Sightline Control Basics for Geo-Pointing and Locating - Part 3

by

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Sightline Control Basics for Geo-Pointing and Locating Part 3

A SunCam online continuing education course

<u>Introduction:</u> This final part of the course addresses camera sensor characteristics and requirements for geo-location as they relate to image geo-registration described in Part 2.0 section 4.0. Initially a quick review of sightline control (SLC) and geo-pointing is provided as this still remains an essential function for collecting image scene data. The remainder of Part 3.0 describes camera types, performance parameters, camera scene geometry requirements for scene coverage and resolution.

1.0 <u>Geo-pointing [1,2, 3]</u>

Accurate pointing, detailed in Parts 1.0, 2.0, provides the means to geo-locate or estimate the geographic location of an objects position by determining its geographic coordinates. Precision pointing and enhances the fidelity of the sensed image, improving image quality for image registration and geo-location as required to extract feature information. Pointing requires establishing a line of sight (LOS) to a scene reference and stably controlling that LOS until scene image data is collected. A process termed sightline control. A few paragraphs describing SLC from previous parts of the course are provided as a reference for this part.

The line of sight is defined as a vector between points on an observation platform and an observed target location in a North-East-Down (NED) reference coordinate frame as defined in Parts 1.0, 2.0 of the course. Figure 1.0 illustrates a typical pointing scenario.

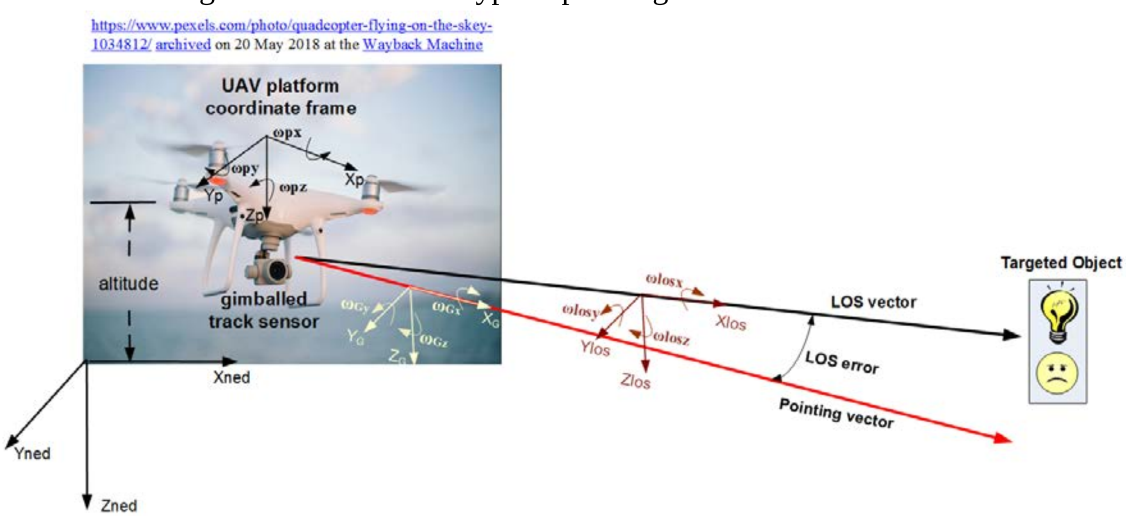

Figure 1.0 LOS Pointing Geometry

The optical sensor, the topic of this section, is required to maintain a target track providing its relative location based on a performance accuracy requirement. Sensors are aligned to the inertial stabilization sensor reference establishing the sightline or bore-sight within a gimbal structure capable of rotating about multiple axes. The gimbal is mounted to a stationary or moving platform. Sightline control (SLC) can be considered *a two part problem*:

- (1) LOS Point/Track: LOS pointing based on sensor performance over a specified the LOS platform to target kinematic envelope. It must meet pointing accuracy required for tracking and accurate location of a target
- (2) LOS Stabilization: LOS stabilization isolates the sensor from platform motion to stabilize the operating environment; rejecting disturbances due to platform motion to achieve the desired track/pointing accuracy. The control system isolating the sensor LOS vector from angular motion is: Stabilizing the LOS

Pointing error is the difference between the actual LOS orientation and the sensor pointing vector to the target. Error is a function of inherent sensor pointing error, platform motion/vibration residual error, and often the atmosphere. Error sources are characterized in the 'error budget' with platform motion ('own ship motion') often driving performance.

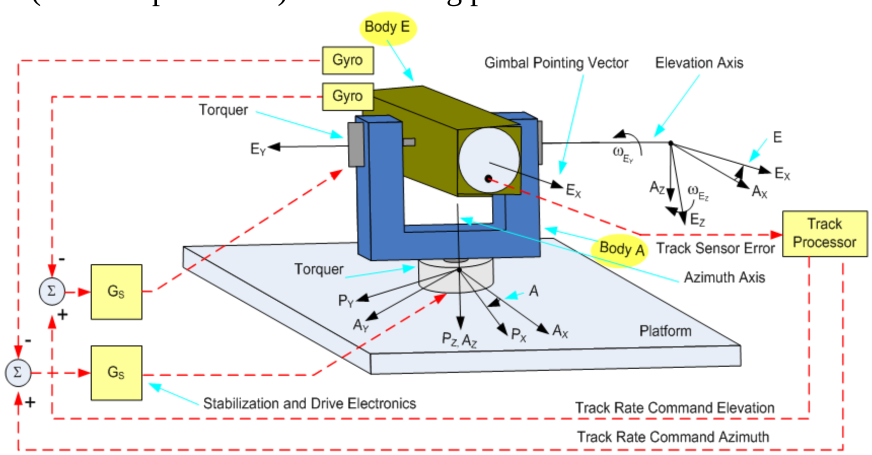

Figure 2.0 Simple 2-axis Elevation over Azimuth Gimbaled Track Sensor Geometry

Figure 2.0 illustrates a simple two axis elevation over azimuth (el/az) gimbal design. This gimbal geometry was discussed in Parts 1.0, 2.0 of the course. It is provided again to illustrate a typical gimbal used to point a camera, whose characteristics are discussed in this section as they apply to geo-location scene coverage and image collection. Geo-location position is defined based upon the latitude and longitude coordinates of a particular location. It may be enhanced further by cross referencing or mapping it to another type of address information depending on the application. Geo-location a point-like object is referenced to the location and orientation of a pointing platform. The geo-pointing vector for location will require several coordinate frames of reference as described in Parts 1.0, 2.0. For a geo-pointing application, one may assume the platform position is known and a targeted objects position at some known range needs to be determined. An optical sensor mounted on the platform may be used to determine target angular position relative to the platform if not known. The sensor is mounted on the 2-axis gimbal (as an example). The other major platform sensors are the gimbal angular position sensors, an IMU for stabilization, an INS for platform inertial orientation, and a GPS. The target location is initially measured in a sensor line of sight (LOS) frame, converted to a position vector, and rotated through a sequence of direction cosine matrices (DCM) to obtain its position in the common frame. For the example, a gimbal mounted sensor is secured to a vehicle and would have coordinate frames that define the: sensor, gimbal, platform body, local surface referenced north east down, and finally the geo-location frame. The most often used geo-location frames are earth centered earth fixed (ECEF) and earth centered inertial (ECI). The ECEF frame is used more often for representing position and velocity of terrestrial objects while ECI for satellite applications specifying celestial objects location. *This course assumes ECEF coordinates and a set of coordinate frames*, often used, illustrated in Figure 3.0 as follows (see Parts 1.0, 2.0 for more definition):

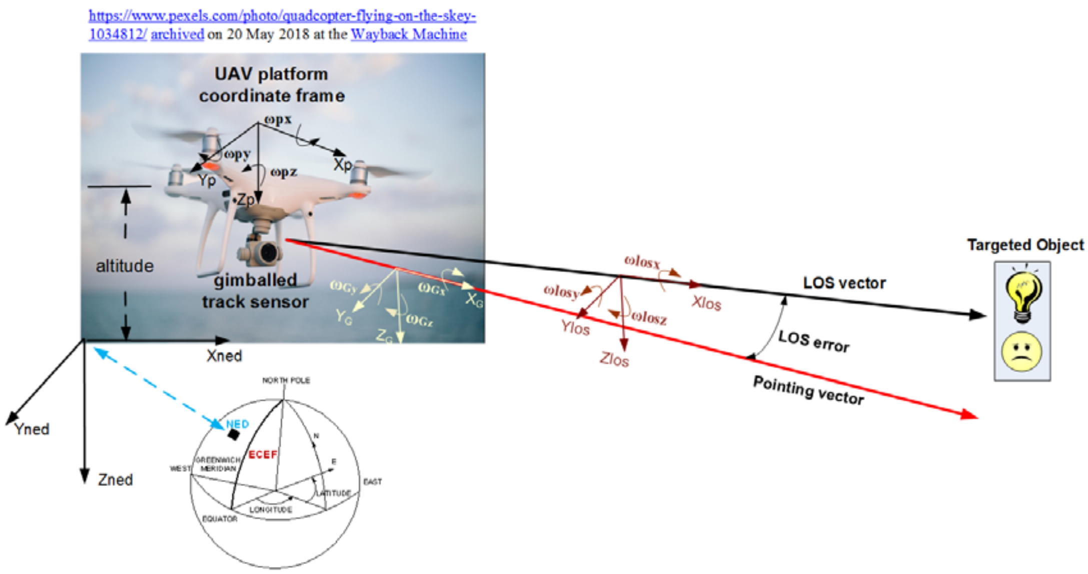

Figure 3.0 Typical coordinate frame geometry for geo-location

- Earth-Centered, Earth-Fixed (ECEF)
- North East Down (NED)
- Platform coordinate frame
- Gimbaled coordinate frame (configuration dependent)
- Line-of-Sight (LOS) frame

Using ECEF coordinates, an objects earth-centered location can be defined as a position in terms of latitude, longitude, and altitude relative to an ellipsoidal Earth model referenced to the World Geodetic System (WGS) 84 datum. The LOS coordinate frame defines the sensor bore sight relative to the LOS. With the sensor mounted on the inner gimbal structure, it is aligned to the gimbal axes. The gimbal frame defines the gimbal orientation relative to the platform body. The body coordinate frame is attached to the platform and often uses standard aircraft coordinates with the x-axis along the platform longitudinal axis, the z-axis pointing down orthogonal to the x-axis, and the y-axis oriented to complete a right handed coordinate system. The body coordinate frame is easily referenced to a north east down coordinate (NED) frame, sometimes referred to as a flat earth or local level model and in context of prior sections of this course was the inertial frame. An INS provides measurements relative to true or magnetic north (heading) and gravity (pitch and roll). The NED frame is then referenced to ECEF coordinates based upon latitude and longitude. For the example, with the gimbaled sensor configuration, the relative target position vector measured in the sensor LOS coordinate frame would rotate through the following sequence of 4 DCMs to obtain its orientation in the ECEF frame:

$$D\bar{C}M_{LOS}^{ECEF} = D\bar{C}M_{NED}^{ECEF}(\Phi_P, \Lambda_P) \cdot D\bar{C}M_{PLAT}^{NED}(\omega, \theta, \psi) \cdot D\bar{C}M_{GIMBAL}^{PLAT}(\alpha, \beta) \cdot D\bar{C}M_{LOS}^{GIMBAL}(\varepsilon x, \varepsilon y)$$

Angles are defined as follows:

- Platform GPS: Φ_P: geodetic latitude (WGS84), Λ_P: longitude (WGS84)
- Platform INS: θ : platform pitch , ω : platform roll , ψ : platform heading
- Gimbal Angles: α : azimuth (gimbal) , β : elevation (gimbal)
- Δx: measured sensor LOS x-target offset from center
  εx = pixel $\Delta x * IFOV_{sensor}$ (for a camera)
- Δy: measured sensor LOS y-target offset from center
  εy = pixel $\Delta y * IFOV_{sensor}$ (for a camera)

Each DCM is the product of two or three rotations defined as follow. The LOS will be referenced to a sensor. The geo-pointing problem is locating a target vector in ECEF coordinates, given a target range measurement. The target vector in ECEF coordinates is the sum of the platform position in ECEF coordinates plus the measured relative target position vector, or:

$$\hat{P}_{TGT}^{ECEF} = \hat{P}_{PLAT}^{ECEF} + range \cdot D\bar{C}M_{LOS}^{ECEF} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

The DCM is determined based upon the measured gimbal angles, INS, and GPS data. Range equates to distance. For a short distance between platform and target (flat earth model applies), measurable with a rangefinder or triangulation, range is often used. For longer distances dependent on the earth curvature, models that account for curvature and obtain distance from differences in latitude and longitude are required; as will be discussed. Platform position in ECEF Cartesian coordinates is obtained from the vehicle geodetic latitude, longitude, and altitude as described in Parts 1.0, 2.0 of the course. To obtain the ECEF angular coordinates of the target, longitude can be obtained as:

$$\Lambda_T = \tan^{-1}\left(\frac{P_{TGTX}^{ECEF}}{P_{TGTY}^{ECEF}}\right)$$

There is not a direct solution for geodetic latitude but it can be determined iteratively with an initial estimate as:

$$\Phi_T \approx \tan^{-1}\left(\frac{P_{TGTZ}^{ECEF}}{\sqrt{(P_{TGTX}^{ECEF})^2+(P_{TGTY}^{ECEF})^2}}\right)$$

There are also converters available on the internet that will do the x, y, z to latitude, longitude, and altitude conversion such as: https://www.mathworks.com/matlabcentral/fileexchange/7941-convert-cartesian-ecef-coordinates-to-lat-lon-alt. However as this is obtained from an iterative estimate there will be an associated error. Geo-pointing error, due to several sources, must be compensated. In general, the geo-pointing errors or deviations can be categorized as those:

- associated with the measured angles in the DCM sequence due to the gimbal/platform ***sensors*** , and
- associated with the platform location in ECEF coordinates caused by GPS location accuracy relative to the pointing vector.

The errors relative to the DCM, including sensor errors, relate back to the pointing bias and jitter error budgets described in Parts 1.0, 2.0 and can be summarized as:

- Gimbal Pointing Error Budget (see section 1)
    - ***sensor*** noise and accuracy
    - gimbal alignment related to the track sensor
    - gimbal angle (encoder, resolver, etc.) noise and accuracy
    - gimbal rotation axis alignment, orthogonality
    - IMU accuracy and measurement noise (scaling, resolution, ARW, drift)
    - In general see section 1.0 pointing jitter and bias error budget
- INS accuracy and measurement noise
- GPS latitude and longitude angle errors
- INS to gimbal alignment (discussed below)
- INS to IMU alignment (discussed below)
- Quantization
- Measurement timing latencies, different sample rates relative to each sensor

A metric is required to evaluate position accuracy. As error sources with the greatest effect are predominantly random; a probability measure describing performance is useful. A simple measure of a systems locating accuracy is the circular error probable (CEP) geo-location error. This is the radius of a circle, centered on a mean, whose boundary defines the region in which a pointing estimate falls 50% of the time or effectively the median error radius. The mean offset relative to the actual targeted point is the bias. CEP is a metric used when measuring the accuracy of a position obtained by a GPS navigation system.

As discussed in Part 2.0, improved geo-location accuracy is possible using geo-registration to a geo-referenced image. This shifts the burden of precision pointing from the inertial angle and rate sensors to image registration between a sensed and geo-referenced image. Image geo-registration still requires inertial sensors for coarse pointing but with less precision which translates to much less SWaP and cost. The geo-registration approach requires a camera sensor with performance characteristics capable of meeting the geo-location requirements as described in the next section.

Section 1.0 Key Points Summary

- ***SLC two part problem: (i) LOS Track/Point and (ii) LOS stabilization***
- ***Performance defined by geo-pointing sensor accuracy requirements***
- ***Definition of key coordinate frames provided; geo-location frame is ECEF***
- ***The DCM sequence between ECEF coordinates and LOS coordinates is shown***
- ***Pointing angles between two geo-referenced locations, platform and target are determined from geo-pointing vector***
- ***Disturbances are described; jitter and bias associated with pointing plus the addition of inertial positioning errors***

2.0 Geo-location (see Part 1.0, 2.0 Ref)

This section focusses on sensor requirements for geo-locating using image geo-registration. The method requires the alignment of a sensed frame of image data with a geo-located (latitude, longitude, and elevation based) calibrated reference image. Aligning a sensed image of even a small region with a geo-referenced map may provide more accurate geo-location than attainable with a geo-pointing system alone. Similarly the information within the image may be of significant value so image quality beyond that required for registration could be critical. Sensor characteristics and requirements for image geo-registration critical for performance are described in more detail.

2.1 Geo-location Geo-Registration Architecture and Sensor Requirements (see Part 2.0 Ref)

There are two general geo-location geo-registration techniques; (i) direct geo-registration and (ii) image geo-registration. Direct is effectively the geo-pointing problem described in Parts 1.0, 2.0 of the course and requires *navigation grade inertial sensors*. Image geo-registration compares a sensed image with a precision geo-referenced image of the same region. This method is a significant part of many geo-location algorithms and the discussion will focus on the sensors required to implement this method. The image processing requirements are generally intensive and can vary significantly depending on the available amount of a priori information; often dependent on the application. Processing usually consisting of several steps which in general fall into some form of feature and/or image correlation processing algorithm(s). The platform size can constrain the sensor and pointing architecture limiting data quality and quantity. Large platforms, are less constrained, and can carry payloads with high precision inertial sensors, high resolution cameras and multi-axis pointing gimbals. A small UAV may have a payload capacity for only a small low resolution camera and tactical or less grade inertial sensors. Application requirements will drive the choice of the camera sensor with performance characteristics chosen based upon:

- Sensor type and performance characteristics
    - FOV
    - Resolution (defined by FOV and pixel or line density)
    - Exposure time and frame rate
    - spectral band
- Sensor Data Acquisition and Storage
- Sensor Data Rate and Processing
- Sensor LOS Control; pointing and stabilization (platform motion/vibration)
- Processing requirements

Spectral band will dictate the type of camera sensor used as follows:

- Visible (VIS) and near infrared (NIR) (0.38um-1um) applications generally use a silicon based material structured as either a:
    - *charge coupled device (CCD) or*
    - *complementary metal oxide semiconductor (CMOS) sensor*.
- Short wave infrared (SWIR) (1um-2.9um) detectors are mostly indium gallium arsenide (InGaAs)
- Mid-Wave infrared (MWIR) (3um-5um) are either indium antimonide (InSb) or mercury cadmium telluride (HgCdTe)
- Long wave infrared (LWIR) cameras are
    - HgCdTe photoelectric sensor arrays
    - Thermal micro-bolometers temperature sensitive amorphous silicon, vanadium oxide

Specialty sensors such as hyper-spectral imaging sensors, high resolution mega-pixel cameras, synthetic aperture radar (SAR), and LIDAR are also used in geo-locating applications. Large airborne platforms can accommodate precision inertial and optical sensor suites. They will generally use a fully stabilized gimbaled pointing system to direct the sensor field of view. Inertial scanning techniques, used with either geo-registration method, are also of critical importance in terms of matching the scan pattern and rates with the FOV coverage required for geo-location. FOV requirements as they relate to coverage and resolution will be described. For image geo-location, visible and NIR sensors are often used. The two main technologies used for the image sensor are CCD (Charge-coupled Device) and CMOS (Complementary Metal-oxide Semiconductor). Discussions that follow will focus on these detector types. The visible or NIR irradiance from a scene is captured by the camera lens optics, focused and directed onto an image sensor consisting of picture elements, or pixels that convert photons into electrical signals. The photoelectric sensing elements collect the light intensity, capturing photons within an intrinsic region of a p-type and n-type semiconductor sandwich structure. This results in the formation of charge carries or electron hole pairs within an intrinsic region; with the number of electrons created proportional to the number of photons absorbed. The electrons are converted into a voltage read by an analog to digital (A/D) converter which generates an equivalent digital number processed by the camera. The basic design and tradeoffs between the CCD and CMOS type sensors are discussed in the sections that follow. It is important to note that sensor noise and resolution all flow back to the pointing error budgets described in previous parts of the course which ultimately impact image quality.

2.2 CCD versus CMOS Sensor Technologies [4, 5]:

CCD Technology [5]: The light or photons captured by a CCD pixel sensor surface are converted to electrons (charge). Each pixel sensor is configured as a p-doped metal oxide semiconductor (MOS) capacitive element which stores the electron charge; effectively a capacitive well acting as a storage node. A line of pixel nodes terminate at an amplifier. With each update, charges shift one node closer to the amplifier, until a charge is amplified and output. The charges are converted to analog voltage levels, buffered, and finally converted to numbers using an A/D-converter external to the sensor. This process continues until all lines of pixels have had their charge amplified and output. The CCD technology was developed specifically to be used in cameras. Traditionally, CCD sensors have lower noise and higher-quality images, particularly in low-light conditions, compared to CMOS sensors. They also have had the advantages of greater sensor dynamic range, higher resolution and light sensitivity. In recent years, many of these differences have been significantly reduced as CMOS technology has advanced. CCD sensors require more electronic circuitry outside the sensor, are more expensive to produce, and can consume much more power than CMOS sensors. CCD sensors also require a higher data rate, since signals go through just one output amplifier, or a few output amplifiers.

CMOS Technology [4]: CMOS sensors convert pixel photon measurements to electrons on the sensor. All pixels measurements are processed simultaneously. *An amplifier within each pixel results in a smaller, faster and more flexible sensor*. Having an amplifier in each pixel, compared to the few amplifiers of a CCD, causes some blockage resulting in less photon capture area. This problem is resolved using micro lenses in front of each pixel that focus the light onto its photodiode so it is not blocked by the amplifier. Some CMOS imaging sensors also use back-side illumination to increase the number of photons collected by the photodiode. CMOS sensors can potentially be implemented with fewer components, use less power, and provide faster readout than CCD sensors. Modern CMOS sensors use improved sensor technology increasing sensor quality and light sensitivity that enhances image quality combined with lower costs. This is driving the use CMOS-based cameras for many applications previously dominated CCD cameras. Due to CCD sensor frame rate limitations at high resolutions, this trend is likely to continue.

CCD vs. CMOS Comparison Summary [4, 5, 6]

- CCD cameras can provide high-quality low noise images, whereas CMOS cameras are more susceptible to noise and often require more light to generate a low noise image.
- *CCD cameras possess better light sensitivity and large effective imaging area so are better for low light conditions* than CMOS sensors due to partial blockage by amplifier circuitry, although micro-lenses and back illuminated designs tend to mitigate the issue.
- CMOS sensors have a faster readout and higher external noise immunity while consuming less power within a smaller area and system size.
- The CMOS chip incorporates all components to produce an image; detector, amplifier and A/D-converter, and are easily produced which lowers camera cost.
- CMOS sensor chips have better camera integration functions such as auto exposure, color encoding, and image compression although the addition circuitry can result in more structured noise.
- *CMOS sensors allow for individual pixels to be read so that 'windowing' of sensor area regions of interest can be read out*, rather than the entire sensor area, allowing for higher frame rates
- CMOS cameras are a good choice for a high-frame requirement since the CMOS image sensor has a very fast processing speed.

Key requirements for geo-location are wide dynamic range, due to the wide variation in ambient lighting, a high saturation level consistent with dynamic range, and a high signal to noise ratio (SNR). High frame rates can be an advantage in a dynamic platform environment. Specific requirements need to be evaluated relative to camera specifications when choosing the best camera for the geo-location application.

2.3 Camera Performance [4, 5, 6]

In Part 2 section 8 a camera performance model was described as being an important part of most image geo-registration processing algorithms. Extrinsic and intrinsic parameters were described that impact performance. Extrinsic referred to pointing and position angles associated with the LOS DCM while intrinsic referred to camera related parameters such as focal length and sensor offsets. This section goes into further detail on sensor parameters that impact geo-registration performance. Camera performance can be divided between camera sensor and optical system functions. As a sensor, parameters that drive sensitivity and noise at a pixel level are critical. These include quantum efficiency (QE), dynamic range, quantum well saturation, noise sources and signal to noise. As an optical system parameters include the system optics aperture, focal length, sensor size and pixel density, exposure time, fame rate and lens match to sensor geometry. This section provides brief descriptions of many of these parameters and the significance and tradeoffs required when applied to the geo-location problem.

2.3.1 Key Camera Sensor Characteristics [4, 5, 6]

As with any sensor, *the camera sensor for a geo-location imaging application should have as little noise as possible and high sensitivity to maintain a high signal to noise ratio (SNR*). Sensitivity and noise can also impact a platforms operating limits. More sensitivity equates to requiring less exposure time to measure a signal. This allows the platform to move at higher speed since there is less time for a scene to change, causing blur, during exposure. Noise relates directly to a camera's useable gain, as gain amplifies both signal and noise, lower noise allows for higher gain while maintaining image data integrity. There are several other performance parameters that need to be addressed in order to achieve a high SNR over a wide range of operating condition as occur when geo-locating from an airborne platform. A detailed discussion of sensitivity and noise follows.

• **Sensitivity:** A camera's absolute sensitivity threshold (AST) can be defined as the number of photons required to increase a pixel's value by one [8]. It is the lowest intensity signal detectable above the sensor noise floor. AST combines QE and noise providing a highly significant sensitivity metric of the weakest signal distinguishable from the noise read at the signal output; the lower the level the more sensitive the detector. Sensitivity can partitioned into conversion and collection efficiency.

- **Conversion**: A camera is effectively a photon detector. The pixels are photodiode detector elements that convert the photons to electrons producing an electrical charge. The charge generates a current or an equivalent voltage as the pixel output. *Quantum efficiency (QE_λ) is a measure the pixel photon to electron conversion efficiency* and is defined as the percent of photons converted to electrons at a specific wavelength by the sensor. Roughly the ratio of photons in to electrons out. Some sensors, especially single element photodiodes use a responsivity measure as a response metric. Responsivity (R_λ) is defined as amps/watt; practically a more measurable engineering quantity than photons and electrons. Effectively this measure converts incoming intensity (w/steradian) or irradiance (w/m^2) to photons per second based on the QE_λ of the detector to estimate electrons per second which is then converted to a current. *Quantum efficiency is proportional to responsivity* and related as:

$$R_\lambda = QE_\lambda \frac{\lambda \cdot q}{h \cdot c} \;\; ; \; \lambda\text{-wavelength(m)} \;\; ; \; q=1.6\times10^{-19}\text{coulambs}$$

$$\text{c-speed of light}=2.998\cdot10^{8}\,\frac{\text{m}}{\text{sec}} \;\; ; \; \text{h-plancks constant}=6.63\cdot10^{-34}\text{ Joule-sec}$$

- **Collection**: *The larger the size of the pixel, the more area to collect photons and therefore the more electrons generated*. If collection is defined at the camera aperture; than the camera optics transmission (primary optics as well as micro-lenses over a pixel) as well as the detector geometry (dead space between pixels) impact collection efficiency. *Note that as larger pixel size improves collection efficiency it reduces resolution, smaller is better,* so a tradeoff is required. Another improvement to collection efficiency is using a backside illuminated (BSI) pixel structure. Typically the light sensitive photodiode is located on the back side of the sensor, sitting behind the readout circuitry and sandwiched between the photodiode and the micro lenses used to direct light into the pixel. The BSI design inverts the layout of this pixel structure placing the photodiodes directly under the micro lens collecting photons more efficiently yielding a higher collection efficiency.

- **Other Improved Collection Methods**: There are high amplification designs that improve sensitivity. The intensified CCD (ICCD) uses an intensifier tube (photon multiplier) consisting of a micro-channel plate (MCP) in front of the CCD sensor to amplify the incoming signal before it reaches the CCD array. An electron multiplication CCD (EMCCD) uses a sensor with a read out register that amplifies the collected electronic signal using a process called ion impact ionization.

• **Noise and Clutter**: Noise sources that impact the sensor signal to noise ratio (SNR); a staple figure of merit for nearly all sensors, include:

- Shot noise (η_{shot})- Shot noise is inherent within the detector junction structure and a result of the discrete nature in the photon generated (electronic) signal (S). It is related to fundamental quantum physics of the photodetector. It is inherent with any signal and a dependent on the signal amplitude.
- Dark noise (η_{dark}) - dark noise is both thermal and time dependent. It is due to the thermally generated dark current from the electrons thermally generated within the pixel and is a function integration time as well as temperature. Cooling the sensor is an often used approach to reducing this as an issue.
- Readout noise (η_{RO}) - Read noise occurs with every camera image frame and is due to noise from the output electronics (amp and A/D converter). This noise is in the readout electronics and occurs prior to transmitting the digitized signal the processor. Slower readout rates and precision low noise clock pulses help reduce the noise.
- Clock induced charge noise (η_{CIC}) – occurring primarily in CCD sensors, it is generated when clocking pixels; moving the charge out of the sensor. Precision high resolution clocking pulses can reduce this noise source.
- Other noise sources - include sensor non-uniformity; pixel cross coupling, timing, and digital quantization. It is also of importance to note, that although most detectors have these noise sources there impact can vary depending on the detector spectral band; however as mentioned this discussion concerned with Vis/NIR cameras.

In general, system noise can be estimated as the RSS sum of these four noise sources. The sources are often represented as a current, as the photodetector response to an optical signal is normally a current. All noise and signals can also be converted to an equivalent readout signal. The signal current generated by a photodiode can be estimated as:

$$I_{\mathrm{PIX}} = \varepsilon \cdot \frac{\eta_\lambda}{K_{P\lambda}} \cdot \frac{QE_\lambda}{K_I} \cdot \tau_{\mathrm{int}} \cdot A_S \cdot \frac{A_{CAM}}{R^2} \cdot e^{-\alpha \cdot R}$$

ε-emissivity , α-atmospheric transmission constant (km^{-1})

τ_{int}-camera integration time (s) ; QE_λ-quantum efficiency

$K_{P\lambda} = h \cdot \dfrac{c}{\lambda}$; $\dfrac{\eta_\lambda}{E_\lambda}$ – photons per sec ; $K_I = 6.242 \cdot 10^{18}$ electrons/sec/amp

$\mathrm{A}_{\mathrm{CAM}}$-camera aperture area ($\mathrm{m}^2$), A_S-source area (m^2), R- range (m)

η_λ-integrated spectral radiance weighted by atmosphere

$$\eta_\lambda = \int_{\lambda_L}^{\lambda_U} \eta_\lambda \cdot \mathrm{D}_\lambda \cdot \mathrm{TA}_\lambda \cdot d\lambda \ (\mathrm{W/sr\text{-}m^2})$$

spectral transmittance (TA_λ) and detector response (D_λ)

The scene spectral radiance can be due to many sources within the camera FOV. In the visible, reflection is often the most dominant source but there may also be emitting sources within the surface. A rough estimate of SNR, in terms of current, is given by:

$$SNR \approx \frac{I_{PIX}}{\sqrt{\eta_{SN}^2 + \eta_{DN}^2 + \eta_{RO}^2 + \eta_{CIC}^2}}$$

SNR is often measured in decibels (dB) or Bits and the higher the signal to noise usually means the better the system performance for nearly all sensor based systems. This is a dynamic metric and the ratio of the measured signal to the measured noise and often used in systems to adjust threshold and gain values. A maximum value for a system is defined as the maximum signal level to maximum noise level or effectively the ratio between the signal at saturation and the noise at saturation. For a SLC tracking system, high SNR levels generally translate to excellent tracking performance and for imaging high SNR yields better contrast and clarity, as well as improved low-light performance. Another major signal detection issue is clutter as it relates to extracting scene features. For the geo-location problem, clutter is really scene features not pertinent to image registration; large scene areas that reduce contrast relative to desired features. Clutter for this problem is generally removed by spatial filtering as was discussed in Part 2 section 4 of the course.

When comparing sensors, it is important to consider multiple performance criteria. Image sensors are designed to balance trade-offs, and relying on a single metric can result in poor overall performance if other important criteria are ignored. A description of other camera parameters that impact performance follows.

Saturation Capacity: As a pixel photodiode can hold only a finite amount of charge, this is a measure of the maximum amount of charge it can hold. A higher saturation capacity equates to sensor capable storing more electrons and capturing a wider range of intensity. Generally, the larger the pixel surface area, the greater the saturation capacity. At saturation, additional photons entering a pixel will not result in a further increase in intensity recorded by the pixel. A small saturation capacity may also limit dynamic range.

Dynamic Range: Dynamic range is a metric that defines the range of magnitude over which a sensor can measure a signal. A higher the dynamic range is generally better. It is the ratio of the maximum detectable signal at saturation to the minimum signal the sensor can measure. A high dynamic range enables a sensor to measure a signal over a wide range of ambient lighting condition, capturing spatial detail in shadows or shaded areas as well as highly illuminated conditions. It is important in geo-location for image fidelity and feature extraction.

Gain: Gain on a CCD camera is the conversion factor between electrons to digital counts, or equivalently Analog-Digital Units (ADUs). It is the number of electrons necessary to induce a bit or count change in 16 bit ADUs or increase a 16-bit greyscale pixel value to one value higher. Gain is expressed as the number of electrons that get converted into a digital number, or electrons per ADU (e-/ADU). Sensors with higher gain are more sensitive so a high gain is useful for detecting very weak signals in low light conditions.

Bit Depth: The bit depth of a camera indicates the numerical resolution to which each pixel is capable of measuring. It is effectively the pixel's quantization level as well as associated quantization noise. Bit depth requirements are dictated by the system's design. For airborne platform measurements of a scene image, usually more than 8-bits are required to obtain better intensity resolution for image feature extraction.

Exposure time, Frame Rate, and Shutter types: Exposure time is the time interval during which the targeted scene is exposed to the camera sensor. Frame rate is the frequency with which a scene image is recorded. Exposure time cannot exceed the frame time, so one parameter limits the other depending on the image collection metric considered. A shutter controls the exposure time. Long exposure times necessitate low frame rates while short exposure times accommodate high frame rates. There are two main types of mechanical shutters, rolling and global. Global shutter sensors have the readout circuitry on each pixel; as with a CMOS sensor, enabling every sensor pixel to be read simultaneously. Rolling shutter sensors read each row out sequentially; as with a CCD sensor. In general, a global shutter is essential when imaging from a moving aircraft as they can capture moving objects without distortion avoiding the image skew associated with a rolling shutter. With the rolling shutter sensor, objects in the camera field of view continue to move as the line by line readout is occurs. Objects are then in a different positon from line to line, dependent on the object speed which causes image distortion. Electronic shutters are used in many industrial grade cameras. They are beneficial to aerial imaging since their not susceptible to vibration causing image blur and with no moving parts are not susceptible to mechanical failures. In many longer wavelength cameras, exposure time is also referred to as integration time. This is often an adjustable camera control parameter. The camera's sensitivity relates directly to the camera exposure time and frame rate. For aerial geo-location applications, a more sensitive sensor allows for the shorter exposure times and higher frame rates. The exposure time is generally half the frame period. Higher frame rates can capture quality scene images in the presence of greater platform motion, so the higher rates allow for grater platform velocity without motion blur. A camera with high sensitivity and shorter exposure times allows more platform dynamics.

Resolution, Pixel Size, and Optical Format [7, 8]: Resolution, pixel size and optical format are inter-related parameters whose characteristics must be matched to achieve a required image geo-registration performance. Optical format is the physical dimensions of the image sensor; normally measured across the sensor diagonal. It defines the image circle diameter a lens must produce to completely illuminate the sensor. Sensors can have different aspect ratios with the same optical format. Increased resolution with the same optical format requires a decrease in pixel size. Smaller pixels of the same pixel architecture provide more resolution but will generally have less collection quantum efficiency and saturation capacity. As sensor size increases providing larger optical formats, normally the required lens assembly size also increases; accompanied by an increase in weight and cost. Matching the optical format of the lens and sensor is critical. A sensor with a smaller optical format will work with a lens for a larger optical format. However a sensor with a larger optical format than its lens will not. The lens image circle will be smaller than the sensor image circle leaving outer regions not illuminated. The ability of the optical system to resolve objects to a pixel level is important; dependent on its contrast and resolution performance. Typically a high contrast space between objects is desired for proper detection. Ideally optics should resolve a scene to detect a number of objects equal to half the number of sensor pixels (i.e. Nyquist limit). These factors are typically defined by the lens' Modulation Transfer Function (MTF). The camera optics focal length and aperture size will generally drive the size of the optics assembly; which could be significantly larger than the camera itself. The focal length divided by aperture size is referred to as the 'F' number. As wider apertures, allow more light, and shorter focal lengths, wider coverage, lower F numbers are often used for the scene image collection.

2.3.2 Key Camera Optics Geometric Factors [6, 7]

For a given optical sensor size, pixel count, and optics focal length, angular resolution and coverage are constant. Linear coverage will varies with range and altitude and linear coverage is most important for geo-location image geo-registration. Camera coverage is generally defined by the camera FOV. This is roughly the dimension of the camera sensor divided by the effective focal length of the optics. As many sensors are not square, there are often different x and y FOV. The diagonal dimension is used as a size metric. For geolocation, land area coverage and feature or control point resolution dimensions are most critical. The relationship between the camera sensor size parameters and the scene geometry are described in this section.

2.3.2.1 Camera FOV, IFOV Angular Coverage [6, 7]

There are several camera parameters important in geo-pointing and location. A few were mentioned as part of the camera model intrinsic parameters in Part 2 section 4. The camera will project an object in local coordinates onto the image plane of a detector housed within the camera. Several camera characteristics that need to be considered for image geo-registration were described in the last section. They could be divided into sensor response and geometric categories. The sensor response has been discussed, referring to the quality of the image sensed. Geometric are those that impact the region of coverage and ground sampling resolution and will be described in detail within this section. As with most performance parameters they are inter-twined and so there are always the inevitable tradeoffs. For simply pointing or tracking a feature or control point, the cameras total and instantaneous field of view are important. The nominal geo-location pointing and coverage geometry is illustrated in Figure 4.0. The camera optics will project an image of a scene within its FOV, considered the object, onto the sensor. *The total FOV depends on the camera sensor dimensions and focal length.* As the x, y sensor dimensions are not necessarily the same, the FOVx, FOVy vary accordingly. *The pixel FOV, or instantaneous FOV (IFOV) depends on the sensor pixel dimensions and focal length*. These can be estimated as:

$$\mathrm{FOV}_X \approx 2 \cdot a\tan\left(\frac{Ls_X}{2 \cdot FL}\right) \quad ; \quad \mathrm{FOV}_Y \approx 2 \cdot a\tan\left(\frac{Ls_Y}{FL}\right)$$

Ls_X -camera sensor x-dimension ; Ls_Y -camera sensor y-dimension

FL-camera optics effective focal length

$$IFOV \approx 2 \cdot a\tan\left(\frac{Lpix}{2 \cdot FL}\right) \quad ; \quad Lpix\text{-pixel size dimension}$$

These angle depend upon the optics focal length (FL) and the sensor and pixel dimensions. The IFOV defines the angular resolution of the tracker based upon the size of a pixel. For tracking an object, possibly a scene image feature defined for geo-pointing, it effectively limits track accuracy. For image geo-registration, the linear geometry derived from projecting the angular coverage on the ground are most critical and described next.

2.3.2.2 Geo-location Coverage and Feature Sample Size [6, 7, 8]

For geo-location the linear dimensions of the scene and scene features are most important; as discussed in Part 2 section 4. These are a function of the total FOV and instantaneous IFOV, just mentioned, as well as distance to the scene to be imaged. Distance in general is defined as the slant range, the distance from the scene to the camera aperture which is a function of altitude as well as ground distance. For geo-location, to minimize distortion generally the ground distance is small and the slant range will be mainly the altitude. This will be assumed for the remainder of the course discussion. The nominal geo-location pointing and coverage geometry is illustrated in Figure 4.0. The total FOV is within the yellow dotted line while the orange tan squares are the pixel IFOV whose size is based upon estimated feature size as will be discussed.

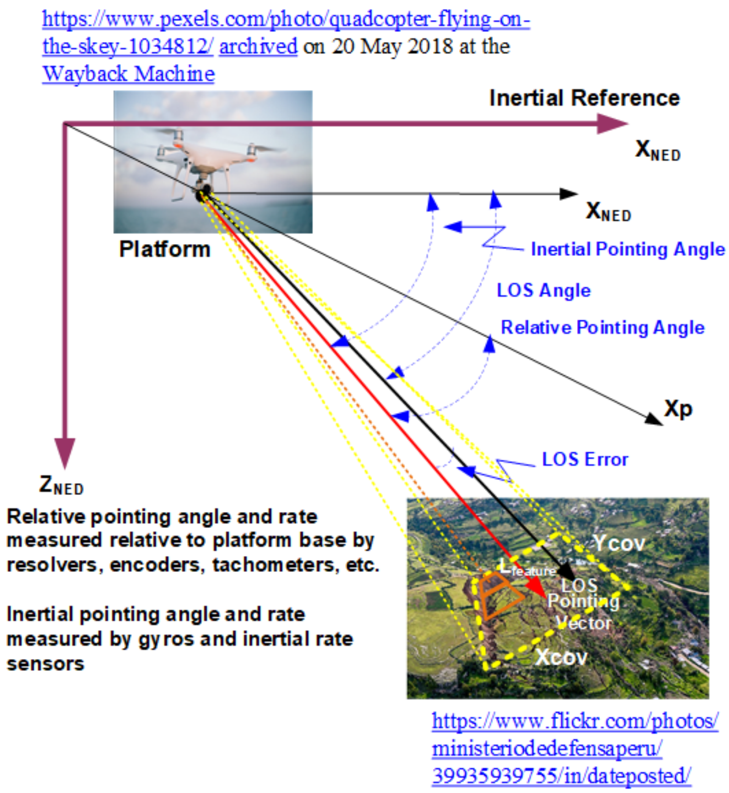

Figure 4.0 General Geo-location Operational Concept

The ground coverage geometry dimensions, illustrated in Figure 4.0, are a function of the altitude and the camera total FOV as:

$$X_{COV} = 2 \cdot altitude \cdot \tan\left(\frac{FOV_X}{2}\right) \quad ; \quad Y_{COV} = 2 \cdot altitude \cdot \tan\left(\frac{FOV_Y}{2}\right)$$

Using the formulas in the last section, then

$$X_{COV} = altitude \cdot \frac{Ls_X}{FL} \quad ; \quad Y_{COV} = altitude \cdot \frac{Ls_Y}{FL}$$

$$FL = altitude \cdot \frac{Ls_X}{X_{COV}} \quad \text{noting} \quad \frac{Ls_X}{X_{COV}} = \frac{Ls_Y}{Y_{COV}}$$

An initial estimate of the required FL can be obtained using the last equation. As sensor size decreases or increases, the required focal length will decrease or increase proportionally for the same coverage and altitude. As the required focal length increases, camera optics size will usually increase impacting SWaP. A larger FOV provides more ground coverage for a given data collection path, resulting in fewer less flights over an area to obtain geo-location data. This equates to less air time and associated cost. The IFOV defines resolution. The smaller the IFOV, the smaller the ground feature sampling resolution. However, a criterion is required to obtain sufficient spatial data of a feature to use for image geo-registration. The Johnson Criteria is often used to evaluate surveillance system performance. This criterion defines the image pixel coverage required for a 50% probability to detect, recognize, and identify a target. The Johnson Criterion (John Johnson was a scientist at the U.S. Army Night Vision & Electronic Sensors Directorate) is defined:

> **For Detection:** to have knowledge of the presence of an object the critical object dimension needs to be covered by 1.5 or more pixels.
> **For Recognition**: recognizing an object shape meaning the distinction between a person, a car, a truck or any other object. The object needs to be subtended by at least 6 pixels across its critical dimension.
> **For Identification:** to determine uniform (i.e. 'friend of foe), symbols, model type, or other identifying features the critical dimension of the object in question needs to be subtended by at least 12 pixels.

The criterion assumes high contrast conditions, good visibility, and neglects atmospheric turbulence. Using the identification criterion, it is assumed that a feature should be covered by at least 12 pixels to identify its spatial content. If the feature dimension is $L_{feature}$, then equating image and object geometry dimensions the desired pixel size needs to be roughly:

$$\frac{Lpix}{FL} = \frac{\frac{Lfeature}{12}}{altitude} \quad ; \quad Lpix = \frac{Lfeature}{12} \cdot \frac{FL}{altitude}$$

This pixel size will dictate ground sampling resolution and should be small enough to identify the feature spatial frequency or content. So small pixels provide for better resolution, but as described in the previous section they also reduce sensitivity impact exposure time and maximum flight speed. Given the pixel and sensor size, the pixel array size can then be estimated from:

$$NXpix = \text{int}(\frac{Ls_X}{Lpix}) \ ; \ NYpix = \text{int}(\frac{Ls_Y}{Lpix}) \ ; \ Npix = NXpix \cdot NYpix$$

Other parameters derived from these calculations are pixel density and coverage defined as:

pixel density: $DPix_X = \frac{NXpix}{X_{COV}} \ ; \ DPix_Y = \frac{NYpix}{Y_{COV}}$ pixels/meter

pixel coverage: $CPix_X = \frac{1}{DPix_X} \ ; \ CPix_Y = \frac{1}{DPix_Y}$ meters/pixel

It is generally assumed that the camera FL and sensor size are constant once the camera is chosen so that coverage and resolution variations depend on the geo-location geometry.

The ground sampling geometry is illustrated in Figure 5.0 showing the different parameters discussed.

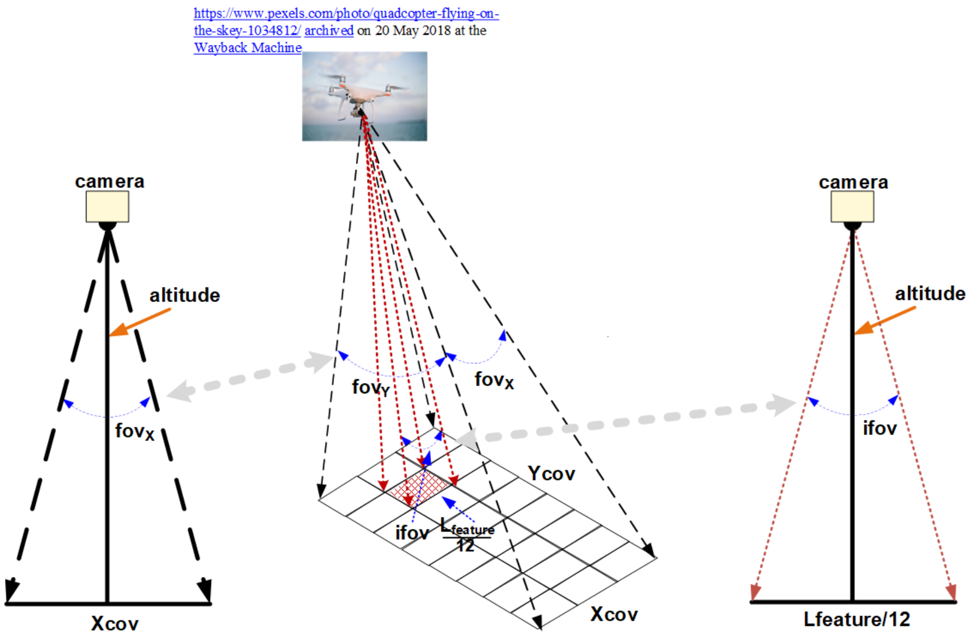

Figure 5.0 Ground Sampling Geometry

Some examples are provided to illustrate the analysis. It is assumed the camera FL and sensor size are constant once the camera is chosen so that coverage and resolution variations depend on the geo-location geometry. The focal length can be estimated based upon desired coverage and altitude as shown above. Once the FL is estimated, the required pixel size can be determined from the estimated feature size and number of pixels necessary to identify a feature. Finally one can estimate the number of detector pixels required. As an example, assume the parameters below and use the formulas derived; camera FOV total and IFOV as:

Given : Xcov = 500 m· : Altitude = 2000 feet = 609.8 m·

Lsx = Lsy = 1" =0.0254 m· : Lfeature =1 m

$$\textbf{Focal Length :} FL = 609.8 \cdot m \cdot \frac{0.0254 \text{ m}}{500\ m} \sim 31 \text{ mm}$$

$$\textbf{Pixel Size :} Lpix = \frac{1\ m}{12} \cdot \frac{0.031\ m}{609.8 \cdot m} = 4.24\ um$$

$$\textbf{Npix Size :} Xpix = Ypix = \text{int}\left(\frac{0.0254}{0.00000424}\right) = 6000 \quad ; \quad Npix = 36Mpix \text{ camera}$$

$$\textbf{Camera FOV :}\ fov = 2 \cdot a\tan\left(\frac{0.0254}{2 \cdot 0.031}\right) \Rightarrow 44.6°$$

$$\textbf{Camera IFOV :}\ ifov = 2 \cdot a\tan\left(\frac{0.00424\ mm}{2 \cdot 31.0\ mm}\right) \Rightarrow 136.8\ urad$$

The camera and optics parameters are a 36 Mpix camera for a 1" sensor, 4.24 um pixel size and 31 m focal length. An off the shelf camera closest to meeting these requirements is needed. Feature size is also quite small; roughly the dimensions of a person. Geo-locating features would often be much larger. Figure 6.0 shows the impact of varying altitude for all other parameters the same as listed. It can be observed that as altitude increases, coverage increases but feature sample size also gets larger which is effectively a decrease in feature resolution. The effect of increasing the feature sample size to 2 m results in two changes, required pixel size gets larger, increasing to 8.5 um and for the same sensor size dimensions the sensor pixel quantity, Npix, decreases to 9 Mpix , a fairly substantial decrease from that required for a 1 m feature sample size. Increasing the required feature size significantly reduces the required sensor pixel density.

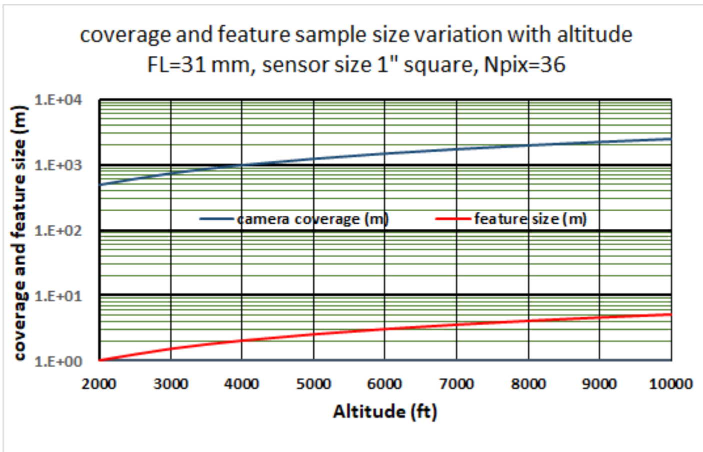

Figure 6.0 Feature sample size (nominal design 1 m) and coverage variation with altitude

The effect of varying altitude for this nominal condition is shown in Figure 7.0 with a plot similar to that shown in Figure 6.0. Finally, the effect of feature sample size on pixel size and Npix is plotted in Figure 8.0. As might be expected, it is observed that as feature sample size increases, required pixel size increases and pixel density decreases

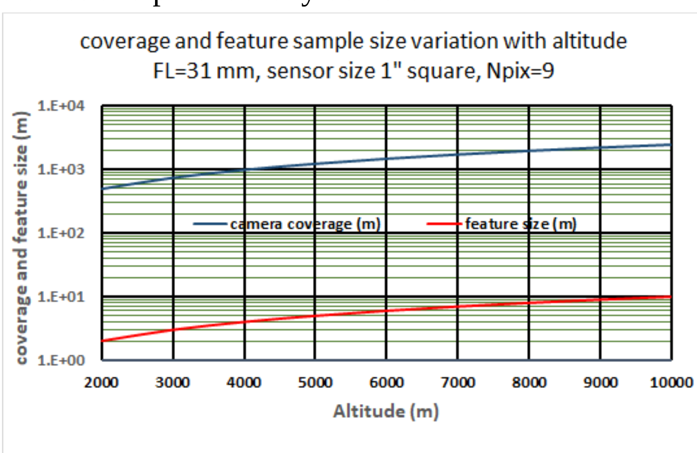

Figure 7.0 Feature sample size (nominal design 2 m) and coverage variation with altitude

Above 10 m sample size, pixel densities are approaching standard pixel densities such as 640x480 (Npix=0.31) or 512x512 (Npix~0.26). Relative to other camera sensor parameters discussed previously, sensitivity also should increase with larger pixels allowing for shorter exposures times. The IFOV will always be driven by resolution. Smaller pixels give better resolution. However because they are smaller they receive less photons and are then less sensitive. They will also have less saturation capacity which reduces dynamic range. For outside applications dynamic range and saturation capacity are critical to compensate for the wide variation in ambient lighting density and would also improve sensitivity. The sensor pixel density will be driven by pixel size, coverage, and limited by sensor size. Feature size will vary depending on the image geo-registration application. For simply registering geographic regions features could be quite large, but matching smaller features will likely result in better image geo-registration accuracy.

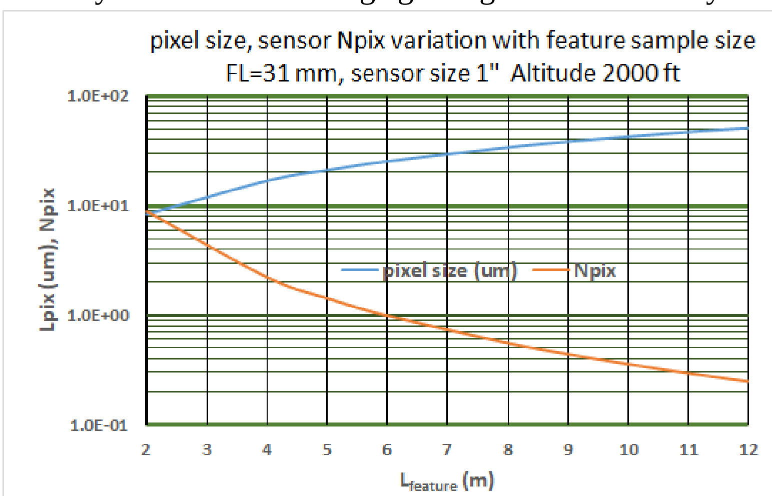

Figure 8.0 Pixel size and Npix variation with s\feature sample size

For surveillance or road maintenance features may be smaller. Relative to surveillance, two measures of target size defined by NATO and used to evaluate surveillance and rangefinder performance criteria are a person (0.5m x 1.5m) with critical dimension 0.75m and a vehicle (2.3m x 2.3m) with a critical dimension of 2.3m.

2.4 Geo-Registration Methods [see Ref. Part 2.0]

There are two general geo-registration techniques; direct geo-registration and image geo-registration. Direct is effectively the geo-pointing problem described in Parts 1.0, 2.0 of the course which requires navigation grade inertial sensors. Image geo-registration compares a sensed image with a precision geo-referenced image of the same region. This method is a significant part of many geo-location algorithms as described in Part 2.0 section 4.0.The previous sections focused on sensor requirements to implement this method.

Direct Geo-registration Geo-location: This geo-registration approach was described in detail in Part 2.0 section 4. This is the ground target geo-pointing problem based on pointing geometry described in section 1.0. Operation requires acquisition and track of a targeted object. The camera centers its FOV on the target object; establishing the LOS vector from the camera sensor to the target that defines the sensor LOS geometry. Given range the object position vector in ECEF Cartesian coordinates can then be determined. The algorithm requires rotation of the LOS vector through the sequence of DCM transformations described in section 1.0. Accurate geo-location using direct geo-registration requires very accurate differential GPS position data, a navigation grade INS/IMU for platform orientation data, a precision time base, as well as GPS aided inertial navigation software as discussed in Part 2.0 section 4.

Image Geo-registration Geo-location [see Part 2.0 Ref]: Geo-location using image geo-registration was described in detail in Part 2.0 section 4.0. It is based upon matching and aligning a camera image with a stored geo-referenced image using image feature discriminants. Once the platform camera image can be registered to the geo-referenced image, the geo-located coordinates of the ground object can be determined. There are two main image registration techniques; correlation based and pattern or feature matching; used as stand-alone or often in concert with each other. The geo-registration process optimally aligns the two images to one common frame for processing with features providing geometric points of reference. Feature fidelity directly impacts alignment accuracy so choosing the right sensor resolution, described previously, is important. The referenced image provides a known latitude and longitude for selected feature points matched to similar points on the unreferenced image after accurately aligning the images. A cross-correlation match criterion is often used as a metric to determine the best image match. One common element required for most geo-registration processing techniques is a camera model. A pinhole camera model is used; as described in Part 2.0, parameterized by what are termed intrinsic and extrinsic characteristics. Intrinsic include camera optics focal length, images offsets and scaling, while extrinsic are the DCM required to rotate an object vector to the image plane with any offsets. The model is generally of the form [see Part 2.0 Ref]:

$$\hat{w}=\begin{bmatrix}u\\v\\1\end{bmatrix}=\bar{M}_{ECEF}^{\text{Image}}\cdot\hat{P}_{TGTPLAT}^{ECEF}\quad;\ \text{where}:\ \hat{P}_{TGTPLAT}^{ECEF}=\begin{bmatrix}\dfrac{\hat{P}_{TGT}^{ECEF}-\hat{P}_{PLAT}^{ECEF}}{range}\\1\end{bmatrix}\quad;\ \text{and}\ \bar{M}_{ECEF}^{\text{Image}}=\bar{M}_{LOS}^{\text{Image}}\cdot\bar{M}_{ECEF}^{LOS}$$

$$\text{intrinsic}:\ \bar{M}_{LOS}^{\text{Image}}=\begin{bmatrix}f_u & s & c_u\\0 & f_v & c_v\\0 & 0 & 1\end{bmatrix}\quad;\quad\text{extrinsic}:\ \bar{M}_{ECEF}^{LOS}=\left[D\bar{C}M_{ECEF}^{LOS},\hat{t}\right]\quad;\ \hat{t}=\begin{bmatrix}t_x\\t_y\\t_z\end{bmatrix}$$

The variables w, v are positions on the image focal plane. The intrinsic rotation matrix maps a vector in the LOS frame to the image plane; parameterized by the optics focal length (f_u, f_v), any image plane reference offset (c_u, c_v) and an x, y scaling factor (s) correction. More detail can be applied based upon other key sensor features described in section 2.3. The extrinsic matrix is just the DCM rotation of a vector from ECEF coordinates to the LOS. It is appended with an offset to account for any coordinate frame offset relative to the image plane.

Geo-pointing data is still required for an initial coarse geo-location estimate; but this approach provides relief in the quality of the inertial data, especially the INS. However as performance depends on image quality, a high grade IMU may still be required to reduce blur and distortion due to LOS disturbances. In general, image registration consists of a set of generic processes that select image features, match the features, use image rotation, translation, and scaling to align the image features, and finally map the unregistered image to the geo-registered reference. This is performed with levels of image resolution that vary from low to high, progressively increasing to their full value. The algorithmic implementation will vary but have similar objectives as follows:

(i) Pre-Processing and Image Projection to a Common Frame: Project the reference and sensed video images to a common coordinate frame using existing geo-pointing data (GPS, INS). This projection initializes image-registration alignment conditions. The camera video image, orientation data, and a model of the image sensor are required for initial coarse alignment of the reference and video images. The reference image is projected to the sensor coordinate frame and course aligned using the available pointing platform/gimbal data; GPS, and INS

(ii) Image Processing [see Part 2.0 Ref]: Image contour or feature processing to provide a feature structure that captures image geometric and intensity characteristics to support matching and alignment of sensed video to reference images. Selecting a set of image intensity features to discriminate a common pattern structure and are invariant to the sensed and reference images is critical to alignment. Good features discriminate against background, exhibit high intensity to background contrast, and have a local dominant orientation or well defined point-like geometry. Once features are matched and coarsely aligned, a mapping function transformation can be created for fine alignment

(iii) Correspondence [see Part 2.0 Ref]: Generate a precision spatial correspondence between the images using global correlation matching techniques for precise alignment of the two images. A key to this final alignment is the camera model to improve correspondence of the two images via a progressive model scaling and orientation refinements. A progressive refinement strategy is used to obtain accurate alignment using the feature points from the previous step for the feature-based registration process. Once the reference Image and the sensed video image have been accurately aligned through feature-based registration, a direct correlation or pattern matching method based progressively increasing resolution of correlated regions is used to provide a final adjustment. Once image alignment is within the desired tolerance, the final algorithm maps the image to a physical location. The sensed image is registered to the reference image whose features are geo-registered to a known latitude and longitude; now mapped to the sensed image.

Section 2.0 Key Points Summary

- ***Key sensor parameters are QE, SNR, dynamic range, saturation***
- ***Quantum efficiency is the photon to electron conversion efficiency of a camera sensor or photodetector***
- ***Noise sources incudes shot, thermal dark current, readout, and clock induced charge***
- ***Larger pixel size improves photon collection efficiency, smaller pixel size improves resolution; there's a tradeoff***
- ***Exposure time and frame rate effect sensitivity and are inter-dependent***
- ***Optical format must match lens size and desired pixel resolution***
- ***Camera FOV and altitude define scene coverage; IFOV and altitude scene sample or pixel resolution***

3.0 Course Summary

Part 3.0 of the course reviewed details associated with the geo-pointing and location problem. Section 1 was effectively a review from Parts 1.0, 2.0 covering LOS definition and geo-pointing. Section 2 described camera sensor characteristics critical to geo-location using image geo-registration. Characteristics were described intrinsic to the sensor that drive SNR, dynamic range, etc. and those associated with the camera optics that define the geometry for image collection FOV and image resolution. Finally image geo-registration was briefly reviewed to relate this process back to the sensor requirements.

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