武漢大學
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# *LECTURE NOTES*

# *2016*

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## CONTENTS

# 1. SENSORS AND PLATFORMS FOR ACQUISITION OF AERIAL AND SATELLITE IMAGE DATA

This chapter will discuss the various sensors that are available for the acquisition of image and other data for applications in photogrammetry and remote sensing, as well as for data collection for GIS, and subsequent analysis. 'Photogrammetry and remote sensing' are often traditional terms used for the extraction of metric and semantic information respectively from aerial, including unmanned aerial systems (UAS, also referred to as UAV, Remote Piloted Aerial Systems RPAS and drones) and satellite images, as well as from images taken at close range to an object. The terms will be used often in these notes. A typical definition is:

*Photogrammetry and Remote Sensing is the art, science, and technology of obtaining reliable information from non-contact imaging and other sensor systems about the Earth and its environment, and other physical objects and processes through recording, measuring, analyzing and representation.*

## 1.1 Types of image sensors

Sensors used in photogrammetry and remote sensing can be separated into 'passive' and 'active'. Passive sensors simply record light, usually solar radiation that is projected by a lens system onto a digital sensor. In the case of close range applications (distances nominally less than 300 metres), the lighting may be from artificial sources. Active sensors emit their own illumination and then record the time and intensity of the signal that is reflected from the ground or other objects.

*Passive Sensors*

- Digital cameras and film cameras, which are referred to 'analogue photographic sensors', record visible and near infra-red electro-magnetic radiation. Film images can be digitised for use in digital photogrammetric systems although this process is being phased out.
- Pushbroom or Whiskbroom (sometimes referred to as electro-optical sensors), which scan the terrain surface, comprising special devices for detecting and then recording multispectral images of reflected electromagnetic radiation.

*Active Sensors*

- Radar sensors emit microwave radiation, and record the time of transmission to the ground and back to the sensor, as well as the intensity of the reflected radiation from the terrain surface. All current systems are based on Synthetic Aperture Radar (SAR). Interferometric SAR (InSAR) is a technique used to determine elevations from SAR images based on the phase differences between SAR images received by two separate antennas.
- Airborne Laser Scan (ALS) or lidar (**Li**ght **D**etection **a**nd **R**anging and also written as LiDAR) are techniques for determining elevations on the terrain surface or characteristics of vegetation canopy from aircraft or satellite. Terrestrial Laser Scanners (TLS) are ground based lidar systems. Only airborne lidar sensors will be discussed in this course.
- Other forms of active imaging may also be used for measurement, such as electron microscope and X-rays.

## 1.2 Platforms

The platforms on which the sensors are placed may be an aeroplane, UAS (unmanned aerial system), a satellite in space, or a suitable mount on or near the terrain surface, if close range imaging is undertaken. The principles of the geometry of sensors will not normally be affected by the platform on which they are placed. However, accuracies of extracted information from images will depend on the distance of the sensor to the object. For aerial photography, the positions of the sensor will be determined by Real-Time Kinematic (RTK) from GNSS receivers installed on the aircraft, while tilts of the camera may be determined by an inertial measuring unit (IMU), also referred to as inertial navigation system (INS). The three position and three tilt parameters are referred to as the parameters of *exterior orientation* of the sensor. These systems may be integrated to provide what is referred to as *direct orientation* of the sensor. The exterior orientation of an earth observation satellite in space may be determined by GNSS, satellite tracking systems and star trackers. In close range photogrammetry, the position of a camera can usually be determined on the ground by standard survey methods.

### 1.3 Digital Aerial Cameras

Digital aerial cameras have only become available in about the last 15 years and have now replaced film cameras in many parts of the world. Their design must satisfy the need to produce high quality images and also provide a wide coverage of the terrain surface. Modern digital aerial cameras continue to be improved as new digital imaging technologies are developed. The characteristics of modern digital aerial cameras are as follows:

- They acquire high spatial resolution images of more than 200 Mpixels, comprising Ground Sampling Distance (GSD) of 5 cm and larger with high geometric accuracy
- They have adequate angles of field of coverage for efficient for geospatial information extraction
- They take advantage of the particular characteristics of digital image acquisition, with quantization levels of 11 bit or 12 bits, that is, 2048 or 4096 grey scale values and improved image quality.
- They acquire 4 bands of multispectral images with the same or lower spatial resolution as the panchromatic images.

Currently digital aerial cameras used in photogrammetry are classified as '*high-resolution'* and '*medium resolution'*. High spatial resolution digital aerial cameras have the potential to collect hundreds of Mpixels while medium spatial resolution cameras usually are based on a smaller single area array chips with about100 Mpixel.

**Advantages** of using digital images are:

- Image processing for target location, automatic height measurement and semi-automatic information extraction can be carried out on the image data, using stereo observation on the screen
- Digital orthophotos can be automatically derived from the data, thus providing for much greater flexibility in correcting variations in density of neighbouring images
- Future developments based on machine vision techniques will enable the automatic extraction of semantic information from the images

**Disadvantages** of using digital images:

- An analogue photo is an extremely efficient way to store information about an object and can be stored for decades.
- Algorithms for the automatic extraction and identification of information from images have not been developed, which impacts on the type of products that can currently be extracted from digital aerial images.
- Storage of digital image data requires regular backups onto new storage technology and as the old storage devices become obsolete.

Since digital aerial cameras are undergoing continual development and new models and types are being released onto the market on a regular basis. In the development of the new digital high spatial resolution aerial cameras two approaches have been adopted as described below.

### 1.3.1 High Spatial Resolution Digital Aerial Cameras

**(i) Systems based on CCD linear arrays - referred to as 'Pushbroom' sensors**. Linear array scanners acquire data by scanning the terrain with one or more linear arrays oriented normal to the flight direction as the aircraft moves over the terrain, (likened to a broom sweeping a surface). The Leica system comprises three linear arrays, one pointing forward, one pointing vertically and one pointing backwards to acquire **three separate overlapping images** of the terrain surface. The acquisition of overlapping images is essential for determining 3D coordinates of objects, including elevations, as will be described later in these notes. The systems are usually designed for acquiring panchromatic (ie black and white) and also colour or multispectral images including in the short wavelength infrared region of the spectrum (CIR – colour and infrared), with wavelengths up to about 0.9 μm wavelength, at the same or reduced resolution as the panchromatic images. **An integrated GNSS/IMU (Inertial Measuring Unit) system is essential** for this camera configuration for determining camera position and tilts, because the image acquisition is a continuous process and not frame based. Images from pushbroom sensors cannot be processed by standard frame image software. An example of this type of digital camera is:

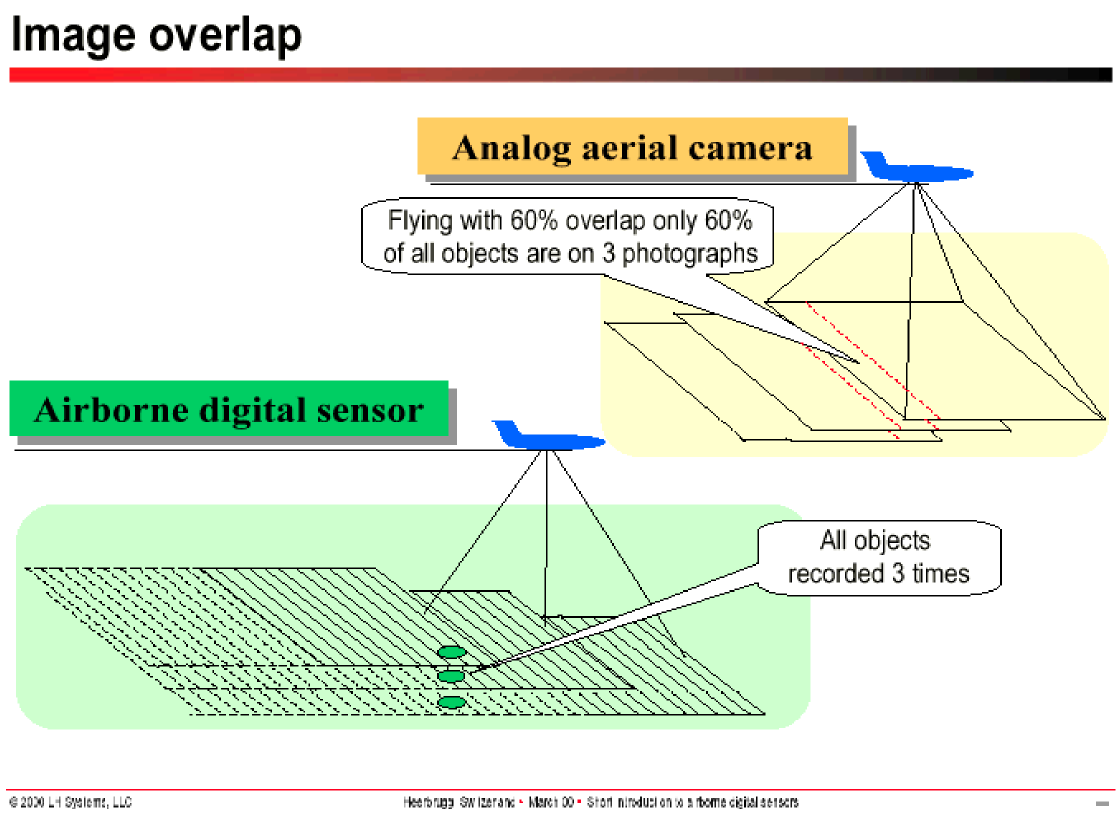



**Figure 1.1 Comparison of linear array camera of Leica Geosystems (ADS100) and normal frame camera configurations**

- **Leica ADS100** (Figure 1.1) acquires overlapping panchromatic and multi-spectral images, all with the same resolution, by 3 CCD linear arrays, looking forward, vertical and aft, by the SH100/SH120 camera heads.

**(ii) Frame systems based on area arrays.** These systems involve single large rectangular array or multiple small area arrays whose images are stitched together to form larger usually rectangular frame images. These images can be processed using standard digital photogrammetric software for frame images. GNSS/IMU systems are not essential for the operation of this type of camera, but some or all components of such a system may be included as an option. Cameras based on this configuration are:

- The DMC (Leica) cameras. The 1st generation was composed of 4 separately directed camera heads (7kx4k) for panchromatic images which were stitched together, and 4 camera heads (3kx2k) for 4 channels of multispectral images, each pointed so that they cover the required area of the terrain. The 2nd DMCII and 3rd generations DMCIII (various versions with different chip sizes are available) are based on a single monolithic area array. The multispectral images have a resolution 3.2 times less than the panchromatic images. The 3rd generation with 390 Mpixels is based on CMOS sensor (as opposed to CCD sensor for DMCII) with pixel sizes of 3.9 μm, 26113 pixels across the swath and 15,000 in the flight direction, together with mechanical forward motion compensation (FMC).
- The Vexcel UltraCam (Figure 1.2) is based on 'syntopic' imaging by 9 small format frame cameras for the panchromatic images, which are recorded sequentially during flight with 4 CCD arrays, so that the image acquisition for all arrays is based on the perspective centres of the cameras cones being in the same position. The separate images are stitched together to form a single area array. The multispectral images are acquired with 4 cameras cones each on a single CCD array at a lower resolution than the panchromatic images.

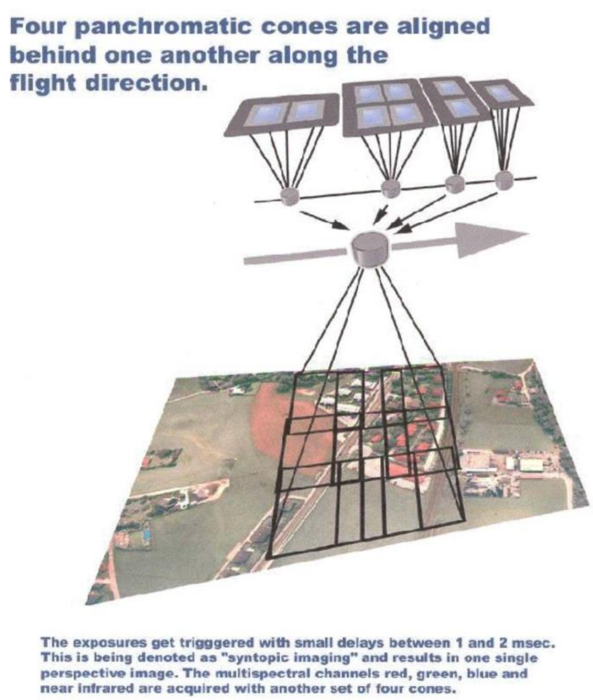



**Figure 1.2 Digital frame camera (UltraCam) configuration by the Microsoft Vexcel Camera**

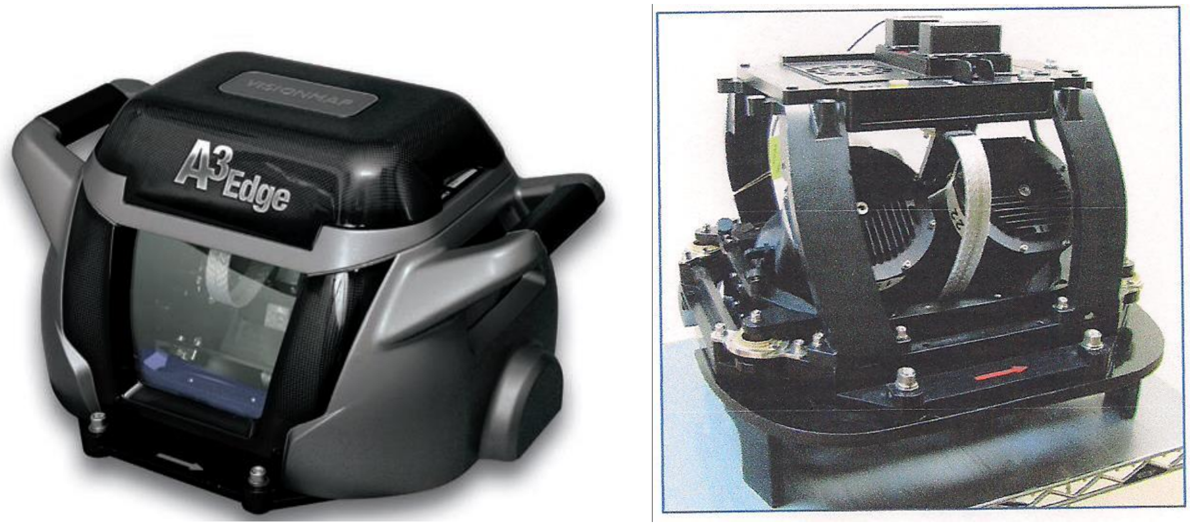



**Figure 1.3  VisionMap A3 Edge camera and scanning system**

- VisionMap System A3 Edge (Figure 1.3) from Israel is based on a double camera scanning system by which sequences of frames frames are imaged in the cross-track direction achieving very wide angle coverage of 100º FOV (field of view).  The systems consist of dual CCD arrays with 300 mm lenses, a fast data compression system and a dual frequency GNSS system but no IMU is required.  Given the unusual design, special fully automated software is required to process the data, which is also supplied by the company.  The company claims that the advantages of this system are the higher productivity than other digital aerial cameras since it has much higher angle of field and very high scan rates.

### 1.3.2  Medium Resolution Digital Aerial Cameras

Medium resolution cameras, as the name suggests, are of lower resolution than the high resolution cameras, with most comprising a single area array of varying sizes for the capture of multi-spectral images.  There are a number of these cameras on the market developed by different companies and they are undergoing considerable development with resolutions increasing as the development of chip technology improves.  They are suitable for lower resolution aerial mapping or in combination with other forms of data, such as lidar.

### 1.3.3 General description of high spatial resolution near vertical aerial photogrammetric image acquisition

Most so-called 'near vertical aerial photography' is recorded with tilts from the vertical of less than 2˚.  This has been traditional approach for film aerial photography and generally still applies for digital images.  Such small tilts limit the distortions in the images which enable their processing to orthophotos to be less problematic.  That is not to say that images with larger tilts cannot be processed to orthophotos, but the significant scale variations of photos with large tilts can lead to variations in the quality of the orthophoto, and large tilts can also cause important areas to be hidden behind buildings.

The theoretical assumptions made about the geometric processing of images are that all frame images are perspective projections.  That is, all light rays forming an image pass through a single point, called a 'perspective centre'.  For linear array or pushbroom cameras the assumption of a perspective projection only applies along each scanline formed by each linear array.  All aerial images are subject to certain distortions, due to tilts of the camera, elevation differences on the terrain for aerial images, deformations in the image formation process, particularly in the lens and atmospheric refraction which is a minor effect.

All photogrammetric measurements are based on overlapping images in order to obtain 3D object geometry. Typical overlaps on film images were 60% along track (forward overlap) and a minimum of 15% to 20% side overlap (sidelap) as shown in Figure 1.4. For the new era of digital imaging using area array cameras, the forward overlaps can be as large as 85%-90% and as high as 60% for sideways overlap between neighbouring strips of photography, also called 'sidelap'. For linear array cameras the 3 overlapping strips are acquired simultaneously. The side overlaps between strips may be 15% or larger.

Close range photographs are recorded with attitudes, ie tilts, designed to suit the particular application, but usually the optical axis of the camera will be directed approximately horizontally. The procedures for close range photography are therefore significantly different from aerial photography. Tilts may be much larger than 2° and the overlaps between photos may be up to 100%.

The original images recorded for film and digital photography are in the so-called negative plane as shown in Figure 1.4. The reproduction of the equivalent positive for a digital image is a trivial task. Therefore, all reference to images in these notes will assume the positive image is used.

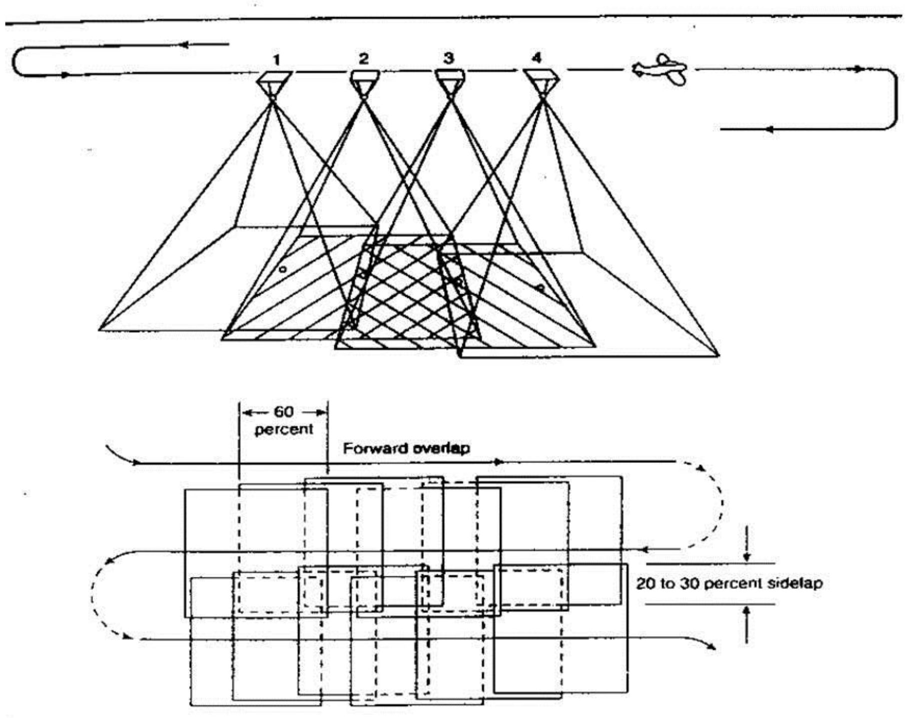



**Figure 1.4 Configuration of aerial imaging with minimum overlap**

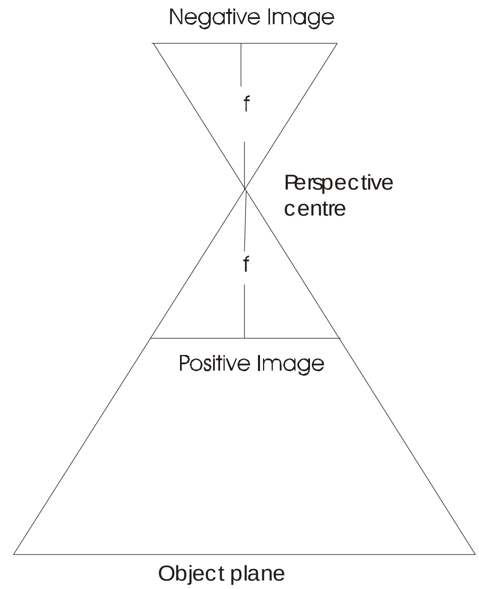



**Figure 1.5 Geometric relationships between positive and negative image planes**

The *principal distance* ‘f’, often called the *focal length*, defines the distance between the negative and positive image planes and the perspective centre (some textbooks use the symbol ‘c’ for the principal distance to avoid confusion with ‘f’ the focal length). As stated above the perspective centre defines the theoretical point in the camera, through which all light rays forming the image, are assumed to pass. The *principal point* is defined as the foot of the perpendicular from the perspective centre to the image plane. Hence the 3 components of what is known as the camera’s ‘*interior or inner orientation’* comprise $x_0$ and $y_0$ the x and y coordinates of the principal point and the principal distance ‘f’. (see Chapters 2, 3 and 6 for more details of their definitions) These components must be known before accurate measurement can be made from photographs.

### 1.3.4 Lens Distortion

All lenses will be subject to errors in image geometry due to design factors and manufacturing. The design of a lens is a compromise between the competing requirements of high image quality and near zero errors in the geometry of the image. Lens distortion is the deviation from a straight line path of the rays forming points in the images, which pass from the object through the perspective centre to the image plane. The largest component of lens distortion is radial to the principal point (Figure 1.6), while smaller tangential components may also occur in some lenses, but not those lenses specially designed for aerial photography. Aerial cameras will be subject to radial lens distortion of less than 5 µm, which will be symmetrical about the centre of the photograph. Recent research on digital aerial camera lenses has revealed distortions considerably less than 5 µm. Some 'non-metric' cameras used for close range photogrammetry may have lens distortions of the order of 100 µm. Lens distortions are determined as part of the process of camera calibration. It has been shown that radial-symmetric lens distortion in aerial lenses can be modelled by an odd-order polynomial of the form $dr=k_1r^3+k_2r^5+k_3r^7$, where dr is the radial distortion of a point on the image plane and r is the radial distance of the point measured from the principal point on the image plane, $k_1$, $k_2$ and $k_3$ are constants describing the characteristics of the distortion of a particular camera.

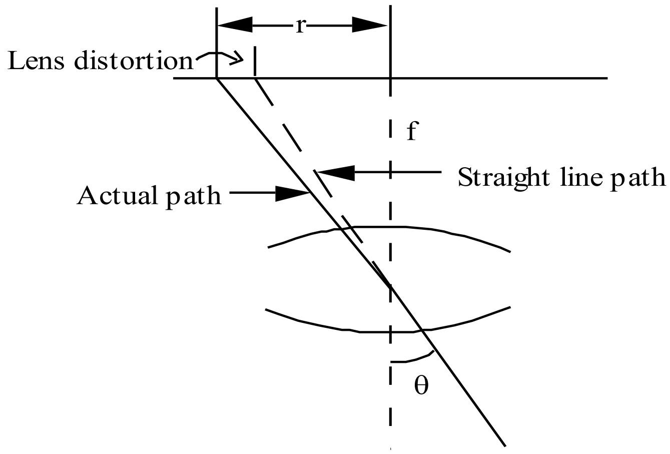
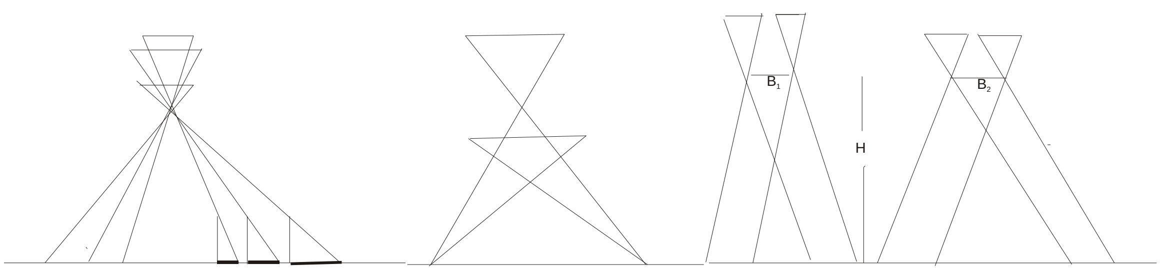



**Figure 1.6 Radial lens distortion**

### 1.3.5 Significance of the Angle of Field of a Camera

The angles of field of lens cones have a significant effect on the characteristics of photography acquired by cameras. The following general principles apply:

- The wider the angle of field, the greater the coverage for a given flying height - Figure 1.7a
- The same coverage, and hence the same scale of photography, can be obtained by varying the flying height for cameras with different angles of field. This means that for wider angle cameras, the flying height will be less - Figure 1.7b.




1.7(a) 1.7 (b) 1.7 (c)

**Figures 1.7a to 1.7c Examples of the relationships between the different camera lens cones**

- The wider the angle of field, the greater will be the dead areas, ie obscured or occluded areas, hidden by buildings and steep terrain - Figure 1.7a
- The wider the angle of field, the larger the Base/Height (B/H) ratio - Figure 1.7c. In principle this will have an impact on the accuracy of height measurement.

### 1.3.6 Measurement of Exposure

Exposure is dependent on both the aperture in the lens and the exposure time. Doubling the aperture should enable halving the exposure time. The aperture is defined by an f/number, as a fraction of the focal length of the camera, as follows:

$$\text{Aperture f/number} = \frac{\text{Focal length (mm)}}{\text{Apertures stop diameter (mm)}} \qquad (1.1)$$

Increasing the aperture number, that is, reducing the size of the aperture, will reduce the effects of aberrations in the lens, and also increase the depth of field of the lens, ie the range over which objects are in focus. However, reducing the aperture size will also require an increase in exposure time, which may result in large image movement if either the object or camera is in motion, as is the case for aerial photography. To reduce the effects of image motion all modern digital aerial CCD frame cameras incorporate, *forward motion compensation* (FMC) by TDI (Transfer Delay and Integration ). TDI is not possible with pushbroom cameras or CMOS sensor cameras, and hence other procedures need to be developed such as mechanical movement of the image plane. For close range photogrammetry, apertures would be selected to suit the application and if an object is in motion synchronized multiple cameras should be used.

### 1.3.7 Multi-Camera Systems

While multi-camera systems have existed for about 80 years, they have only come into regular use in modern aerial surveys over the past few years. The first modern multi-camera system was introduced by Pictometry more than 10 years ago. The system was based on 5 low cost cameras, one looking vertically and the other 4 looking obliquely in 4 directions at right angles as shown in the Figure 1.8. Subsequently other companies have developed their own version of multi-camera systems with high quality metric camera lenses, as for example the Vexcel Osprey, the IGI DigiCAM, comprising various options from one to five cameras (Penta DigiCAM), the Leica camera based on the RCD30 medium format camera and with up to 5 cameras.

**Figure 1.8 Configuration of Pictometry imaging**

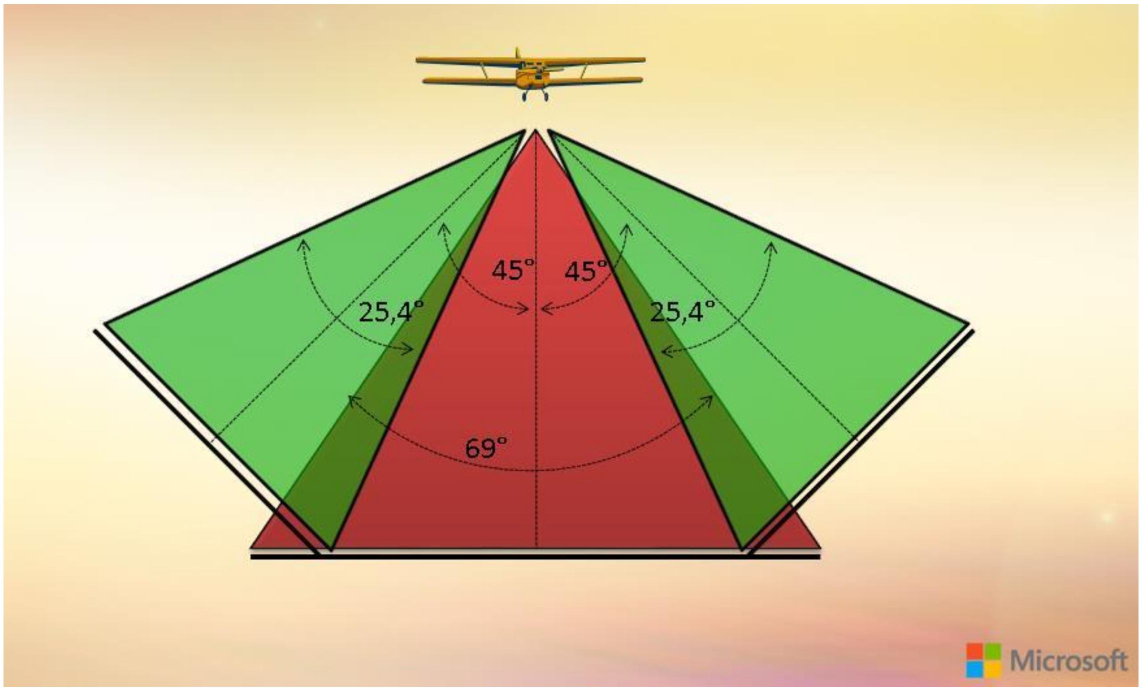



**Figure 1.9. Plan view of overlaps between vertical and oblique images for Vexcel Osprey camera**

The UltraCam Osprey camera for example, is designed with overlaps between the oblique and nadir images (Figure 1.9). All cameras are mounted rigidly on the platform with photogrammetric grade accuracy and are calibrated with respect to geometry and radiometry. These cameras are relatively new and therefore their applications are still being developed.

### 1.4 High Spatial Resolution Pushbroom Satellite Sensors

The design of satellite sensors is based on their specific purpose, but the recently developed so-called 'high spatial resolution' satellites are based on pushbroom sensors. They have resolutions or ground sampling distances (GSD) varying from about 2.5 m to about 0.3 m. Usually they detect both panchromatic images, which are black-and-white and cover the whole of the visible spectrum at the highest resolution, and up to 8 multispectral bands that have a GSD of 3 to 4 times larger than the panchromatic images. Stereo images are usually acquired by tilting the satellite forward and backwards during orbit. Most of these satellites are referred to as 'agile', since they can also acquire images by tilting sideways. Hence these satellites can acquire images within a day or so over anywhere on the earth. Typical currently available satellites with their respective ground sampling distances (GSD) are:

- IKONOS II (USA) launched in 1999 with 0.80 m panchromatic images and 3.2 m multispectral images
- Quickbird (USA) launched in 2002 with 0.60 m panchromatic images and 2.4m multispectral images; it is but now no longer operating but archive images are available
- WorldView-1 (USA) launched in 2007 with 0.50 m panchromatic images only
- CartoSat2B (India) launched in 2007 with 0.8 m panchromatic images
- GeoEye 1 (USA) launched in 2008, with 0.41 m panchromatic images and 1.65 m multispectral images

- WorldView-2 (USA) launched in 2009, with 0.4 m panchromatic images (originally supplied at 0.5 m resolution but currently available at 0.4 m resolution) and 1.85 m multi-spectral with 8 bands
- PLÉIADES (Europe) launched in 2011 with 50 cm Panchromatic and 2 m multi-spectral
- WorldView-3 (USA) launched in August 2014 with a GSD of 31 cm and 1.3 m multispectral.
- Terra Bella (formerly Skybox and now owned by Google) series of 21 satellites of which 2 are currently in orbit and all planned to be launched by end 2017. The satellites acquire panchromatic and multispectral images with <0.9 m spatial resolution and 1.1 m spatial resolution video images.
- Planet labs with over 100 microsatellites called 'Dove', with 3-5 m spatial resolution acquiring RGB using commercial grade CCD sensors. Their claim: 'In 2016 Planet Labs will have enough satellites in orbit to image the entire globe, every single day.'
- Urthecast has a sensor mounted on the International Space Station (ISS) can provide medium and high resolution imagery, with up to 75 cm pansharpened imagery available as well as video data.

The geometric processing of images from these satellites requires different procedures as will be described later.

### 1.5 MultiSpectral Sensing

Since the CCD technology used in pushbroom sensors is unable to detect electro-magnetic wavelengths longer than about 0.9 µm, other technologies and sensors are required to detect multiple bands with longer wavelengths for extraction of semantic information for remote sensing applications. These systems are referred to as either multispectral or hyperspectral sensors and usually described as 'whisk-broom' sensors although the designs of commercial satellites are 'commercial-in-confidence'. They are usually based on an optical scanning system, comprising a rotating mirror for aerial sensing and an oscillating mirror for satellite systems.

A typical configuration of these systems is based on either:

- **Across-track scanners** scan the Earth in a series of lines using a rotating mirror (A). The lines are oriented perpendicular to the direction of motion of the sensor platform. Successive scans build up a two-dimensional image of the Earth´s surface. The incoming reflected or emitted radiation is separated into spectral components that are detected independently and dispersed into their constituent wavelengths. A bank of internal detectors (B), each sensitive to a specific range of wavelengths between 0.4 µm at the blue end of the visible spectrum, to about 15µm in the thermal region of the spectrum, detects and measures the energy for each spectral band and then, as an electrical signal, they are converted to digital data and recorded for subsequent computer processing. The width of the bands varies according to the system design and wavelength being recorded. They may be of the order of several µm for thermal sensors to as little as 1-2 nm for hyperspectral systems, which may detect and record hundreds of very narrow bands. The IFOV (C) of the sensor and the altitude of the platform determine the ground resolution cell viewed (D), and thus the spatial resolution. The angular field of view (E) is the sweep of the mirror, measured in degrees, used to record a scan line, and determines the width of the imaged swath (F). Because the distance from the sensor to the target increases towards the edges of the swath, the ground resolution cells also become larger and introduce geometric distortions to the images. Also, the length of time the IFOV "sees" a ground resolution cell as the rotating mirror scans (called the dwell time), is generally short which influences the design of the spatial, spectral, and radiometric resolution of the sensor.

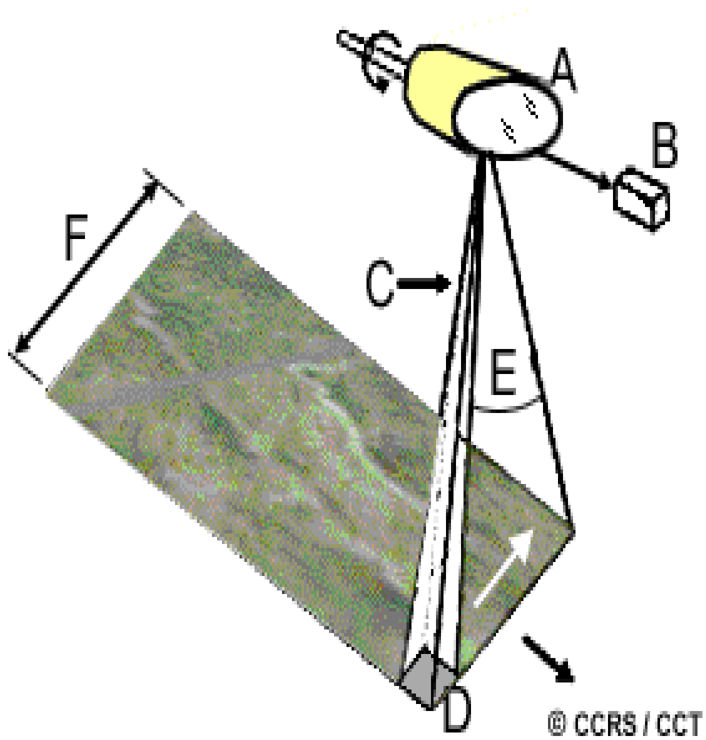



Figure 1.10  Multispectral Scanner Using a Scanner Mirror

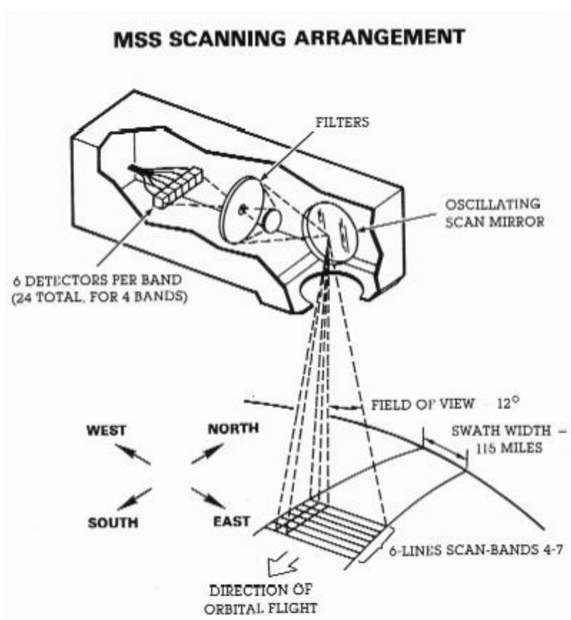



Figure 1.11  Oscillating mirror scanner used in Landsat satellites

- Satellite systems, such as a number of Landsat satellites, are usually based on an oscillating mirror as shown in Figure 1.11. The swath width of an oscillating mirror scanner can be limited to 100 km or so, based on small rotations of the mirror, and hence is preferred over a rotating mirror which would record a very large part of the globe from space.

### 1.7 Radar Sensors

Airborne or spaceborne imaging radar sensors are active microwave remote sensing systems which emit radiation from an antenna, and record the time of transmission for the radiation to be returned to the antenna. They primarily measure angles and distances based on the time of travel the reflected radiation, T. The radar beam is emitted sideways from the platform, approximately normal to the direction of flight, at an inclination to the horizontal, as shown in Figure 1.12.

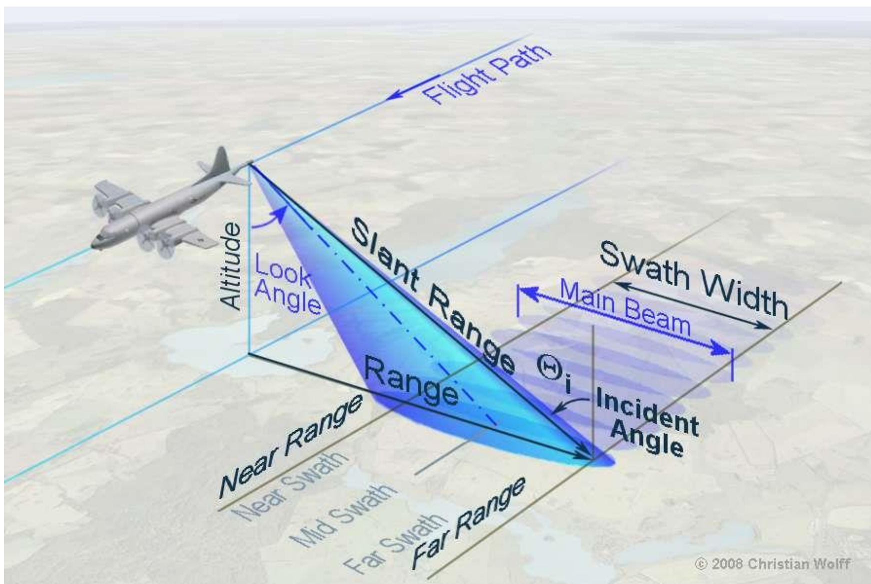



Figure 1.12 Data Acquisition by Radar System

The range, R, is therefore derived from the formula:

$$\mathbf{R=cT/2} \qquad (1.2)$$

where c is the velocity of the electro-magnetic radiation in the atmosphere. The range resolution, at right angles to the flight direction, is a function of the *pulse repetition frequency* (PRF) of the radar signal transmission. The azimuth resolution, in the direction of flight, is a function of the length of the antenna. To achieve a small azimuth resolution of the image, it is necessary to use an extremely long antenna (several km). A *synthetic aperture radar*, or SAR, overcomes this problem of achieving a suitable spatial resolution in the azimuth direction by synthesising a very long antenna, by processing the reflected signals that are acquired as the platform progresses. The azimuth resolution of SAR images can be shown to be approximately equal to d/2, where d is the actual length of the antenna on the platform. This means that the resolution of the images will decrease ie, improve as the antenna decreases in size. In addition, the azimuth resolution is independent of the elevation of the platform and the frequency of propagation. The limits of azimuth resolution are constrained, because the complexity of the radar system. Data storage and processing requirements all increase with increasing range and wavelength, while power requirements increase sharply as the antenna decreases in length.

Radar images are affected by geometric errors, which are functions of the combination of the elevation angle of the signal and variations in the elevations in the terrain. These errors are layover, foreshortening and shadow, as shown in Figure 1.13. Layover is caused by the imaging characteristics of radar, since ranges (distances) are measured from the antenna to the terrain. Elevated points are closer to the antenna than points below them and these points will therefore be imaged closer to the nadir point in the image. This effect will increase as the elevation or look angle of the emitted radiation decreases. Foreshortening will occur when slopes in the terrain facing the antenna are compressed in size due to the effects of layover. Shadows are image voids caused by certain areas being hidden from the radar beam, because of the intervening terrain features. In addition to errors caused by terrain elevations, the continuous process of data acquisition of SAR data will result in geometric distortions caused by variations in the platform attitude during flight.

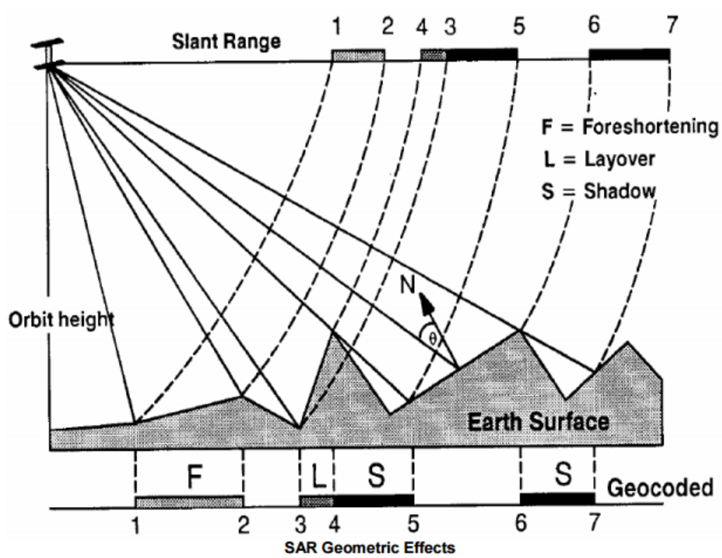


Figure 1.13 Geometric Distortions in SAR Data

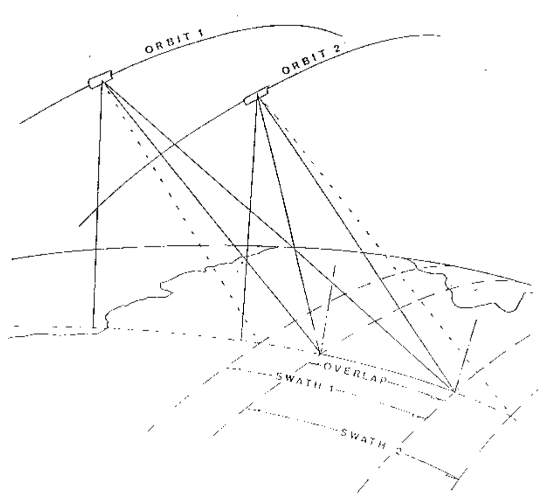


Figure 1.14 Same–side data acquisition for stereo observation of radar images

### 1.7.1 Overlapping Radar Images

Overlapping images for elevation computations are derived by the acquisition of two parallel passes as show in Figure 1.14, which demonstrates the so-called 'same-side' stereo configuration. That is, the antennas view the terrain from the same side of the platform. Opposite side configuration is also possible but there are limitations in the suitability of this configuration for computation of elevations because of the large geometric distortions as described above. The accuracy of elevation computation from overlapping radar images is usually poor. A more accurate method being developed is referred to as interferometric radar.

### 1.7.2 Interferometric SAR (InSAR and also referred to as IfSAR)

A SAR image of a scene comprises amplitude and phase information. In Figure 1.15, two antennas $A_1$ and $A_2$ with a baseline length B, record the echoes of the signal emitted by one of the antennas. The range distance from an illuminated point on the ground to antenna $A_1$ is r, while $r + \delta r$ is the distance to antenna $A_2$ from the same point. The difference in phases in wavelengths, between the signals received at the two antennas can be used to determine the difference in range $\delta r$ and hence terrain elevations with high accuracy. After registering the two images, the phases are calculated and differenced on a pixel by pixel basis, resulting in a phase difference image or interferogram.

Accuracies of elevations determined by interferometric SAR depend on the parameters of the radar system and can be better than 0.5 metre for low wavelength airborne radar systems. Accuracies of the order of several metres are achievable with spaceborne systems. An approach called differential InSAR is based on the acquisition of SAR images in two or more epochs and can be used for monitoring small changes in elevation, such as those that occur due to earthquakes and mine subsidence. Accuracies of differential InSAR can be of the order of 1 cm, even when the images are recorded from space.

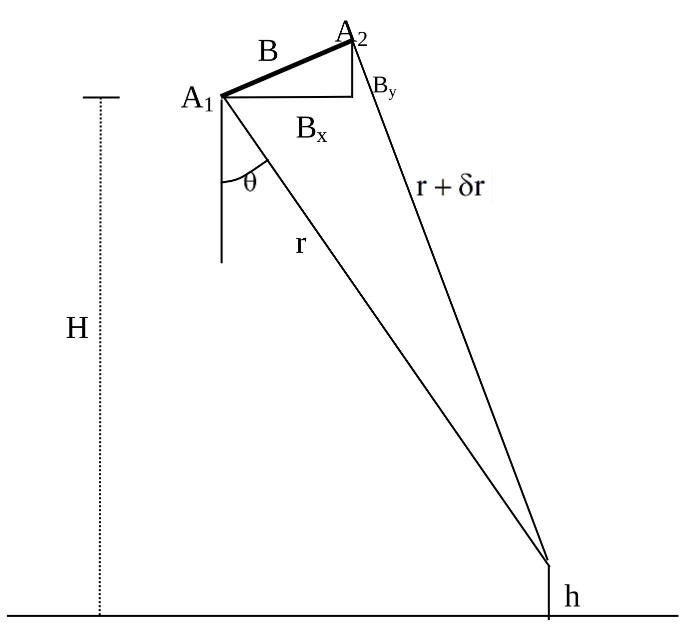



**Figure 1.15 A schematic diagram of InSAR.**

## 1.8 Airborne Lidar or Airborne Laser Scanning (ALS)

In airborne lidar (**Li**ght **D**etection **A**nd **R**anging also written as LiDAR) or airborne laser scanning (ALS), a laser scans the terrain surface normal to the flight direction of an aircraft AS SHOWN IN Figure 1.16. The measured distance from the aircraft to visible points on the terrain surface will enable the position and elevation of points to be determined. A lidar system includes the following equipment:

- The laser scanning normal to the flight direction for which the range to the object and rotation angle of the scanner are determined
- GNSS equipment to determine the location of the aircraft based on kinematic measurements
- IMU to continuously determine the tilts of the aircraft.

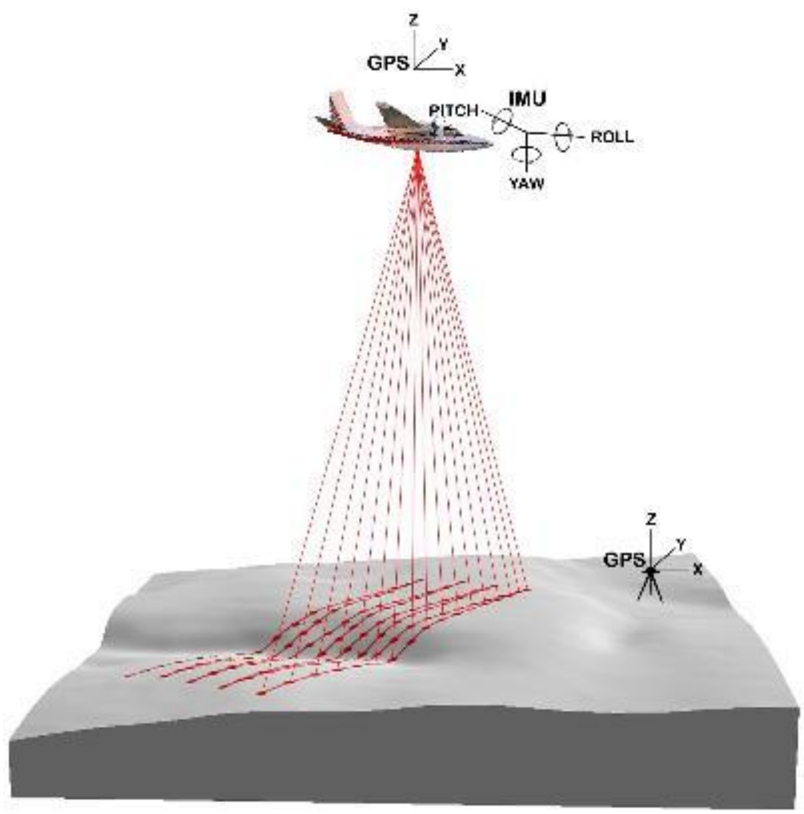



**Figure 1.16 Airborne lidar system**

Lidar systems acquire a dense set of elevation posts (XYZ coordinates), referred to as a *point cloud*, at a separation typically of 1 m or less for modern lidar systems, that represent a digital surface model (DSM) of the visible terrain, that is, objects such as buildings and trees, but also the terrain surface if the laser beam penetrates the vegetation. The accuracy of the elevation posts is of the order of 10-20 cm, although tests have shown that accuracies of interpolated hard surfaces better than 5 cm are achievable. The separation of the posts will depend on the configuration of the lidar equipment and the scanning frequency, which is increasing as the systems are developed further. This technology is also referred to as 'linear lidar' to differentiate them from single photon lidar (SPL) and Geiger systems as described below.

Some lidar systems can register multiple returns or echoes of the laser beam, but most systems will register, as a minimum the *first* and the *last pulses*. For example, if the laser beam hits a tree, a part of the laser beam will be reflected by the canopy, resulting in the returned signal being registered by the sensor as the *first pulse*. The rest of the beam may penetrate the canopy and, thus be reflected from further below the top of the tree, maybe even by the soil. The *last pulse* registered by the sensor corresponds to the lowest point from which the signal was reflected. In certain cases, the difference in elevation between the first and last pulses can be assumed to measure the heights of trees or buildings.

Along with the time of transmission of the signal from the sensor to the terrain and back to the sensor, the *intensity* of the returned laser beam is also registered by lidar systems. Lidar systems typically operate in the infrared part of the electromagnetic spectrum and therefore the intensity can be interpreted as an infrared (IR) image. However, this intensity image is usually under-sampled and thus very noisy, because the footprint of the lidar is about 0.3 m-0.5 m and the average sampling point distance is 0.3 m to 1 m apart. As well as the laser data, images of the terrain surface may also be recorded by a separate medium or high resolution digital camera. These images may be used to identify the location of points on the terrain surface. The combination of colour and the IR as multi-spectral images can provide valuable information for information extraction of the terrain surface. Multi-spectral lidar systems have now been developed incorporating 2 or 3 lidar beams with different wavelengths.

Technological advances have resulted in new systems being developed, referred to as single photon lidar (SPL) and Geiger systems, which enable the collection of data with much higher point densities. They offer better use of the photons generated by the laser source, resulting in a dense point cloud from the same or a less efficient laser source. These systems are not available on the market year, but they are likely to be available in a year or so.

Typical applications of lidar data may include:

- DEMs of the bare earth surface
- Beach erosion studies
- Infrastructure analysis
- Flood risk analysis, flood simulation, and drainage design
- Ground subsidence
- Visibility analysis
- Telecommunications planning
- Noise propagation studies
- Volume change monitoring
- Buildings extraction for 3D city models
- Forest analysis

The economics of lidar equipment require it to be used over large areas, and hence GBytes of data are likely to be acquired in a single mission (250,000 points may be recorded in a few seconds). Therefore, it is essential that automatic processes are developed that enable the extraction of information from the lidar data. There are described in more details later in these notes.