane rectangular coordinate system of the newer city plan maps are unavoidable results of using that system. This is not an issue in typical map work, but it is of some interest here because of the desire for unusually accurate specifications of distance. Although more accurate distances can be calculated theoretically from geographical coordinates, the calculations are extremely difficult. Furthermore, the specification of distance with such great precision on a spherical or ellipsoidal surface involves detailed geometrical considerations as to what path on the surface is being used to define the distance between two points. And, at the

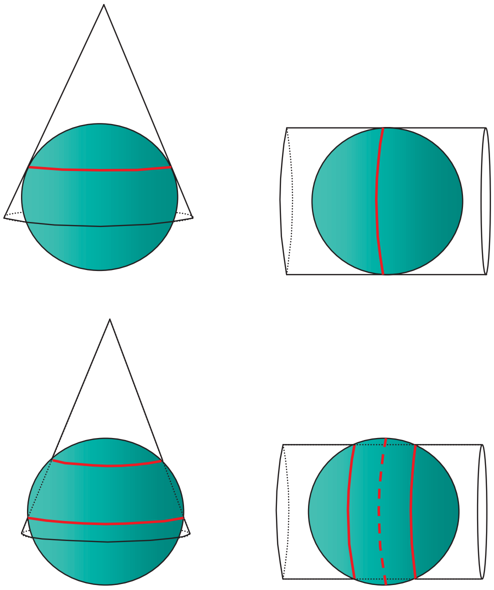

Figure 4. *Conical (left) and transverse cylindrical (right) projections. Simple (top) and secant (bottom) types are shown. The heavy red lines are lines of tangency. The central meridian of the secant-type transverse cylindrical projection (bottom right) is shown as a dashed red line. The distance between parallels in the secant projections is exaggerated for purposes of illustration.*

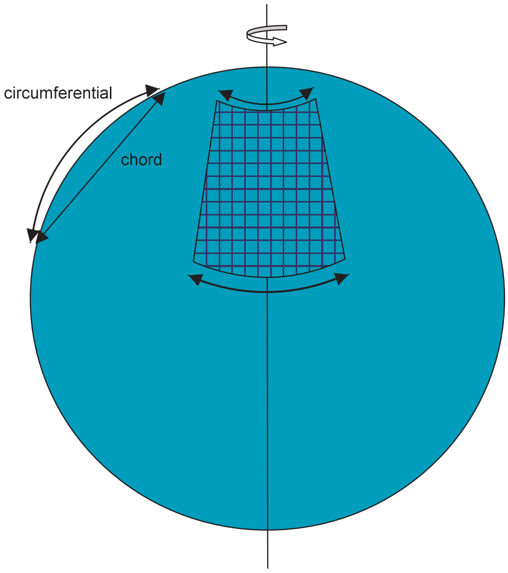

Figure 5. *Circumferential vs. chord length, and distance along a parallel as a function of latitude.*

Table 2. Intrinsic errors in the coordinate system of the newer city plan maps due to map projection: Differences in scale at three corners of a 2.5 × 1.75 km map tile

X	Y	Longitude	Latitude	m/deg longitude	m/deg latitude	% difference in m/deg longitude[a]	% difference in m/deg latitude[a]
-178	26.9995	132.4603468	34.39490743	91.9361306			
-178	27.0005	132.4603577	34.39490740				
-177.9995	27	132.4603522	34.39491192		110.9082109		
-178.0005	27	132.4603522	34.39490290				
-178	29.4995	132.4875395	34.39483914	91.93643977		0.00034	
-178	29.5005	132.4875504	34.39483911				
-177.9995	29.5	132.4875450	34.39484363		110.9084928		0.00025
-178.0005	29.5	132.4875449	34.39483461				
-179.75	26.9995	132.4602917	34.37912859	91.95338025		0.0188	
-179.75	27.0005	132.4603026	34.37912856				
-179.7495	27	132.4602971	34.37913309		110.9079245		-0.00026
-179.7505	27	132.4602971	34.37912407				

[a] Differences taken with respect to the values centered at –178.000, 27.000.

scale of interest in this work, the earth's surface does not even correspond to the idealized ellipsoid, because of the altitude variation in the terrain. A more accurate system than the one developed here might be possible by defining a projection tangent to the earth at the hypocenter and using a three-dimensional coordinate system. However, that is well beyond the scope of this work, and the reduction of error so achieved would be small in comparison to many other errors that cannot be reduced, related to uncertainty in the locations of hypocenters, samples, and survivors.

Alignment of Maps

In the following sections, the geodetic considerations of the map problem are discussed, and it is established that a map alignment based solely on geodetic calculations is not possible at the desired level of accuracy. That is, the geographical coordinates of the U.S. Army maps cannot be accurately transformed into those of the newer city plan maps by calculations based on the *datum* involved in each set of maps. This leaves only empirical methods based on the alignment of the features depicted on the two maps. In this light, the work done earlier with paper maps is reviewed. Then the new method that was developed using the GIS is explained in detail and is compared and contrasted to the earlier work.

Geodetic Considerations

If both sets of maps were based on the same datum and both had control points with specified longitude and latitude, it would be a straightforward matter to georeference them and compare them. If the control points in the two sets of maps have longitude and latitude specified in different *data*, then the problem becomes complicated. In the latter case, if the *data* in question had been "connected" to each other by geodetic surveys or other methods based on measurement, then a transformation of longitude and latitude between *data* would have been established. In the absence of such a connection, authoritative sources (Tobita 2002) suggest that a coordinate transformation of sufficient accuracy for the present purposes (i.e., a few meters or less) cannot be made on the basis of theoretical calculations using the parameters of the ellipsoids and the center of gravity of the earth as defined for the *datum* of each set of maps (Defense Mapping Agency 1984).

Furthermore, it has not been possible to establish authoritatively which *datum* was used for the U.S. Army maps, and it is even less clear that the compilers of the U.S. Army maps would have been able to appropriately take account of the geodetic assumptions of the earlier Japanese Imperial maps and other sources on which they based their maps. For these reasons, it appears to be impossible to make a reliable coordinate transformation based on a geodetic calculation, even if additional information about the geodetic assumptions of the U.S. Army maps were to become available.

Previous Work Commissioned by RERF

As noted above, the alignment and comparison of U.S. Army maps and the newer Japanese city maps has been a longstanding concern at RERF. The initial idea was simply to effectively put the two maps into the same frame of reference by physically aligning them, i.e., laying one on top of the other and then moving them until the depicted features were perfectly superimposed, based on the assumption that such an alignment could be found. Ultimately, the goal of that work was to allow any feature that is depicted on only one of the maps to be located on the other, or more generally, to allow a transformation from the map grid (plane rectangular) coordinate system of one map to that of the other, just as in the present work.

Prior to the introduction of the GIS, investigators tried to align the maps by making one of them into a transparent overlay and then physically manipulating them in an attempt to bring various common features into alignment. Geometrically, this amounted to using a photographic technique to reduce the newer Japanese city plan maps in scale by a factor of 1/5 and then using a combination of translation and rotation to attempt an alignment. What is actually being attempted in this case is to compare the shapes of the maps in terms of their relative positioning of common features, without using any explicit global frame of reference. The original assumption was that both maps had the same, correct shape and scale, and merely needed to be aligned in this manner in order to achieve the goals stated above. However, when a reasonably good alignment could not be found, the situation appeared ambiguous and troubling.

The Work of Fukuken Choosa Sekkei

In 1985, RERF retained the firm Fukuken Choosa Sekkei to perform work on the map alignment. The 1.75 × 2.5 km tiles of the newer Japanese city plan maps were arranged to produce a composite photograph, which was printed on a clear acetate overlay on a scale 1/5 of the paper maps, in order to match the nominal scale to the 1:12,500 scale of the U.S. Army maps. Then, the alignment as described above was attempted. First, an alignment using the seven specific points shown in Table 3 was attempted. Then, when the persons doing the work felt that this method did not yield acceptable results, an alignment was made by visual inspection of the maps, based on subjective judgment of those performing the alignment.

The report of Fukuken Choosa Sekkei, entitled “Data for Dose Reassessment, November, 1985,” provides vector drawings and corresponding tables for the sample locations listed in Table

4. All of the listed locations are important locations for dosimetry measurements. The table in the original report lists
1) a new map value of distance from the hypocenter,
2) old map value of distance from the hypocenter, and
3) the difference between 1) and 2);
4) a new map value of azimuthal direction (angle in degrees) from the hypocenter,
5) old map value of azimuthal direction from the hypocenter, and
6) the difference between 4) and 5).

Unfortunately, the only documented numerical values of the actual alignment that was produced by the method using visual inspection, which was the method adopted as being more acceptable, are the locations on the newer Japanese city plan maps that corresponded to the hypocenters on the aligned U.S. Army maps. For Hiroshima, the hypocenter location in the plane rectangular coordinates of the newer city plan maps was determined to be (26.735, -178.3995). The report contains coordinates on both maps for the locations listed in Tables 3 and 4, and a wealth of detail about the locations of sample collection sites listed in Table 4, including annotated copies of enlarged maps. But all of these data are given only in the context of one map or the other. None is given in a common frame of reference, and none except the hypocenter is documented in coordinates transformed from one map to the other.

The wording of the report's main statement, which appears to be the only written text therein, as translated by the RERF Translation Section, is

Measurement Method of Dosimetry Reevaluation

1) *Locations of the requested buildings were numerically established based on their respective coordinate lines using the old map (1/12500) and the new map (1/2500) to compare the ratio of distance and angle from the hypocenter.*
2) *Several clear map points of places in the hypocenter's vicinity were used as a condition for coordinate change of the hypocenter. Due to the large error, and the poor precision of the old map, however, topographic maps were superimposed to obtain the coordinates of the hypocenter.*

Hubbell gives a similar English-language version of the report's remarks on these issues in his 1986 report (following section, "The Work of Hubbell").

The Work of Hubbell

In 1986, RERF requested Harry Hubbell, Jr., the lead author of RERF Technical Report No. 3-69, *The Epicenters of the Atomic Bombs* (Hubbell et al. 1969), to study the map alignment problem. He produced a report entitled "Effect of New Japanese Maps on Atomic Bomb Hypocenter and Other Location Coordinates in Hiroshima," dated October 6, 1986. This report was furnished to RERF but it is not a published document.

Hubbell performed several alignments using different methods. One exercise was a repetition of the method used by Fukuken Choosa Sekkei, based on visual inspection. This exercise confirmed the result of Fukuken Choosa Sekkei for the location of the hypocenter, within about two meters' distance; the location given by Hubbell for this method was (26.733, -178.400), as opposed to (26.735, -178.3995) for Fukuken Choosa Sekkei.

Another type of method used by Hubbell involved the use of a particular set of "presumably unmoved objects" depicted as features on both maps, and used a least-squares optimization to

Table 3. Hiroshima locations used by Fukuken Choosa Sekkei (FKE) to attempt map alignment

No.	Apparent location[a]	Army map coordinates	
FKE No. 0 (Hubbell No. 100)	Hypocenter	744.298	1261.707
FKE No. 1 (Hubbell No. 101)	Summit el. 237.4 m NW of Yamatecho	742.137	1264.352
FKE No. 2 (Hubbell No. 102)	S pt of pier on Tenma gawa just S of Fish Hatchery	741.411	1258.863
FKE No. 3 (Hubbell No. 103)	NE corner of Lumber Storage Pool just W of Ujina Grade School	744.567	1257.993
FKE No. 4 (Hubbell No. 104)	Summit el. 261.1 m W of Hesaka-mura	747.459	1265.103
FKE No. 5 (Hubbell No. 105)	mid-span of Yokogawa Bridge	743.874	1263.064
FKE No. 6 (Hubbell No. 106)	mid-span of Honkawa Bridge	743.861	1261.61
FKE No. 7 (Hubbell No. 107)	SE corner of small island in Hiro Castle moat at entrance	744.814	1262.292

[a] Evaluated as part of the present work by using the GIS to examine the depicted map features at the indicated coordinates on the U.S. Army map (site name not given by Fukuken Choosa Sekkei).

Table 4. Sample locations surveyed by Fukuken Choosa Sekkei

Hiroshima	Nagasaki
1. Elementary school affiliated with Hiroshima University, Theory (genri - ?) department	1. Ieno cho
2. Hiroshima University Faculty of Science	2. Asahi machi
3. Hiroshima Regional (Postal) Savings Office (Chokinkyoku)	3. Urakami Cathedral
4. Hiroshima Red Cross Hospital	4. Sakamoto cho Foreigners' Cemetery
5. Chugoku Electric Co. (Denka)	5. Zenza cho Seitoku Temple
6. Hiroshima Telephone Co. (Denwa Kyoku)	6. Chikugo machi Higashi Hongan Temple
7. Japan Electrometer Inspection Co.	7. Nishiyama machi Water Bureau (Suidokyoku)
8. Hiroshima University Faculty of Engineering	8. Ieno cho 5-21
9. Hiroshima City Hall (Old/former main building)	9. Nishi machi 1371
10. Myosenji Temple	10. Shiroyama cho 1-17
11. Hiramoto Residence (Kannon Honmachi)	11. Sakamoto cho Foreigners' Cemetery
12. San'in Gohdoh Bank	12. Chikugo machi Honren Temple
13. Army Provisions Storehouse	13. Eri machi 7-16
14. Nishi Hakushima Machi 139 (Old/former address/residence)	14. Ebira machi 401
15. Nobori Machi 152-1 (Old/former address/residence)	15. Shiroyama cho 2-410
16. Yayoi (Yanagi?) Cho 1-23 (Old/former address/residence)	16. Ieno cho
	17. Hachiman Shrine
	18. Shiroyama Elementary School
	19. Nagasaki University Hospital
	20. Mitsubishi Nagasaki Machinery Office

minimize the squared distances between the pairs of locations. The more complete of these used a set of 18 locations, *which includes the estimated location of the hypocenter on the newer Japanese city map as determined from the method based on visual inspection.* The first seven of these locations are the same as the seven locations used by Fukuken Choosa Sekkei (Table 3), although Hubbell's measurement of the map coordinates differs slightly in some cases. As Hubbell gives only the U.S. Army and newer city plan map coordinates in his report and does not name or identify the points, they were evaluated for this work by using GIS, which resulted in an unambiguous identification of the locations given in Table 5. Hubbell's optimization was slightly different from the present work because it involved only a translation, which Hubbell described as an unknown offset in the X and Y directions of the origins of the two map systems, and a pure rotation.

Hubbell reported that he had confirmed the correctness of the relative scales of the two maps by a separate exercise, to a good precision, and he used the nominal values of scale as constants in this optimization. In addition, the pure rotation has one less degree of freedom than the rotation and skewing or warping allowed by the two cross-term parameters in the linear affine transformation of the present work.

Hubbell reported that the method with 18 "presumably unmoved objects" confirmed the nominal value of the difference in rotation of the two maps (i.e., that based on the orientations of

Table 5. Hiroshima locations used by Hubbell for map alignment

No.	Apparent location[a]	Army map	Coordinates
Hubbell No. 100	Hypocenter	744.298	1261.707
Hubbell No. 101	Summit el. 237.4 m NW of Yamatecho	742.137	1264.352
Hubbell No. 102	S pt of pier on Tenma gawa just S of Fish Hatchery	741.411	1258.866
Hubbell No. 103	NE corner of Lumber Storage Pool just W of Ujina Grade School	744.567	1257.993
Hubbell No. 104	Summit el. 261.1 m W of Hesaka-mura	747.459	1265.103
Hubbell No. 105	mid-span of Yokogawa Bridge	743.872	1263.06
Hubbell No. 106	mid-span of Honkawa Bridge	743.867	1261.61
Hubbell No. 107	SE corner of small island in Hiro Castle moat at entrance	744.814	1262.288
Hubbell No. 111	NE corner of Hiro Univ "E" Faculty of Science Bldg	744.619	1260.24
Hubbell No. 112	Postal Savings Regional Office (Chokin Kyoku) (?) along streetcar St. S of Red Cross Hosp.	744.364	1259.966
Hubbell No. 113	N corner (wing along streetcar St.) of Red Cross Hospital	744.232	1260.123
Hubbell No. 114	NW corner of Chugoku Electric Co. Bldg.	744.357	1260.974
Hubbell No. 115	E end of bldg next to Naka Telephone Office	744.715	1261.356
Hubbell No. 117	W end of long bldg along street on N edge of Technical School campus	744.141	1259.658
Hubbell No. 118	E end of N wing of City Hall (along streetcar St.)	744.298	1260.634
Hubbell No. 125	NE corner of A-bomb dome bldg	744.184	1261.856
Hubbell No. 126	center of dome at A-bomb dome	744.169	1261.822
Hubbell No. 127	SW corner of intersection at SE corner of Daini Middle School lot	742.46	1261.082

[a] Evaluated as part of the present work by using the GIS to examine the depicted map features at the indicated coordinates on the U.S. Army map (site name not given by Hubbell).

their vertical coordinate axes with respect to true north) to a good approximation, and it resulted in a fitted value for the offset of the origins of the coordinate systems that was only about 3 m different from the method based on visual inspection. That is, the parameters estimated by Hubbell's numerical optimization would have placed the hypocenter on the new city plan maps about 3 m west of the location suggested by the method based on visual inspection, at (26.730, -178.401), as opposed to (26.733, -178.400).

In comparing this result to the present work, it must be noted that Hubbell used different control points, which is discussed further in the section entitled "Choice of Control Points for Fitting the U.S. Army Map," and his optimization was considerably more constrained, i.e., three degrees of freedom versus six. That is, separately evaluating the scale factor and concluding that the nominal factor given on the map is correct to a certain reasonably small tolerance, and using that nominal value as a constant in the optimization, is not equivalent to including the scale factor as a variable in the optimization. In addition to the constrained nature of Hubbell's optimization, it must also be noted that his 18 "presumably unmoved objects" included the location of the hypocenter on the new city map that was determined by the method of visual inspection described above. Although his method used a least-squares numerical optimization similar to that used in the present work, it was *not independent of the method based on visual inspection and subjective judgment.*

Several of Hubbell's conclusions as stated in his abstract were the following, quoted verbatim:

1) *Although some significant discrepancies exist between the positions of presumably unmoved objects as shown on the two maps, it is felt that the worst errors occur in regions far from the hypocenter, where the radiation doses were negligible.*
2) *Calculations from the coordinates on both maps of the 18 points including the hypocenter confirmed the rotation angle of the Army coordinate system with respect to true North, and the scale factors between the maps. The mean absolute difference in distance between pairs of points as computed from the two maps was about 22 meters, with a standard deviation of 20 meters.*
3) *The east-west and north-south origin offset between the maps was calculated from the 18 points mentioned.*
4) *Transformation equations were developed, and a FORTRAN program written to calculate the coordinates of a point on either map from those given for the other, and a set of sample data points is given.*

Hubbell noted various limitations of his work, for which he did not have sufficient time in Japan and other resources available to make a careful study. For example, Hubbell did not have copies of the newer city plan maps available to him when he completed his study after his return to the U.S., and he was able to measure the coordinates of only "about half" of his 18 points on those maps while in Japan. Thus, he used the coordinates given by Fukuken Choosa Sekkei for the other points. It is not clear that he had all of the appropriate information (e.g., the annotated enlargements of the newer city plan maps) as to exactly what part of a building or other structure they pertained (see the translated designations for the sample locations evaluated by Fukuken Choosa Sekkei, many of which correspsond to the last 11 of Hubbell's 18 "presumably unmoved object" points, as given in Table 4. The particular part of the building or other structure to which a given set of coordinates relate is not named, and is only apparent in the annotated photocopies of portions of the newer Japanese city maps in the detailed attachments to the report of Fukuken

Choosa Sekkei).

The transformations suggested by Hubbell, based on his least-squares optimization of his 18 points with respect only to the X and Y offset of the map origins, were

$$X_{new\_city} = M((X_{US\_Army} - 740)\cos T - (Y_{US\_Army} - 1250)\sin T) + G + 20$$
$$Y_{new\_city} = M((X_{US\_Army} - 740)\sin T - (Y_{US\_Army} - 1250)\cos T) + H - 185 \quad (3)$$

wherein M is the units conversion of 0.9144 m/yd, T is a rotation of 0.0250164 radians, and G and H are the coefficients fitted by Hubbell for the offset of the map origins, 3.069 km and -4.201 km, respectively. An almost identical transformation is defined by the method used by Hubbell that was based on visual inspection, repeating the work of Fukuken Choosa Sekkei and RERF staff: it differs only in a few meters for the offset values, i.e., G = 3.072 km and H = -4.200 km. A detailed comparison of Hubbell's transformations vs. those recommended in this work, as tested on the set of 23 control points used in this work to align the U.S. Army map to the newer Japanese city plan maps, is given below in the section "Hiroshima" under "Results" of the following section, "A Method of Map Alignment Using the GIS."

A Method of Map Alignment Using the GIS

Geographical Information System software can be used to do many types of comparisons and integrations of various maps, aerial photographs, drawings, and other sources of information. RERF acquired such software to review the locations of survivors, sample collection sites, and other points of interest in work related to dosimetry, such as terrain features. In order to accomplish this work, the first and most fundamental problem that needed to be addressed was to decide on how to use the U.S. Army maps and the newer Japanese city plan maps in the context of the GIS, given the well-established problems that were known to exist in the alignment of the two sets of maps. Since the GIS both requires some frame of reference and facilitates the georeferencing of maps, it was natural to approach the map alignment issue as a problem in obtaining a compatible and accurate georeferencing of both sets of maps in a common, well-established frame of reference, which was chosen to be a geographical coordinate system, for the reasons discussed below.

Capabilities of the GIS in Contrast to Manual Methods

The GIS, in addition to making map work much easier and quicker, offers a number of new capabilities. These include

1) an ability to apply transformations to the image rasters that include skewing/warping in addition to fully variable translation, scaling, and rotation,
2) an ability to produce a *numerically optimized* fit of one map or aerial photograph to another,
3) an ability to add aerial photographs to the maps, georeference them, and use them in overlays for all kinds of comparisons, and
4) improved accuracy in all of these procedures over manual work with paper maps.

The ability to apply transformations to the image rasters is part of the georeferencing process and can be used for purposes such as removing systematic distortions, as well as for simple manipulations such as changing scale, changing orientation, etc.

The ability to produce a numerically optimized fit of one map or aerial photograph to another is also inherently part of the georeferencing process and can be done by using a common set of control points and georeferencing the two rasters in sequence. The first raster can be georeferenced in any desired way, and the second can then be georeferenced to the first by using a set of features common to both maps to define a set of control points and then linking the depictions of those features in the second image to those in the first.

This process is more flexible than the earlier manual work because of the transformations that can be applied. In the GIS, the location, scale, rotation, and warp in each raster are automatically determined by a progressive optimization as the georeferencing is performed. In the manual work,

1) the scale of a map to be used as an overlay must be determined *a priori* and then the overlay made,
2) it is not practical to change the scale independently in two orthogonal directions, as it is with the GIS, and
3) the additional degree of freedom that is available in the first-order GIS transformation, which is associated with the sorts of warping shown in Figure 1, cannot be included.

The process of performing a numerical optimization to minimize the overall discrepancy in the locations of a set of control points is greatly facilitated by the GIS. When the work in 1985 and 1986 was done (sections on “The Work of Fukuken Choosa Sekkei” and “The Work of Hubbell” above), the alignments performed manually according to the judgment of the persons performing the work were adopted as being the most useful. Although Hubbell did perform a very constrained optimization by a least-squares fit on a set of control points, its specific results and implications were not explored beyond the suggestion that it verified with fairly good precision the respective scales of the two maps and the rotation that Hubbell had determined by other methods. In general, the implications of such an optimization could only be explored in those days by tedious calculations of the transformed coordinates of individual points, or by directly viewing the acetate overlay superposed on the U.S. Army maps in the indicated alignment. The GIS, on the other hand, immediately displays the results of an optimization in the form of the superimposed maps, which can be reproduced in any desired view at any later time, and it updates them each time that a new control point “link” is added or removed.

The ability to add aerial photographs to the maps, georeference them, and use them in overlays for various comparisons is not technically new in a strict sense. But it is greatly facilitated, not only by obviating the need to make re-scaled reproductions of the photographs, but by making it unnecessary to decide *a priori* the scale and the corresponding magnification or minification of the image that is to be used.

The improved accuracy in all of these procedures over manual work with paper maps is ideally extensible down almost to the level of the pixel size of a high-resolution scanned image of the paper maps and photographs. Practical factors such as the finite size of drawn lines and markings and the blurring on the original map or photograph of the edges of depicted features may effectively limit the obtainable accuracy at a level considerably grosser than the pixel size of a high-resolution scanned image raster. For example, the grid lines on the image of the U.S. Army map have a width that equates to 6 meters or more of actual distance on the surface of the earth in many places. Another source of error, for aerial photographs, is the dependence of an object’s apparent horizontal position on its elevation and the camera angle, as an object is almost never directly below the camera.

Outline of the GIS-Based Method Used for This Work

Because the GIS allows easy and powerful alignments to be performed using its georeferencing tools as just described, it was used to perform an alignment of the maps.

The basic idea was to assume the newer Japanese city plan maps to be correct and use them as a template to georeference the U.S. Army maps *to* the newer maps by using a set of features depicted on both maps. This is akin to a GIS version of the process that was followed in earlier years by taking the acetate overlay of the newer maps and superposing it on the Army map, but it has the additional flexibility of the full first-order affine transformation, and it is explicitly based in a frame of reference consisting of geographical coordinates. Those coordinates are decimal degrees longitude and latitude *as defined by the Tokyo datum*. The method used here is very similar in principle to Hubbell's method of "presumably unmoved objects" as set forth in his 1986 report.

This work could alternatively be performed in the frame of reference consisting of the plane rectangular coordinates (in kilometers) of the Japanese land survey system, on which the newer Japanese city plan maps are based. The method used here was originally chosen to facilitate direct comparisons to the longitude and latitude markings of the U.S. Army maps. Mathematically, the two methods are equivalent. This work develops two linear affine transformations, which relate the plane rectangular coordinate system of each map to geographical coordinates of longitude and latitude in the Tokyo *datum*. The product of these two transformations is itself a linear affine transformation, which relates the plane rectangular coordinates of one set of maps to the plane rectangular coordinates of the other.

Working in geographical coordinates as a pivotal frame of reference has been more convenient for the work done to date, although maps displayed in "degree space" (longitude and latitude) at the approximate latitude of Hiroshima and Nagasaki have a somewhat different aspect ratio than maps displayed in a plane rectangular coordinate system. Because a degree of longitude represents a distance only approximately cos(latitude), or about $\cos(33°) \approx 0.87$ times the distance of a degree of latitude in Hiroshima (Figure 5), a feature that is square in plane rectangular coordinates is shorter in the vertical direction than the horizontal when viewed in degree space, because there are fewer degrees per meter of latitude than per meter of longitude. The "unwarping" of maps by using a first-order affine transformation to georeference a scanned map image raster in geographical coordinates is a standard method (Verbyla and Chang 1997). Geometrically, the linear affine transformation is being used to undo the projection and take the map from the Cartesian space of the plane rectangular coordinates back into the degree space of geographical coordinates. The actual errors produced are therefore mathematically defined as the difference between the linear affine transformation and the full inverse map projection equations. These errors were checked for the plane rectangular coordinate system of the newer city plan maps by calculation for the corners of a true rectangle in the Cartesian space of the plane rectangular coordinates, corresponding to a tile of the newer city plan maps. The results are given in Table 6, and are not more than about 0.1 m in equivalent distance on the earth's surface. (Note that this is a different error than the inherent errors of scale that are contained in plane rectangular coordinates as a result of the map projection, which are discussed above in the section on "Map Projections and the Inherent Errors Associated with the Use of Plane Rectangular Coordinates.")

The steps of the procedure, briefly, were to 1) georeference the newer Japanese city plan maps using the crosshair markings of their map grid coordinate system, at the four corners of

Table 6. Error in the linear affine transformation vs. the full inverse map projection equation (for the corners of a true rectangle in plane rectangular coordinates, corresponding to a tile of the newer city plan map)

Plane rectangular coordinates		Geographical coordinates Tokyo datum (deg)					
		From full projection equation		From linear affine transformation[a]		Error (deg)	
X (km)	Y (km)	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
-178	27	132.4603522	34.39490741	132.4603535	34.39490740	-1.28E-06	1.00E-08
-178	29.5	132.4875450	34.39483912	132.4875437	34.39483913	1.28E-06	-1.00E-08
-179.75	27	132.4602971	34.37912858	132.4602958	34.37912859	1.28E-06	-1.00E-08
-179.75	29.5	132.4874848	34.37906033	132.4874860	34.37906032	-1.28E-06	1.00E-08

[a] The fitted linear transformation was longitude = 132.1725628 + 3.29404E-05*X + 0.010876078*Y, latitude = 36.00057552 + 0.009016465*X + -2.73082E-05*Y.

each map tile, and the full inverse projection equations given by GSI for converting those coordinates to degrees longitude and latitude; 2) mark a carefully chosen set of control points consisting of specific parts of buildings, bridges, etc., on the newer Japanese city plan maps; 3) overlay the newer Japanese city plan maps on the Army map and georeference the Army map by linking the same control points as depicted on the Army map to those depicted on the newer Japanese city plan maps; and 4) georeference two pre-bombing aerial photographs to the newer Japanese city plan maps in exactly the same manner as the Army map, using the same set of control points or the maximum available subset. The photographs could be used to check things such as detailed aspects of the relative alignment, size, shape, and orientation of various features as the appeared just before the bombings. These steps are described in more detail in the following sections.

The optimization used here is simply to minimize the sum of squares of the magnitudes of the vectors constituting the pairwise discrepancies, as illustrated in Figure 6. The validity of this method depends on a number of assumptions, and they should be discussed here. First, the method depends on the notion that the features chosen as control points are geometrically *representative* of all the features on the maps, in the sense that producing an alignment of the maps that minimizes some measure of their pairwise distance in a common frame of reference will similarly 1) align all of the depicted features that are not used as control points, and 2) align the map grid coordinate systems so that an accurate transformation between the two systems is produced.

More specifically, in this case, a decision was made to use the newer Japanese city plan maps as a template and to begin by georeferencing them according to their nominal reference values. The method of using “presumably unmoved objects” in the form of map features begins with two assumptions about the new Japanese city plan maps:

1) The procedure starts by assuming that the markings for the map grid coordinates on the newer Japanese city plan maps are the corners of a true rectangle in the pixel space of the map image raster. The actual results obtained for the georeferencing of a tile of the new city map are shown in Table 7. There is some subjective component to the errors obtained because of ambiguity about the exact intended location of the crosshair mark at each corner. A corner of one of the newer city plan map tiles is shown in Figure 7. These errors are due to small inaccuracies in the placement within the scanned map image raster of the crosshairs on the new city map tile. They could be the results of stretching of the paper map that was scanned,

inaccuracies of scanning, inaccuracies in the original paper map as printed, including the small ambiguities in the intended placement of the mark, or a combination of these.

The small errors are not due to the approximation of using a linear affine transformation in place of the full map projection equations. The errors due to the approximation of using a linear affine transformation are considerably smaller, as discussed above in this section. As an experiment, the same map tile was georeferenced in plane rectangular coordinates, and it was found that errors of the same size as those for the georeferencing in geographical coordinates were obtained.

2) It is further assumed that, given the plane rectangular coordinates defined for a given map tile by the crosshair marks at its corners, all of the features depicted on the newer Japanese city plan maps are correctly placed in the map grid coordinate system with accuracy on the level of one to two meters. The accuracy of the alignment of the U.S. Army map depends on the accuracy of the placement, in the plane rectangular coordinates of the newer city plan maps, of the "presumably unmoved objects" on the newer city plan maps that are used as control points. The present-day national map accuracy standards for both Japanese and U.S. maps are exacting enough to rule out errors larger than about one to two meters in the placement of features on modern maps. For example, the U.S. map accuracy standard says that the errors in "no more than 10 percent of the well-defined map points tested shall be more than one-thirtieth of an inch at scales larger than 1:20,000" (Verbyla and Chang, p. 151). One thirtieth of an inch is 0.084666 cm; at the scale of the new city plan maps, 1:2,500, it corresponds to 2.1 meters in equivalent distance on the earth's surface.

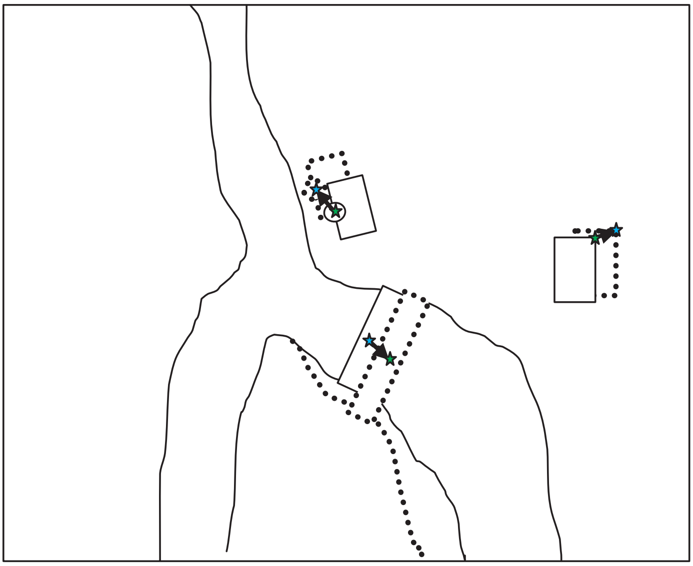

Figure 6. *The optimal alignment is obtained by minimizing the sum of squares of the lengths of the discrepancy vectors. The stars denote specific locations on depicted map features (buildings, bridges, etc.) that define control points on the associated image rasters.*

Table 7. Approximate errors obtained in practice: Georeferencing a tile of the newer city plan map

Plane rectangular coordinates		Geographical coordinates Tokyo datum (deg)					
		From full projection equation		From georeferenced map image raster		Error (deg)	
X (km)	Y (km)	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
-178	24.5	132.433159	34.39497	132.433161	34.394977	-2.00E-06	-7.00E-06
-178	27	132.460352	34.394907	132.460349	34.394907	3.00E-06	0.00E+00
-179.75	24.5	132.433109	34.379191	132.433106	34.379181	3.00E-06	1.00E-05
-179.75	27	132.460297	34.379129	132.460301	34.37914	-4.00E-06	-1.10E-05

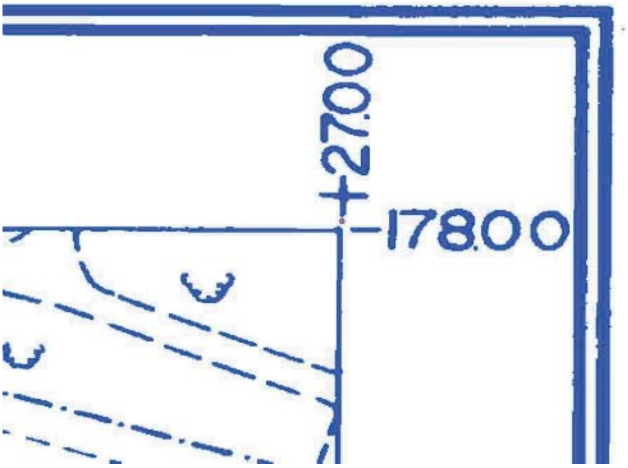

Figure 7. *Example of crosshair mark at corner of a Hiroshima city plan map tile-note, for example, the small horizontal offset between the vertical bar of the "+" sign at "+27.00" and the corner of the actual map tile. The small lavender-colored circle is the location in geographical coordinates of the point (-178 km, 27 km) in the plane rectangular coordinate system of the Japan Land Survey System, Zone 3 (Hiroshima), according to the full inverse map projection equations given by the Geographical Survey Institute.*

The errors in both of these assumptions are acceptably small. Other considerations support the accuracy of the newer city plan maps in addition to those just noted regarding the technical quality of the maps. As noted by Hubbell in his report, these newer Japanese city plan maps are based on extensive modern survey work. One important consideration relates to the correspondence with the older aerial photographs. A notable outcome of this work that will be discussed further below is that in the Hiroshima case the wartime aerial photographs available for this work could be substantially better aligned with the newer Japanese city plan maps than could the U.S. Army map. This provides convincing evidence of the accuracy of the newer Japanese city plan maps in regard to the relative locations of various features depicted on them. It also provides some cogent additional reassurance that the control points were valid, and that large features such as river channels in some locations and some major streets had remained unchanged in location between 1945 and 1979, so that their depiction on the newer Japanese city plan maps is an accurate representation of the way that they *should* appear on the Army map. There is also the prospect of checking the maps against such information sources as commercially available satellite imagery in the future.

Aligning the maps using a set of control points consisting of common features, or “presumably unmoved objects” as Hubbell called them in his 1986 report (see the section on “The Work of Hubbell” above) then has results that further depend on the properties of the U.S. Army maps. The control points, in the aggregate, define a linear affine transformation for the U.S. Army map, which relates pixel address in the U.S. Army map image raster to geographical coordinates. This method allows the geographical coordinates of any depicted location on the U.S. Army map to be estimated directly without reference to the map’s grid system (plane rectangular coordinates) or its longitude and latitude tic marks, based on the pixel address of that location in the map image raster. The parameters of the transformation so obtained are an estimate of the transformation that would minimize the error for all locations depicted on the map. The residual errors in the depicted locations of the control points on the U.S. Army maps vs. their presumed correct geographical coordinates based on the newer Japanese city plan maps provide a basis for estimating the distribution of the errors that would apply, under the optimized transformation, to other locations depicted on the U.S. Army maps. The concern about making these control points representative of all of the other features depicted on the U.S. Army maps, in the sense that their least-squares alignment would provide a good alignment of other features, and that their residual errors under that alignment would be representative of those that should obtain for other features under the same alignment, made it imperative to find as many control points as possible, distributed as widely as possible over a region about 2 km from the hypocenter in all directions.

Another linear affine transformation is defined by the pixel addresses of the intersections of the U.S. Army map grid (plane rectangular coordinates), relating pixel address to plane rectangular coordinates. The product of this transformation and the transformation from pixel address to geographical coordinates defines a transformation from the map grid (plane rectangular) coordinates of the U.S. Army maps to geographical coordinates, or vice versa. Details are given in Appendix A. The quality of the alignment obtained for both sets of maps and the resulting implications are discussed in the following sections.

Georeferencing of the Newer Japanese City Plan Maps

Two sets of the newer Japanese city plan maps were provided by Science Applications International Corporation. The first consisted of unaltered high-resolution scans and were designated as the “raw” images. The second were retouched by removing the margin material at the edges of the maps, i.e., anything not consisting of the actual map features; these were designated as the “clean” images. Because some of the clean images did not contain the crosshair markings at the corners of the maps, which are the only markings for the map grid coordinate system, the raw images were georeferenced first.

The longitude and latitude coordinates of the crosshair markers were calculated from the GIS transformation equations and a point shapefile containing markers at those intersections of the grid system was created. Then each raw image was georeferenced to four points at its corners.

Four well-defined points are sufficient to define the first-order (linear) affine transformation for unwarping a map (e.g., Verbyla and Chang 1997, pages 171-176). As noted in the preceding section, some small ambiguity in the placement of crosshair marks at the corners of the map, along with other errors such as stretching of the paper or slight errors in drawing the corners of the original map, appears to produce some small errors in the locations of the corners vs. the intersections of a true rectangle. These errors (Table 7) are on the order of about one meter or less in terms of actual distance on the earth's surface. The overall accuracy of georeferencing each tile might be slightly improved by using more points for georeferencing, depending on the nature of the source of these errors, i.e., the error in the optimized transformation due to error components of a random nature in the placement of the marks used as control points would be reduced, whereas errors of a systematic nature (e.g., a uniform, proportional stretching of the paper) would not be reduced. Unfortunately, additional points would have to be in the interior of the tile to be really useful in any case, and the only additional marked points available on the paper maps are along the margins.

One other possibility for obtaining additional control points for tiles of the newer city plan maps is that the 1979 and 1981 new city plan maps could be georeferenced to the newest, GIS-based maps, in the same manner as the U.S. Army maps have been georeferenced to the 1979 and 1981 new city plan maps. This would require the careful selection of control points according to the same criteria that were used for "presumably unmoved objects" for aligning the U.S. Army maps, which are described in detail in the next section. It is not clear that any real improvement would be obtained by such a method, when the small size of the errors in the placement of the crosshair markers at the four corners of a map tile in the present work is considered, especially given the other errors that would be involved in the process of georeferencing the 1979 and 1981 maps to the newest available maps.

After the raw images were georeferenced, the clean images were superposed as an overlay and were georeferenced to the raw images using just 3 points. Because the clean images are a subset of the raw images, and can be perfectly superimposed, pixel-by-pixel, the three points used could be arbitrarily chosen, and a little effort resulted in an overlay that was almost perfect at the pixel level.

Choice of Control Points for Fitting the U.S. Army Map

The choice of control points for matching the U.S. Army map to the newer Japanese map is very important. A careful consideration of the intended purpose suggested the following criteria:

1) The point must be a feature that is clearly depicted on both maps. Since a point should be able to be localized within a meter or two, this means that the specification of the control point must be detailed. A point should refer to a specific corner of a building or some other part of the chosen feature that can be clearly identified on the depicted outline of the feature as shown on both maps. Hubbell gave similar criteria in his 1986 report. This suggests further that the outline of the feature should be reasonably similar on both maps in size, shape, and orientation.
2) One must be certain that the feature was not moved or substantially altered in a way that would change its depiction on the map, during the time between 1945 and 1979. After some research, it seemed apparent that the best kinds of features in this regard were large, uniquely identifiable buildings, and bridges. All of the features chosen as control points were checked

carefully. Two very valuable resources in this regard are the book *Architectural Witnesses to the Atomic Bombing: A Record for the Future*, published by the Hiroshima Memorial Peace Museum (1996) and a similar book published by the City of Nagasaki (1996). These books contain extensive photographs, drawings, and historical and architectural information. Additional information about bridges in Hiroshima was also compiled from the U.S. Strategic Bombing Survey (USSBS 1947). The principal author and other authors of this section have personally visited many of the sites in both cities as well, although some have changed since 1979.

3) It is also preferable that the site be visible on the aerial photographs so that the related control point can be used to georeference the photographs.

The actual control points used in the procedure are documented in detail in Table 8, along with detailed reference information about each building or other structure associated with each control point, including dates and details of demolition and/or reconstruction that affect its true

Table 8. Hiroshima control points and final discrepancies vs. 1979 Japanese city plan map: Georeferenced U.S. Army map and aerial photograph

Control point; Reference No. in *Architectural Witnesses* (Hiroshima Memorial Peace Museum 1996), status as of 2003	GR (m)	Army map discrepancy (m)	Aerial photo discrepancy (m)
Motoyasu Bridge, mid-river; 1-15, rebuilt in same location 1992	116	7.7	1.7
Center of dome of A-bomb Dome; 1-1, existing	147	8.8	2.6
Fukoku Seimei Bldg, SW corner; 2-15, demolished 1982	334	1.6	5.1
Teikoku Bank, NE corner; 2-18, existing (Andersen's)	386	2.3	6.9
Bank of Japan Hiroshima Branch, SW corner; 2-16, existing	394	7.5	7.5
Honkawa Bridge, mid-river; 1-16, spans destroyed in 1945 and rebuilt on same piers in 1949, existing	398	10.2	5.7
Naka Telephone Bldg, SW corner; 2-20, demolished 1982	548	5.4	9.7
San'in Godo Bank, NW corner; 2-27, demolished 1983	626	10.5	6.0
Kirin Beer Hall, NE corner; 2-24, demolished 1991 (now site of PARCO Building)	697	3.9	8.0
Chugoku Electric Co. (Chuden) Bldg, SW corner; 5-1; demolished 1984	698	1.9	6.5
Fukuya Dept. Store, NW corner; 2-25, existing (Tenmaya)	709	11.7	4.1
Hiroshima Castle moat, SW outside corner; 4-1, existing	715	12.2	5.7
Kodo National School, center; 6-1, demolished 1987	734	21.0	2.9
Yorozuyo Bridge, mid-river, 5-22; demolished 1981	883	6.5	6.6
City Hall, SW corner, 5-6; demolished 1985	1054	6.9	1.0
Hiroshima Telephone Co. West Branch, SW corner; 6-2, existing (NTT)	1080	11.9	4.6
Meiji Bridge, mid-river; 5-23, existing	1278	5.4	4.1
Yokogawa Bridge, mid-river; 12-21, demolished 1983	1284	23.1	3.7
Kyo Bridge, mid-river; 3-13, existing	1393	9.3	8.1
Red Cross Hospital, NW corner; 5-11, demolished 1993	1459	9.7	6.5
University "E" Bldg, NW corner; 5-7, existing	1401	10.9	0.6
Sakae Bridge, mid-river; 3-11, existing	1529	8.3	7.9
Hijiyama Bridge, W end at river bank; 8-24, existing	1673	10.1	9.1
Mean absolute discrepancy:		**9.0**	**5.4**

outline and location from 1945 to 1979 or 1981, and to the present day.

It should also be noted that Hubbell used four rather distant points among his 18 locations, ranging from about 3.1 to 4.2 km from the hypocenter, which were also used by Fukuken Choosa Sekkei. Two of these were points with noted elevations on mountain summits to the north, which Hubbell called “triangulation points,” and two were points where canals entered into the harbor in the south. These points were not used in the present work for several reasons:

1) The points used in this work were constrained to be within about 1.8 km of the hypocenter in order to produce the best possible fit in areas near the hypocenter and in order to cover approximately the same area that was involved in the triangulations by which the hypocenter was determined
2) The four more distant points are not as well defined and thoroughly documented, particularly with respect to whether they represent the same exact locations on both sets of maps, as the 23 locations used for this work.
3) The two “triangulation” points in the mountains to the north, by their nature, cannot be identified on aerial photographs and so cannot be used to align an aerial photograph.

The control points were identified on the georeferenced new Japanese city plan maps and their exact longitudes and latitudes were measured with the tool that the GIS provides for that purpose. A point shapefile for the control points was then created, to place a small marker at each of these locations. This has the added advantage that, when the Army map is being georeferenced, the overlay consisting of the newer Japanese city plan map can be removed from the image display if it obscures the feature of interest on the Army map. Another advantage is that the control points can be viewed without the maps for ease of visualizing their spatial relationships to each other and to the hypocenter.

The control points for Hiroshima are shown in Figure 8 and those for Nagasaki are shown in Figure 9. It will be noted that the distribution is not uniform, which is an inevitable result of various factors such as where the urban areas with large buildings were located, which areas were extensively reconstructed after the war, and which bridges in Hiroshima survived the flood damage noted in the USSBS report. There were substantially fewer possibilities for control points in Nagasaki, due to the geography of the city and the comparative lack of large, massive buildings in areas close to the hypocenter.

One unfortunate aspect of this situation, in both cities, is that residential areas where large numbers of survivors were located at the time of the bombing are the least likely to have large buildings that would serve as good control points. This makes it all the more important that care be taken to ensure that the georeferencing is done in a manner that will yield the best possible results for such areas. Even with an affine transformation that preserves the geometrical relationships among the features as depicted on the map, it will still be true that the overall fit will be best in areas where there are the most control points. Fortunately, other checking can be done to verify that the fit obtained is a good one over the larger area of concern, as discussed below in the section on results.

Georeferencing the Army Map to the Japanese City Plan Map

The Army map image was georeferenced to the control points determined as discussed above. This is a process that requires some skill and judgment, particularly in light of the fact that the outline of the feature of interest on the Army map is almost never identical in size, shape, and

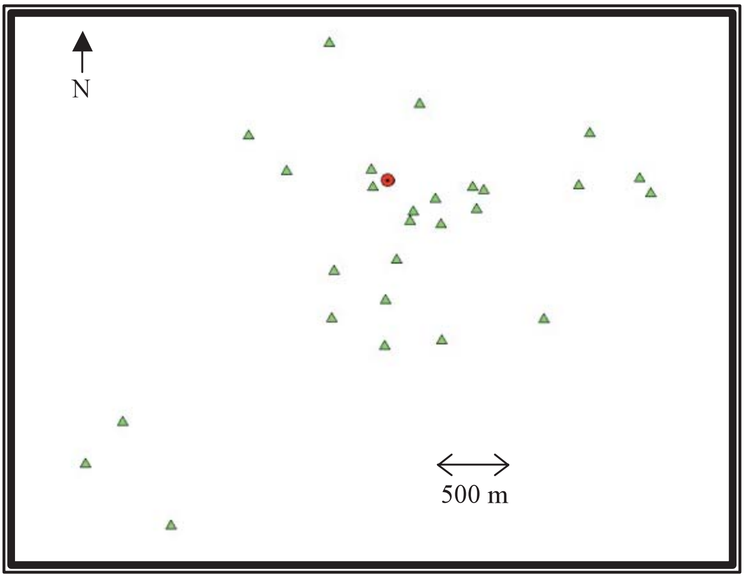

Figure 8. *The available control points in Hiroshima are somewhat unevenly distributed about the hypocenter.*

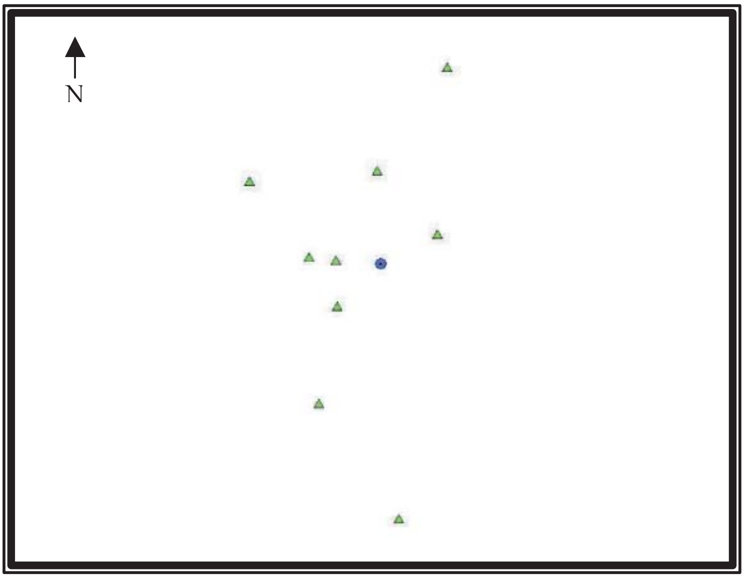

Figure 9. *The distribution of the available control points in Nagasaki is strongly affected by the geography of the valley in which the city lies.*

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