Chapter 16.
Control for Aerial Photogrammetry

16-1. Introduction

- Photogrammetric control traditionally consists of any points whose positions are known in an object-space reference coordinate system and whose images can be positively identified in the photographs
- In aerial photogrammetry the object space can be defined by various reference ground coordinate systems
- Photogrammetric *ground control*, as it is commonly called in aerial photogrammetry, provides the means for orienting or relating aerial photographs to the ground
- Almost every phase of photogrammetric work requires some ground control
- Aircraft-mounted GPS/INS systems can also be used as control for photogrammetric surveys by directly measuring the position and attitude of the camera during acquisition

16-1. Introduction

- Photogrammetric ground control is generally classified as either *horizontal control* (the position of the point in object space is known with respect to a horizontal datum) or *vertical control* (the elevation of the point is known with respect to a vertical datum)

- Separate classifications of horizontal and vertical control have resulted primarily because of differences in horizontal and vertical reference datums, and because of differences in surveying techniques for establishing horizontal and vertical control

- Also, horizontal and vertical control are considered separately in some photogrammetric processes

- Often, however, both horizontal and vertical object-space positions of points are known, so that these points serve a dual control purpose

16-1. Introduction

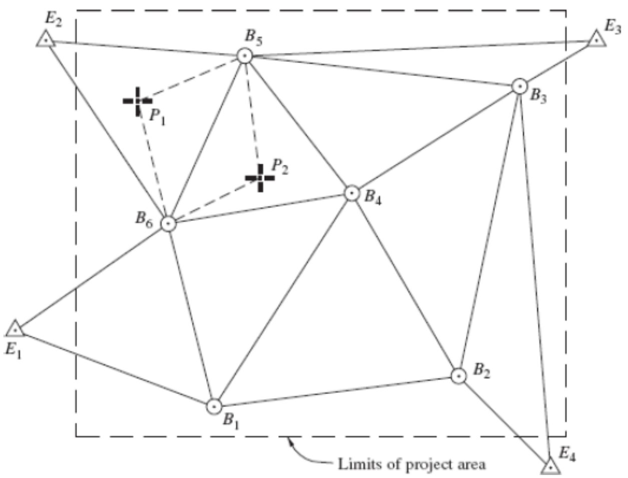

Figure 16-1. Field surveys for establishing photogrammetric control.

- Field surveying for photogrammetric control has historically been a two-step process, although now with the widespread use of GPS, this distinction is not as clear
- **The first step** consists of establishing a network of *basic control* in the project area
  - This basic control consists of horizontal control monuments and benchmarks of vertical control which will serve as a reference framework for subsequent photo control surveys
- **The second step** involves establishing objectspace positions of *photo control* by means of surveys originating from the basic control network
- Photo control points are the actual image points appearing in the photos that are used to control photogrammetric operations
- The accuracy of basic control surveys is generally higher than that of subsequent photo control surveys
- If GPS is used for the control surveying work, in some cases the intermediate step of establishing basic control may be bypassed and photo control established directly

16-1. Introduction

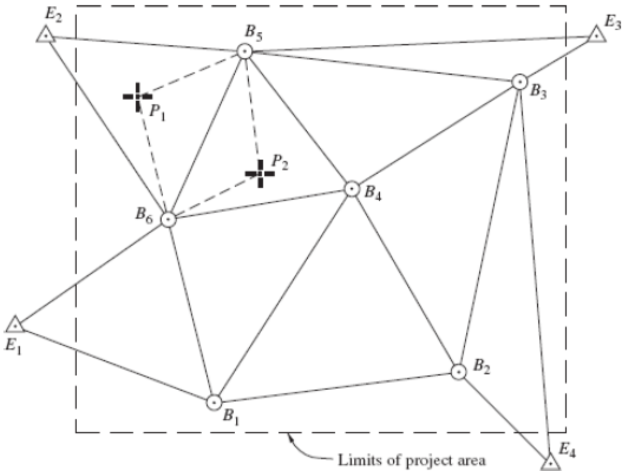

Figure 16-1. Field surveys for establishing photogrammetric control.

- The two-step procedure of field surveying for photogrammetric control is illustrated in Fig. 16-1
- In the figure a basic GPS control survey originates from existing control stations E_1 through E_4 and establishes a network of basic control points B_1 through B_6 in the project area
- With these basic stations established, the second step of conducting subordinate surveys to locate photo control can occur
  - This is illustrated with the surveys that run between B_5 and B_6 and locate photo control points P_1 and P_2

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- The accuracy of finished photogrammetric products can be no better than the ground control upon which they are based
- Because of its importance, the ground control phase of every photogrammetric project should be carefully planned and executed
- Planning is an essential step before carrying out a photogrammetric ground control survey
- The required accuracy and consequently, the type of equipment and field techniques to be used should be settled early
- Required accuracy of photo control depends primarily upon the accuracy necessary in the photogrammetric mapping or other project that it controls
- However, another consideration is whether the control will serve other purposes in addition to controlling the photogrammetric work

16-1. Introduction

- The *national map accuracy standards* (NMAS) are commonly used to govern accuracy requirements of maps and therefore indirectly will govern control surveying accuracy

- As a general rule of thumb, photo control should contain error no greater than about one-fourth to one-third the horizontal map accuracy tolerance
  - ➪ Basic control must be more accurate than photo control.

- To meet the standard, a rule of thumb in topographic mapping states that elevations of vertical photo control points should be correct to within plus or minus about one-fifth of the contour interval
  - ➪ but as an additional safety factor, some agencies require that their accuracy be within one-tenth of the contour interval
  - ➪ Basic control must be more accurate than this

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- A more current set of accuracy standards drafted by the Federal Geographic Data Committee is titled *Geospatial Positioning Accuracy Standards*
    - These standards are readily applicable to digital maps, which are stored in a computer and manipulated with CAD software
    - Accuracy is expressed with separate horizontal and vertical components
- Other sets of accuracy standards have also been established by various organizations such as the **American Society for Photogrammetry and Remote Sensing**, the **Federal Highway Administration**, and the **American Society of Civil Engineers**
- In planning the control survey, maximum advantage should be taken of existing control in the area
- The **National Geodetic Survey** has established numerous horizontal control monuments and vertical control benchmarks in its work of extending the national control network
- The **U.S. Geological Survey** has also established a network of reliable horizontal and vertical control monuments in its topographic mapping operations
- In certain localities, other agencies of the federal government such as the **Tennessee Valley Authority, Army Corps of Engineers**, and **Bureau of Land Management** have established control

16-2. Ground Control Images and Artificial Targets

- In general, images of acceptable photo control points must satisfy two requirements:
  - (1) They must be sharp, well defined, and positively identified on all photos
  - (2) They must lie in favorable locations in the photographs

- Control surveys for photogrammetry are normally conducted after the photography has been obtained
  - ⇨ This ensures that the above two requirements can be met. Photo control images are selected after careful study of the photos

- The study should include the use of a stereoscope to ensure a clear stereoscopic view of all points selected
  - ⇨ This is important because many of the subsequent photogrammetric measurements will be made stereoscopically

- A preliminary selection of photo control images may be made in the office, but the final selection should be made in the field with the photos in hand
  - ⇨ This enables positive identification of objects to be made, and it also permits making a firsthand assessment of object point accessibility, terrain conditions, and surveying convenience

16-2. Ground Control Images and Artificial Targets

- When **selecting the position of a control point** associated with an object, one should also take into consideration the precise measurement of the point in the images that will take place
- For example, if the chevron-shaped feature shown in Fig. 16-2a is to be used as a control point, it may be tempting to use the point formed by the edges of the two legs
- However, due to blurring along the edges, it will be difficult to precisely measure the position of the point in the image

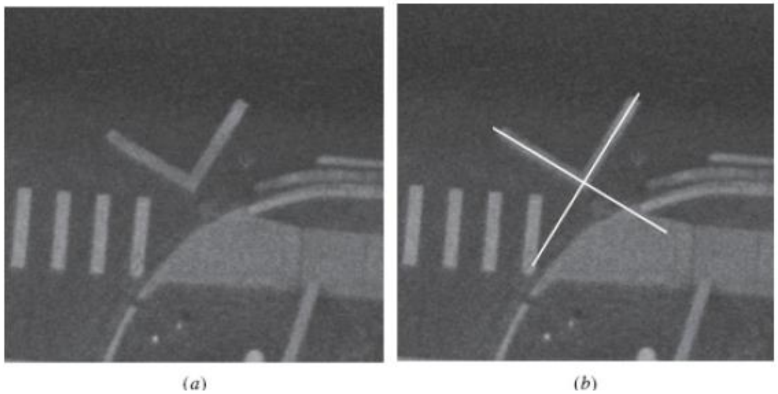

Figure 16-2. (a) Control point image with blurred edges. (b) Intersection of centerlines of legs.

- A better choice is to use the intersection of the centerline of the legs, illustrated in Fig. 16-2b, which is easier to identify than the edges in the image

16-2. Ground Control Images and Artificial Targets

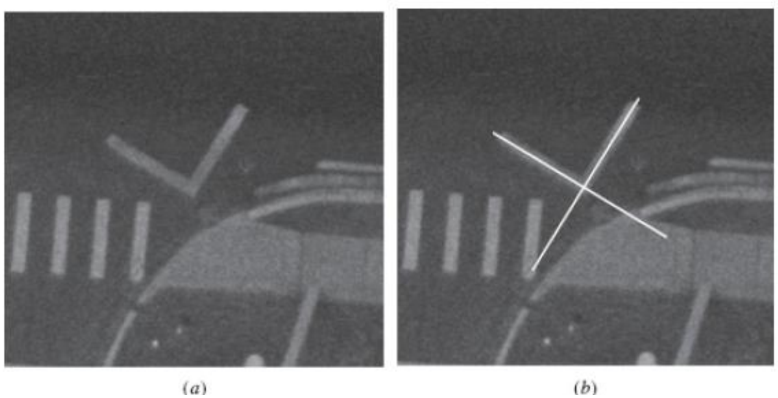

Figure 16–2. (a) Control point image with blurred edges. (b) Intersection of centerlines of legs.

- Images for horizontal control have slightly different requirements than images for vertical control
- Because their horizontal positions on the photographs must be precisely measured, images of horizontal control points must be very sharp and well defined horizontally
- Some objects whose images are commonly satisfactory for horizontal control are intersections of sidewalks, intersections of roads, manhole covers, small lone bushes, isolated rocks, corners of buildings, fence corners, power poles, points on bridges, intersections of small trails or watercourses, etc
- Care must be exercised to ensure that control points do not fall in shadowed areas on some photos

16-2. Ground Control Images and Artificial Targets

- Images for vertical control **need not be as sharp** and well defined horizontally
- Points selected should, however, be well defined vertically. Best vertical control points are small, flat or slightly crowned areas
- The small areas should have some natural features nearby, such as trees or rocks, which help to strengthen stereoscopic depth perception
- Large, open areas such as the tops of grassy hills or open fields should be avoided, if possible, because of the difficulties they cause in stereoscopic depth perception
- Intersections of roads and sidewalks, small patches of grass, small bare spots, etc., make excellent vertical control points

16-2. Ground Control Images and Artificial Targets

- In some areas such as prairies, forests, and deserts, natural points suitable for photogrammetric control may not exist
- In these cases artificial points called *panel points* may be placed on the ground prior to taking the aerial photography
- Their positions are then determined by field survey or in some cases by aerotriangulation, and this procedure is called *premarking* or *paneling*
- Artificial targets provide the best possible photographic images, and therefore they are used for controlling the most precise photogrammetric work, whether or not natural points exist
- Artificial targets are also used to mark section corners and boundary lines for photogrammetric cadastral work

16-2. Ground Control Images and Artificial Targets

- **Disadvantages** of **artificial targets** are that extra work and expense are incurred in placing the targets, the targets could be moved between the time of their placement and the time of photography, and the targets may not appear in favorable locations on the photographs

- To guard against the movement of artificial targets, the photography should be obtained as near as possible to the time of placing targets

- To obtain target images in favorable positions on the photographs, the coverage of each photo can be planned in relation to target locations, and the positions of ground principal points can be specified on the flight plan

- A number of different types of artificial targets have been successfully used for photogrammetric control

- The main elements in target design are good color contrast, a symmetric target that can be centered over the control point, and a target size that yields a satisfactory image on the resulting photographs

- Contrast is best obtained using light-colored targets against a dark background or darkcolored targets against light backgrounds

16-2. Ground Control Images and Artificial Targets

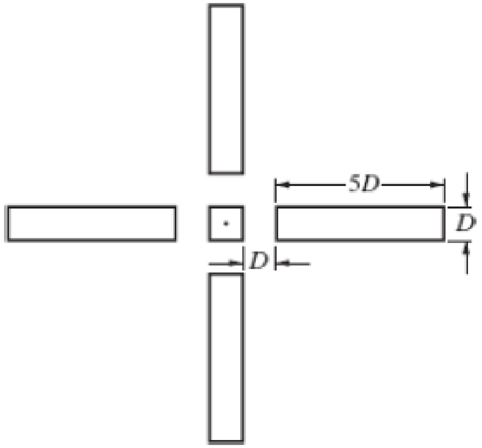

Figure 16–3. Artificial photogrammetric target.

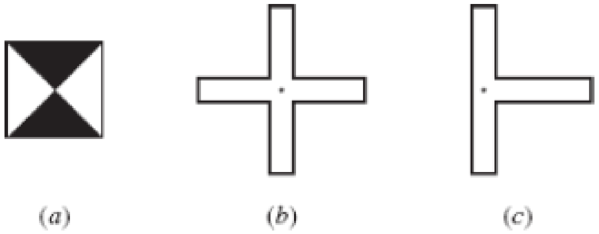

Figure 16–4. Other common artificial targets.

- The target shown in Fig. 16-3 provides good symmetry for centering over the control point
- The middle panel of the target should be centered over the control point, since this is the image point to which measurements will be taken
- The legs help in identifying targets on the photos, and also help in determining the exact center of the target should the image of the center panel be unclear
- The target shown in Fig. 16-3 is perhaps the ideal shape, circumstances may dictate use of other target shapes
- Figure 16-4a shows a target which is often used where a smaller target is needed
- The target of Fig. 16-4b is nearly as effective as that of Fig. 16-3, and it has the advantage of being more easily and quickly constructed
- The target of Fig. 16-4c is less than optimal due to lack of biaxial symmetry; however, it may be needed in confined areas such as edges of highways

16-2. Ground Control Images and Artificial Targets

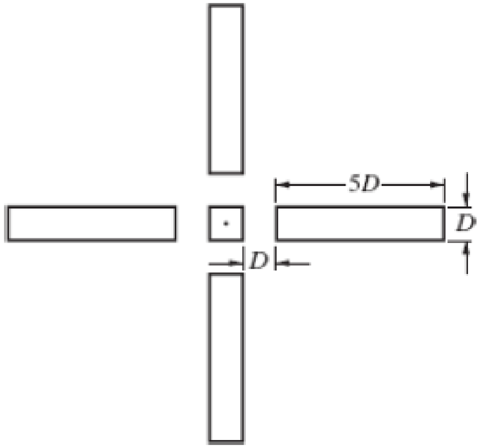

Figure 16−3. Artificial photogrammetric target.

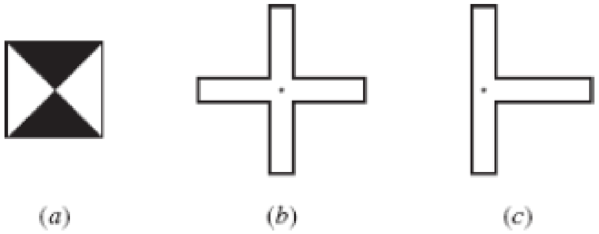

Figure 16−4. Other common artificial targets.

- ❖ Target sizes must be designed on the basis of intended photo scale so that the target images are the desired size on the photos
- ❖ An image size of about 0.03 mm to about 0.10 mm in film photography and about 10 to 20 pixels in digital photography for the sides of the central panel is suitable
- ❖ As shown in Fig. 16-3, if the ground dimension of the central panel of the target is D, then the leg width should also be D, leg length should be $5D$, and the open space between the central panel and the leg should be D
- ❖ Target sizes are readily calculated once the photo scale and optimum target image size are selected
- ❖ If, for example, a central panel size of 0.05 mm is desired and photography at a scale of 1:12,000 is planned, then D should be 0.6 m

16-2. Ground Control Images and Artificial Targets

- In some cases, satisfactory targets are obtained by simply painting white crosses on blacktop roads
- In other cases, targets are painted on plywood, masonite, or heavy cloth, in which case they may be salvaged and reused
- Satisfactory targets have also been made by placing stones against an earth background in the shape of a cross
- Lime placed in the shape of a cross against a dark background has also produced satisfactory targets
- Old tires painted white centered over the control points are also good for low-altitude, large-scale photography

16-2. Ground Control Images and Artificial Targets

- If panel points are needed in an area after the photography has already been obtained a procedure known as *post marking* can be performed
  - In this method, targets as described above are placed in the desired positions
- Supplemental vertical photographs are taken of each target and its surrounding area with a small-format camera carried in a light aircraft flying at low altitude
- Flying height can be calculated for the supplemental photography so that it has the same scale as the original photography
- Locations of the targets can then be transferred by superimposing scaled supplemental photography over the original photography
- The importance of exercising extreme caution in locating and marking objects in the field that correspond to selected photo images cannot be overemphasized
- Mistakes such as this can be avoided by identifying enough other details in the immediate vicinity of each point so that verification is certain
- A pocket stereoscope taken into the field can be invaluable in point identification, not only because it magnifies images but also because hills and valleys which aid in object verification can be seen both on the photos and on the ground

16-3. Number and Location of Photo Control

- The required number of control points and their optimum location in the photos depend upon the use that will be made of them

- For a very simple problem such as calculating the flying height of a photo which is assumed to be vertical, only the horizontal length of a line and the elevations of its endpoints are needed

- A line of as great a length as possible should be chosen

- For controlling mosaics, only a sparse network of horizontal control may be needed
  - ➪ The network should be uniformly distributed throughout the block of photos.

- In solving the *space resection* problem for determining the position and orientation of a tilted photo, a minimum of three XYZ control points is required

- The images of the control points should ideally form a large, nearly equilateral triangle

- Although three control points are the required minimum for space resection, redundant control is recommended to increase the accuracy of the photogrammetric solution and to prevent mistakes from going undetected

16-3. Number and Location of Photo Control

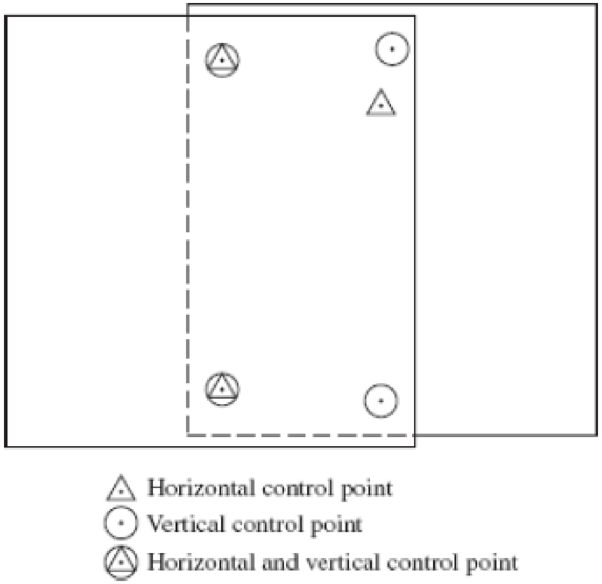

Figure 16–5. Control recommended for orienting stereomodels in a stereoscopic plotting instrument.

- If photo control is being established for **the purpose of orienting stereomodels in a plotting instrument for topographic map compilation**, the absolute minimum amount of control needed in each stereomodel is three vertical and two horizontal control points

- Again, the prudent photogrammetrist will utilize some amount of redundant control

- As a practical minimum, each stereomodel oriented in a plotter should have three horizontal and four vertical control points

- The horizontal points should be fairly widely spaced, and the vertical control points should be near the corners of the model

- A satisfactory configuration is shown in Fig. 16-5. Some organizations require a fifth vertical control point in the center of each stereomodel

16-3. Number and Location of Photo Control

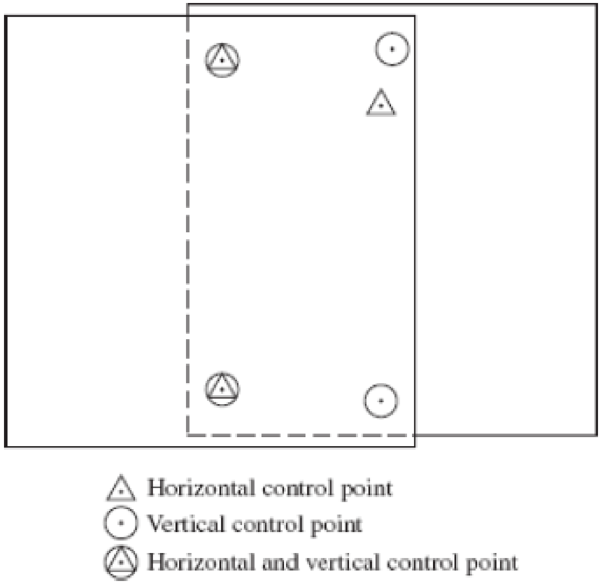

Figure 16–5. Control recommended for orienting stereomodels in a stereoscopic plotting instrument.

- If aerotriangulation is planned to supplement photo control, then fewer ground-surveyed photo control points are needed

- The amount of ground-surveyed photo control needed for aerotriangulation will vary, depending upon the size, shape, and nature of the area to be covered, the resulting accuracy required, and the procedures, instruments, and personnel to be used

- In general, the more dense the ground-surveyed network of photo control, the better the resulting accuracy in the supplemental control determined by aerotriangulation

16-3. Number and Location of Photo Control

- There is an optimum amount of ground-surveyed photo control, however, which affords maximum economic benefit from aerotriangulation and at the same time maintains a satisfactory standard of accuracy

- On average, if aerotriangulation of a strip of photos is to be performed for the purpose of obtaining control for orienting stereomodels in a stereoplotter, a minimum of about **two horizontal and three or four vertical ground-surveyed photo control points** should appear in approximately every fifth stereomodel along the strip

- This configuration is shown in Fig. 16-6. For aerotriangulation of blocks of photos, the ground-surveyed control should be systematically arranged throughout the block
  - Best control configurations consist of horizontal control along the periphery of the block with a uniform distribution of vertical control throughout the block

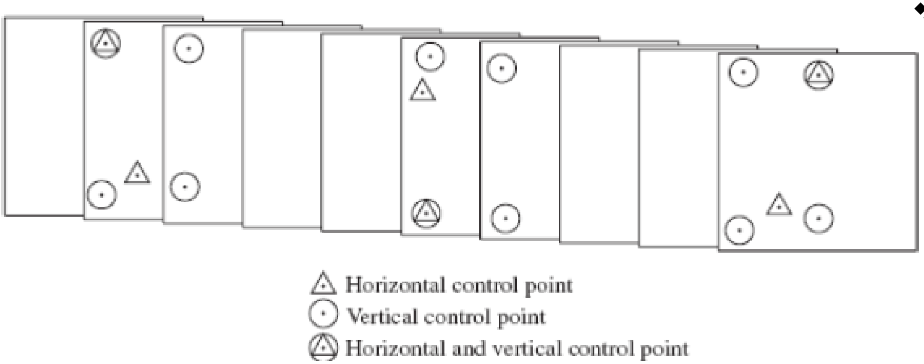

Figure 16-6. Example control configuration for a strip of photographs.

- Experience generally dictates the best control configurations to use, and organizations involved in aerotriangulation normally develop their own standards which meet accuracy requirements for their particular combination of procedures, instruments, and personnel

16-4. Traditional Field Survey Methods for Establishing Horizontal and Vertical Control

- Traditional field methods are divided into **surveys for horizontal** and **vertical control**
- **Horizontal control surveys**, both for basic control and for photo control, may be conducted using any of the traditional field methods: *traversing* , *triangulation*, or *trilateration*
- **Total station instruments** are most commonly used for measuring the angles and distances associated with these methods
- **Traversing**, the most common of the three mentioned, consists of measuring horizontal angles and horizontal distances between consecutive stations of a closed network
  - ⇨ The existing reference control stations are included in the network
- Based on the existing control coordinates and reference direction, along with the newly measured horizontal angles and distances, coordinates of all new stations may be calculated trigonometrically in the rectangular coordinate system of the existing reference control
- An adjustment, typically least squares, is normally made to account for measurement errors

16-4. Traditional Field Survey Methods for Establishing Horizontal and Vertical Control

- Triangulation involves measurement of horizontal angles between intervisible stations of a network of triangular figures, and trilateration involves measurement of horizontal distances in such a network
- Often, triangulation and trilateration are combined in a given network
  - A least squares adjustment can be performed on the combined network to yield coordinates for the new stations
  - Using triangulation-combined trilateration enables highly accurate coordinates to be determined
- For any horizontal control survey, an important task which must precede the taking of field measurements is establishing the network of stations in the project area whose positions are to be determined
- In basic control surveys, the stations will normally be artificial monuments such as wooden stakes or iron rods driven into the ground
  - These are carefully referenced to permanent nearby features so that they can be recovered later if lost
- In photo control surveys, some of the stations will be artificial monuments and others will be the natural features selected for photo control points

16-4. Traditional Field Survey Methods for Establishing Horizontal and Vertical Control

- For vertical control surveys, *differential leveling* is a common field procedure
- The basic equipment for differential leveling is a leveling instrument and a graduated rod
- The leveling instrument consists of a sighting telescope with reticle for reading the graduated rod and a means for orienting the telescope's line of sight in a horizontal plane
- Another technique for determining differences in elevation is **trigonometric leveling**
- It may be used where moderate accuracy is required and is especially well suited for rugged terrain

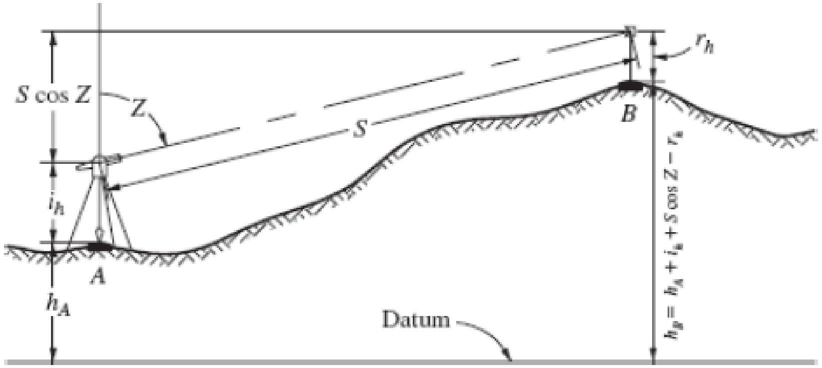

Figure 16-7. Trigonometric leveling.

- In trigonometric leveling, as illustrated in Fig. 16-7, vertical (zenith) angle Z and slope distance S are measured from the instrument at A to the reflector at B

16-4. Traditional Field Survey Methods for Establishing Horizontal and Vertical Control

- These measurements can be conveniently made with a total station instrument
- The difference in elevation from the center of the instrument to the center of the reflector is $S \cos Z$
- The elevation of point B is then equal to the elevation of point A, plus the instrument height i_h , plus $S \cos Z$, minus the reflector height r_h, as illustrated in Fig. 16-7
- Compensation for errors due to earth curvature and atmospheric refraction is generally made by standard correction formulas found in many surveying texts

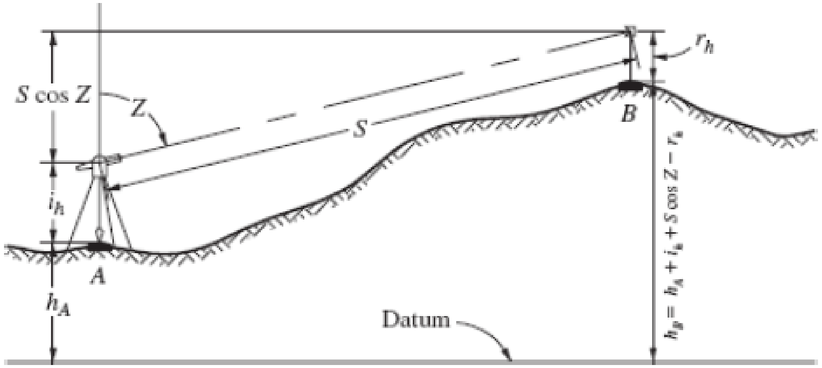

Figure 16–7. Trigonometric leveling.

- For highest accuracy in compensating for these errors, the measurements should be made in both directions and averaged

16-5. Fundamentals of the Global Positioning System

- GPS was implemented by the U.S. Department of Defense to address the problem of navigation and positioning on a global basis
- It currently consists of a network of 31 satellites orbiting the earth at an altitude of approximately 20,000 km, along with associated ground tracking and control stations
- The satellites are arranged in six orbital planes and make a complete revolution every 12 hours (h)
- This arrangement guarantees that at least four satellites will be "visible" from anywhere on earth at any instant in time
- The satellites are equipped with transmitters which can broadcast electromagnetic signals, as well as atomic clocks which establish a highly precise and accurate time basis

16-5. Fundamentals of the Global Positioning System

- Each satellite broadcasts digital messages or codes on two carrier frequencies: $L1$ at 1575.42 megahertz (MHz) and $L2$ at 1227.60 MHz
- The codes are a pseudorandom series of bits (0s and 1s) which have been modulated onto the carrier frequencies
- Two primary codes are broadcast: the C/A or coarse acquisition code, which is carried only by the $L1$ frequency, and the P or precise code, which is broadcast on both $L1$ and $L2$
- In addition to these two primary codes, additional data are broadcast, including timing information and a satellite ephemeris
- An additional carrier frequency, $L5$, is being introduced with the launch of new GPS satellites
- The $L5$ signal is broadcast at 1176.45 MHz, and will add accuracy and robustness to the current system

16-5. Fundamentals of the Global Positioning System

- The C/A code is broadcast at a *chip rate* of 1.023 MHz or 1.023 × 106 bits per second (bits/s)
- Given the speed of light of 2.9979246 × 108 m/s, each bit of the C/A code has an *equivalent length* of 293 m
- **P** code is broadcast at a frequency of 10.23 MHz, giving an equivalent length of 28.3 m/bit
- The carrier waves are broadcast at much higher frequencies and therefore have wavelengths which are substantially shorter than the code bits
- For the **$L1$** frequency the wavelength is 0.190 m, and for **$L2$** it is 0.244 m
- The equivalent lengths of the code bits and the wavelengths of the carrier frequencies relate directly to the precision with which positions can be determined
- Thus positions computed through *carrier-phase* processing can be determined much more precisely than those computed through *code-phase* processing

16-5. Fundamentals of the Global Positioning System

- The **primary components of receivers** used in conjunction with GPS are an **antenna** and a **module** which contains the receiver electronics, a clock, and a computer
- Figure 16-8 shows a typical GPS receiver with the antenna set up on a tripod directly over a control monument

Figure 16–8. GPS receiver with antenna mounted on a tripod. (Courtesy University of Florida.)

- Virtually all GPS receivers are capable of measuring the C/A code phase while fewer can measure the P code phase
- Only the more expensive geodetic-grade receivers can measure the carrier phase
- In addition, some units can receive only the $L1$ frequency while dual-frequency receivers can receive both $L1$ and $L2$
- Newer receivers have the ability to receive $L5$ signals, and some can receive signals from global navigation satellite system (GNSS) signals other than GPS, such as the Russian GLONASS

16-5. Fundamentals of the Global Positioning System

- The **Department of Defense** operates a series of ground tracking and control stations around the globe having GPS receivers which continuously monitor the entire constellation of satellites

- Based on observations from these stations, accurate orbit information, given with respect to the WGS84 datum, is determined for each satellite

- It is periodically transmitted to the satellites for subsequent broadcast as part of the GPS signal
  - This orbit information comprises what is called the *predicted ephemeris*
  - It enables GPS users to compute estimated positions of satellites through extrapolation from previously computed orbit parameters
  - A more accurate *precise ephemeris*, which contains directly computed parameters (as opposed to predicted), may be obtained from the National Geodetic Survey several days after GPS observations have been obtained

16-5. Fundamentals of the Global Positioning System

- The fundamental mode of operation of GPS employs a single receiver and is called *point positioning*
- In this mode, a receiver tracks **the modulated code (C/A or P)** from several satellites simultaneously
- This information, the so-called code phase observable, is used to determine the time it takes for the signal to travel from the satellite to the receiver
- The signal travel times from the various satellites are converted to distances known as *pseudoranges*, by multiplying by the speed of light
- Given the positions of the satellites from the ephemeris, these distances are used in a three-dimensional spherical intersection to determine the coordinates of the receiver
- Generally, at least four satellites are used which enable cancellation of the clock error of the receiver

16-5. Fundamentals of the Global Positioning System

- Errors inherent to point positioning are several
- Most individually contribute an error of perhaps 1 to 5 m in the computed position of the receiver
- These include errors due to ephemeris accuracy, timing accuracy, ionospheric and tropospheric interference, antenna construction, and multipath (or signal reflection)
- These errors are further amplified by a factor known as *PDOP* which is <u>related to satellite geometry</u>
- The accumulation of all these errors can result in an error in receiver position of up to 25 m or more

16-5. Fundamentals of the Global Positioning System

- A GPS method known as ***differential positioning*** using code-phase observations can be used to determine locations of points with much greater accuracy than point positioning
- The basic concept behind differential positioning is to employ two receivers which collect GPS signals simultaneously
- One of the receivers is placed on a control point having known position, called a ***base station***; and the other receiver, the *rover*, is placed at an unknown point
- Since the position of the base station is known, ranging errors to individual satellites can be calculated
- Since both receivers collected data simultaneously, the ranging errors calculated at the base station can be applied to the range measurements at the rover
- Compensation for these ranging errors is made to compute more accurate coordinates of the unknown point

16-5. Fundamentals of the Global Positioning System

- For the ultimate in accuracy, *relative positioning* using carrier-phase observations is employed
- In this approach, the phase changes of the $L1$ and unsually $L2$ carrier wave are measured at the receivers in order to determine their distances from the satellites
  - This is similar to the method employed by total station instruments in measuring distances electronically
- The **fundamental problem** associated with this approach is that any particular cycle of the carrier wave is indistinguishable from the other cycles
- The result is that there will be an unknown number of full cycles of the carrier wave between the satellite and the receiver
  - This *integer ambiguity* is a problem that must be overcome in the software used to process the information
- Modern systems are able to overcome this problem very effectively
  - This is the preferred GPS method for establishing photogrammetric control

16-5. Fundamentals of the Global Positioning System

- Many **modes of operation and data reduction techniques** are available when performing ground control surveys by GPS
- The method chosen will depend primarily upon accuracy requirements, available equipment and processing software as well as the amount of time available to field crews
- The methods are broadly categorized into **code-phase** and **carrier-phase techniques**
- Single-receiver point positioning is far too inaccurate for useful photogrammetric control work ➪ Therefore, differential techniques are used to establish control
- If small-scale mapping is being performed, differential codephase techniques may be employed
- Differential GPS requires that one receiver be placed at a known base station
- One or more roving receivers may then be employed to collect simultaneous observations at unknown points
- Depending on the quality of receivers used and the distance between the base station and rover, errors of less than 5 m can routinely be achieved
- The best-attainable accuracies of differential code-phase GPS are better than 0.5 m

16-5. Fundamentals of the Global Positioning System

- Several **carrier-phase methods of relative positioning** are commonly used for establishing photogrammetric control
  - Of these, the *static* method is the most accurate
- As the name implies, static GPS involves placing fixed receivers on points and collecting carrier-phase data for as long as an hour or more
- After data have been collected, *baseline vectors* are computed between pairs of receivers which give $\Delta X, \Delta Y$, and ΔZ components between corresponding points in a three-dimensional coordinate system
- Generally, interconnected networks (see Fig. 16-1) of these vectors are created which are subsequently adjusted by least squares to obtain coordinates for the unknown points
- Using the **static technique**, coordinates of unknown points can be determined with errors at the centimeter level

16-5. Fundamentals of the Global Positioning System

- If shorter observation times are desired, the method of *rapid static* observation may be employed
- With this approach, station occupation times may be reduced to 10 min or even less, while still achieving centimeter-level accuracy
- The rapid static method requires **more expensive equipment** and **more sophisticated data processing techniques** than static GPS
- Generally, receivers capable of tracking both the $L1$ and $L2$ carrier frequencies as well as the C/A and $\mathbf{P}$ code signals are used
- By including all four phase measurements in a highly redundant solution, accurate coordinates can be determined despite the reduced station occupation time
- While GPS is most often used to compute horizontal position, it is capable of determining vertical position (elevation) to nearly the same level of accuracy
- An inherent problem with the vertical position, however, is that it will be related to the ellipsoid, not the geoid or mean sea level
- To relate the GPS-derived elevation (ellipsoid height) to the more conventional elevation (orthometric height), a geoid model is necessary

16-6. Kinematic GPS Positioning

- Another technique as *kinematic positioning* can be used for establishing ground control
- When performing kinematic positioning, the rover receiver is in constant motion except for the brief period during which a station is occupied
- The method requires a stationary receiver to be located at a known base station, and an initial start-up period during which the rover receiver is held stationary
- This start-up period is required so that the processing software can calculate the unknown integer ambiguities
- Once the ambiguities have been resolved, the rover receiver can be moved, and as long as it remains in contact with the satellite transmissions, the changes in integer ambiguities can be determined
- The accuracy of kinematic GPS can be nearly as good as that of static

16-6. Kinematic GPS Positioning

- A major **drawback** associated with **kinematic GPS** surveys is that loss of signal cannot be tolerated
- When the rover receiver "loses lock" on the satellite transmissions, which can happen if it goes under a tree, bridge, or other obstruction, then it must be returned to a previously surveyed position so that the integer ambiguities can be redetermined
  - ➪ This restricts the use of kinematic GPS to open areas.
- To reduce the inconvenience associated with loss of lock, the technique of **"on-the-fly" (OTF) ambiguity resolution** has been developed
  - ➪ This method of ambiguity resolution is performed by a software technique whereby many trial combinations of integer ambiguities for the different satellites are tested in order to determine the correct set
  - ➪ This essentially trial-and-error approach generally requires a period of uninterrupted data of as much as several minutes in order for the ambiguities to be determined
- Use of dual-frequency receivers which track C/A as well as P code provides redundancy which can greatly enhance the computational process of determining the integer ambiguities

16-6. Kinematic GPS Positioning

- Kinematic GPS can also be used for airborne GPS control
- In this method, the position of the camera is measured using a GPS antenna fixed to the aircraft
- Many of the same concepts from kinematic positioning for ground control apply to airborne control
- For instance, a base station must be used and consequently multiple base stations must be used when mapping large areas to keep the distance to the station under a maximum threshold
- Since loss of satellite lock is detrimental to the solution, care should be taken not to bank the aircraft to high roll angles during turns between flight lines in order to prevent the wings from blocking satellites
- Typically, the maximum tolerated roll is about 15° to 20°
- An important consideration regarding airborne GPS positioning is the synchronization of GPS fixes with the photographic exposures
- The GPS receiver will be recording data at uniform time intervals called epochs, which may be on the order of 1 s each

16-6. Kinematic GPS Positioning

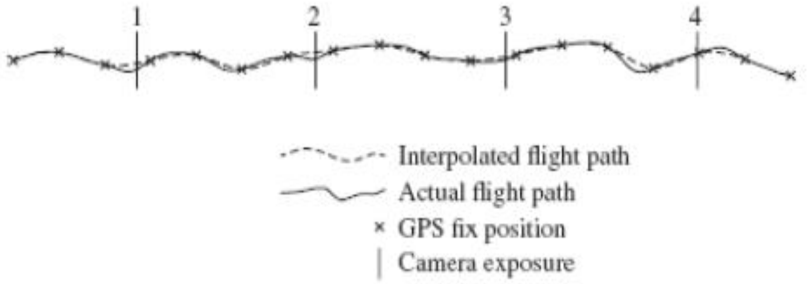

Figure 16−9. Interpolation between GPS fixes for positions at time of exposure.

- The camera shutter, on the other hand, operates asynchronously with respect to the GPS fixes, as shown in Fig. 16-9
- The result is that the position of the GPS antenna must first be interpolated from adjacent fixes before the coordinates can be translated to the lens
- Depending upon atmospheric turbulence and the epoch recording rate of the GPS receiver, the error due to this interpolation can be quite severe
- In Fig. 16-9, interpolation for exposures 1 and 2 results in sizable errors from the actual positions, whereas interpolation for exposure 4 is nearly perfect
- Integration of airborne kinematic GPS and an inertial navigation system (INS) can greatly reduce the error from interpolating by "filling in the gaps" between epochs
  - ⇨ This method can provide position (and attitude) data at a rate of up to 200 Hz

16-7. Inertial Navigation Systems

- For the most part, inertial navigation system (INS) technology has made possible the use of airborne laser scanning (LiDAR), linear array imaging sensors, and different types of radar and sonar for precise mapping
- In the case of aerial photogrammetry, INS can provide a means for reducing or even eliminating the need for ground control
- This is because, especially when integrated with airborne GPS, INS effectively enables the direct measurement of position and angular attitude associated with the exposure of a photograph
- In other words, exterior orientation parameters, $\omega, \phi, \kappa, X_L, Y_L$ and Z_L, can be found without any information from the photography such as the image location of tie and/or control points ⇨ This is commonly referred to as direct georeferencing
- The value of INS is clear when considering the potential reduction of the effort and cost of establishing ground control

16-7. Inertial Navigation Systems

- An INS consists of a computer and an inertial measurement unit (IMU), and the IMU consists of a set of three accelerometers and three *gyroscopes* or *gyros*
- The accelerometers are mounted orthogonally to each other and output directional *specific force*, which is the total acceleration of an object minus acceleration due to gravitational attraction
- For example, an object stationary relative to the earth's surface has specific force of 9.8m/s , whereas an object in freefall has zero specific force
- Specific force is obtained from accelerometers via Newton’s second law by measuring the amount of force required to keep an object stationary under different accelerations and dividing by the mass
- There are multiple methods for mechanically implementing accelerometers
- For instance, many modern devices use a coil in an electrical field to keep a mass in a stationary position
- The gyros are also mounted orthogonally and are used to measure rotational motion

16-7. Inertial Navigation Systems

- The main principle behind traditional gyros is conservation of angular momentum
- One can imagine a toy gyroscope, a spinning top, or spinning plates
- When no external force is applied to a rotating mass, its spin axis will remain constant
- One can measure the torque required to keep a mounted gyro fixed with respect to a moving vehicle, and use it to calculate the vehicle's rate of angular change relative to the gyro's spin axis
- Historically, rigid rotor gyros consisting of discs spinning around their center of mass were used for inertial-based navigation based on conservation of angular momentum
- However, modern gyros, such as fiber optic and ring laser systems, are based on other physical laws
- Although they operate on different principles, the fundamental output—the rate of angular change—is the same for modern gyros and spinningmass gyros

16-7. Inertial Navigation Systems

- *INS mechanization* is a process for obtaining useable information from IMU measurements
- Mechanization involves integrating the specific force from the accelerometers and the angular velocity from the gyros over time to calculate position, velocity, and attitude
- An important consideration in mechanization is the reference frame for the output parameters
- IMU measurements are made with respect to the *inertial reference frame*
- The origin of the inertial reference frame is the center of the earth
- The z axis is parallel with the earth's spin axis
- The x axis is oriented such that its positive end passes through the mean vernal equinox, the intersection of the plane of earth's orbit (the ecliptic) and the equator
- The y axis completes the orthogonal system
- Note that the geocentric coordinate system (see Sec. 5-4) rotates through the inertial reference frame once every 24 hours

16-7. Inertial Navigation Systems

- The inertial measurements must be transformed into a mapping coordinate system such as the local-level frame, which is similar to the local vertical system except that the origin is located at the center of the INS
- When mechanizing in the local vertical frame, the position is calculated in geodetic coordinates, while the velocity and attitude are with respect to easting, northing, and up
- Since the mapping coordinate system is rotating with respect to the inertial reference frame, one must take into account not only gravity, but also the Coriolis effect and centripetal force

16-7. Inertial Navigation Systems

- Since all output from the IMU is relative, one must first initialize the system before INS mechanization
  - This involves resolving an initial position, velocity, and attitude of the sensor
- Although there are dynamic methods, it is simpler to initialize the INS when the platform is stationary
  - Initial position and velocity can be found using GPS
- As for the attitude of the system, tilt can be determined by measuring the specific force when the system is not moving
  - The specific force measured will then only consist of gravity
- The tilt of the system is the rotation that aligns the negative z axis of the sensor with the gravity vector (roughly down in the local-level frame)

16-7. Inertial Navigation Systems

- To initialize the heading one can use gyro measurements when the vehicle is stationary, which are related to the rotation of the earth and the latitude of the initial position
- The sensed rotation in the gyros corresponds to the transformed rotation about the y and z axes, east and north respectively, of the local-level frame relative to the inertial frame
- In practice, the INS software performs initialization automatically with a specific protocol recommended by the manufacturer
- INS navigation where all positions are determined from a single initial position is called dead reckoning
- Inertial sensors, while precise over short intervals, are susceptible to initial biases and random errors over time
- Since in dead reckoning all subsequent measurements relate only to an initial state, errors accumulate in the course of collection
  - For this reason, the best measure of the quality of an IMU is the rate at which the gyros "drift" over time
- The inherent accumulation of errors in position from INS mechanization has led to the widespread integration of GPS with INS

16-8. GPS-INS Integration

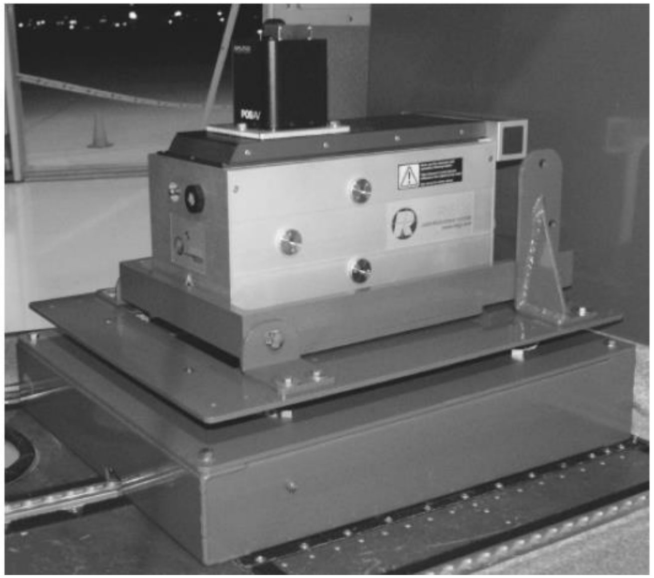

Figure 16-10. Airborne GPS-INS system. (Courtesy of RIEGL USA, Inc.; http://www.rieglusa.com)

- ❖ Kinematic airborne GPS requires interpolation over sometimes significant lengths of time to estimate the position at exposure leading to unreliable values
- ❖ In addition, GPS does not provide an estimate of angular attitude
- ❖ INS can provide angular attitude, however, left unchecked INS estimates of position and attitude have unbounded errors over time
- ❖ This has led to the development of **integrated GPS-INS systems**, and example application of which is shown in Fig. 16-10

16-8. GPS-INS Integration

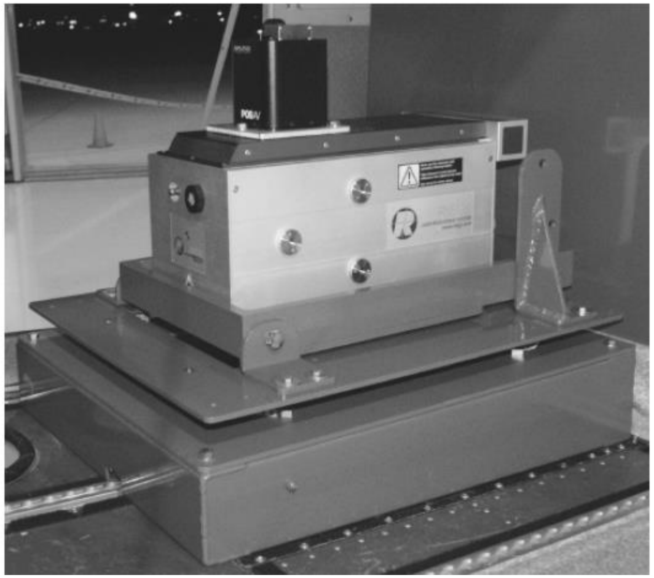

Figure 16-10. Airborne GPS-INS system.
(Courtesy of RIEGL USA, Inc.;
http://www.rieglusa.com)

- In the figure, the black box mounted to the top of the sensor (in this case an airborne laser scanner) is the IMU
- GPS and INS complement each other exceptionally well
- INS provides high-frequency but volatile estimates, while GPS provides independent and relatively low-frequency estimates with bounded errors
- Integrated GPS-INS systems use the GPS to update estimates from the INS
- This could be achieved by simply using the GPS to "reset" the velocity and position from INS mechanization
- However, integration is usually more rigorously accomplished using a *filter*—a mathematical process that provides best estimates of parameters given a function and input measurements
  - ⇨ One such process is the *Kalman filter*

16-8. GPS-INS Integration

- ❖ When integrating, the Kalman filter for INS-GPS operates on the errors associated with the INS

- ❖ INS errors can be estimated through modeling of the system, and GPS enables a measure of the INS errors which can be used to refine their values
  ➪ This "predict and update" scheme is characteristic of Kalman filters

- ❖ It can be implemented at different levels of integration: *loosely coupled, tightly coupled,* and *deeply coupled*

① Loosely coupled integration uses the independently calculated position and velocity from GPS

  - Whenever GPS position and velocity become available (at each epoch), they are subtracted from the values obtained from the INS

  - The difference between the two is used to calculate a new estimate of the error states which are then used to find new estimates of the position, velocity, and attitude

16-8. GPS-INS Integration

- When integrating, the Kalman filter for INS-GPS operates on the errors associated with the INS

- INS errors can be estimated through modeling of the system, and GPS enables a measure of the INS errors which can be used to refine their values
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- It can be implemented at different levels of integration: loosely coupled, tightly coupled, and deeply coupled

② Tightly coupled integration incorporates more basic GPS measurements such as the pseudoranges to estimate the error states of the INS

③ Deeply coupled integration involves the incorporation of even more basic GPS observations, the satellite signals themselves, and requires special hardware to implement

16-8. GPS-INS Integration

- GPS-INS data is typically first processed sing a filter operating forward in time
- That is, each measurement is introduced into the filter sequentially as they were measured to produce the estimates
  - ➪ This means that each estimate is based on previous measurements, and only the very last estimate is derived from all the measurements
- Following the forward filter, a backward-operating process is applied in order to allow forward-filtered estimates of position, velocity, and angular attitude to be adjusted based on subsequent estimates and measurements ➪ This procedure is called *smoothing*
- In practice, integration of GPS-INS is a sophisticated process, and is an ongoing area of research to develop new and more robust methods
- It should be mentioned that other observations can be integrated with GPS and/or INS including those from altimeters, magnetometers, video, radar, and star-tracking devices among others
- In fact, INS and vision-aided navigation in GPS-denied environments has become of particular interest

16-8. GPS-INS Integration

- Modern GPS-INS systems have become accurate and reliable
- They can provide angular attitude accuracies as good as 0.005° rms for ω and ϕ , and 0.008° rms for κ
- Positional accuracies for X_L, Y_L, and Z_L can be achieved at the level of 0.05 m rms
- Furthermore, direct georeferencing of airborne imagery using integrated GPS-INS, in concert with elevation models provided by airborne laser scanning, allows for rapid production of photogrammetric products such as orthophotos
- However, although direct georeferencing via GPS-INS is attractive due to its speed and efficiency, for best results it should be augmented with aerotriangulation
- **Aerotriangulation** provides a check on the directly obtained exterior orientation parameters and can be implemented with directly georeferenced imagery with or without ground control points, although the former is preferred
- In addition, when using **INS-GPS for airborne photogrammetry**, it is necessary to know the relative attitude and position of the navigation sensors with respect to the camera