Introduction to Remote Sensing
Chapter 3
Sensor Models

Prof. Vidya Manian
Dept. of Electrical and Computer Engineering
Overview

• Overall sensor Model
• Spatial Resolution
• Spectral Resolution
• Spatial Response
• Spectral Response
• Signal Amplification
• Simplified Sensor Model
• Geometric Distortion
Remote Sensing Instrumentation

General concept

IFOV = $\beta \cdot H$ (in Nadir!)

Telemetry

Ground receiving station

Instantaneous field of view - ground resolution element

Terrain objects
• Scanning operation converts spatial at-sensor radiance to a continuous, time-varying optical signal on the detectors
• Detectors convert it to electronic signal
• Signal is sampled and quantized into discrete DN values at the A/D converter
• Several transformations of the data occur
  – Radiometric
  – Spatial
  – Geometric
• The sensor degrades the signal of interest.
• Need to understand degradation to properly design image processing algorithms and interpret their results
• Remote sensors are complex systems of optical, mechanical and electronic components
  – These components determine the quality of the data from the sensor
  – The sensor may be considered a “black-box” that converts at-sensor radiance to DNs
The primary components in an electro-optical remote sensing systems
Resolution

• RS systems have resolution in the spectral, spatial and temporal measurement domains

• Any instrument that measures a physical quantity is limited in the amount of detail it can capture
  – This limit is referred to as the instrument’s “resolution”
  – “Resolution” is a term that is widely used, but often misunderstood
LSI System Model

• Model the various systems as Linear Shift-Invariant (LSI)
  – A linear transformation of the input \( x \) results in a similar transformation of the output \( y \)

• Superposition principle
  – If \( T[f_1] = g_1 \) and \( T[f_2] = g_2 \), then \( T[a_1f_1 + a_2f_2] = a_1g_1 + a_2g_2 \)

• Shift invariance: Shifting the input results in a similar shift of the output
  – If \( T[f(x)] = g(x) \), then \( T[f(x-x_0)] = g(x-x_0) \)

• LSI model is generally applicable over the nominal range of operation for these systems
  – Model will break down as performance limits are approached (i.e., system response becomes non-linear)
Instrument as a LSI System

The instrument weights the input signal in the vicinity $(W)$ of $z$ and integrates the result.

$$o(z) = T[i(z)]$$

$$o(z_0) = \int_W r(z_0 - \alpha) i(\alpha) d\alpha$$

$r(z)$ instrument response, $z = (x, y)$ or $\lambda$
• $i(\alpha)$ – input signal
• $R(z_0- \alpha)$=instrument response (unit area), inverted and shifted by $z_0$
• $O(z0)$=output signal at $z=z0$ and
• $W$=range over which the instrument response is significant
• Convolution: $o(z)=i(z)*r(z)$
• Output signal equals the input signal convolved with the response function
The Ideal Sensor: Infinite Precision

- \( r(z) = \delta(z) \)

\[
o(z) = \int_W \delta(z - \alpha) i(\alpha) d\alpha = i(z)
\]

No instrument can measure a physical signal with infinite precision.
Linear Shift-Variant Systems

\[ o(z) = T[i(z)] \]

\[ o(z) = \int_W r(z, \alpha) i(\alpha) d\alpha \]

\( r(z, \alpha) \) is called the system weighting function.

The weighting function of the instrument can depend on the “location” being measured.
Spatial Resolution

- GSI (ground projected sample interval) or GIFOV (ground projected instantaneous field of view)
- Detect smaller objects if the contrast with the surrounding background is sufficiently high
- Ground area larger than GIFOV with 0 reflectance produces a 0 DN, reflectance of 1 produces maximum DN, say 255
- Area within GIFOV contain two materials 5% each then DN is 128
Spatial Resolution

- A “subpixel” object smaller than the GIFOV can be detected, but not resolved.
- Detectability of a subpixel object depends on:
  - object size relative to the sensor GIFOV
  - object radiance contrast to the surrounding background
  - scene noise (“clutter”)
  - sensor noise

Berkeley Pier: 7m wide, concrete and wood
Another Example of Subpixel Detection

60 m wide channel

TM band 4
30 m resolution

MODIS band 2
250 m resolution
Detectability
Dependence of Object Size and Contrast

- Low-contrast subpixel targets must be bigger than high contrast targets for detection
- Contrast ratio (2:1)
• Size of target <10% of a pixel, it falls below threshold (one DN) for detection
• Radiometric quantization, target and background reflectances and sensor GIFOV determine “resolution” of the image
• Sample scene phase: relative location of the pixels and the target, varies from acquisition to acquisition-influences image resolution
Sample Scene Phase

- The measured radiance of a subpixel object depends on the location of the object relative to the pixel samples.
• DN profile along each scan line across the pier is different
• It is not oriented at 90 deg to the scan, hence it is one pixel or 2 pixel wide
• To estimate true width of subpixel object, an interleaved composite of many lines should be made, phasing them to fractions of a pixel
More on Sample Scene Phase
Effects of Atmosphere

Figure 4.4  Poor atmospheric and light conditions can dramatically reduce the effective spatial resolution of a remote sensing system.

These images of the same scene were taken by the same sensor under good (a) and poor (b) atmospheric conditions.

Source: Courtesy of Imagery Resolution Assessments and Reporting Standards Committee.
Spatial Resolution

• Factors in real images
  – Sensor noise
  – Non-uniform targets and backgrounds
  – Variable solar angle and topography
  – Atmospheric conditions

• Spatial resolution is not so simple!

• In general, the term resolution will refer to the GSI
Quiz

• What are the steps to convert radiance to image DNs
• What is resolution
• What is a LSI system
• What size should the target be with respect to background to be detectable. What DNs should the target pixels have to be detectable
Spectral resolution

- Total energy measured in each spectral band is a spectrally weighted sum of image irradiance over the spectral passband
- Example – reflectance data for mineral alunite
- Each band sees an effective reflectance which is the weighted reflectance over the band; weighting function is the spectral response of the sensor in each band
- 50nm wide spectral bands - loss of information about the doublet; averaged away by broad spectral bands
Reflectance of alumnite as measured by an hyperspectral sensor (10nm res)
Reflectance of alumnite as measured by a multispectral sensor (50nm res.)
Simulation of TM band measurements of Kentucky bluegrass
Spectral Resolution Concepts

• Spectral Resolution
  – Bandwidth in nm or Hz
  – Midvalue
  – Sensitivity curve

• Spectral Range
  – Number and position of the bands
AVIRIS

Channel Weighting Function for AVIRIS Channels

Relative Response

Wavelength (nm)
Landsat 7 ETM+
Advanced Very High Resolution Radiometer (AVHRR)

Jensen, 2007
CRI VariSpec
Tunable Imaging Filter

Comparison of the VSWIR spectral bands for MODIS, ASTER and ETM+
Spectral Characteristics of AVIRIS vs HYPERION
Spectral Resolution

• High spectral resolution → imaging spectroscopy

• Multispectral → Placement of bands and spectral bandwidth is important to sensor’s ability to resolve spectral features.
Multispectral is VERY useful

Surface components with very distinct spectral differences can be resolved using broad wavelength ranges.
Spatial response

• The sensor modifies the spatial properties of the scene by (1) blurring due to the sensor’s optics, detectors and electronics (2) distortion of geometry

• Small details are blurred relative to larger features characterized by the net sensor Point Spread Function (PSFnet) – spatial responsivity of sensor
Quiz

• What is spatial resolution
• What factors affect the objects imaged at a pixel
• What is spectral resolution
• When is it good to have a high or low spectral resolution
• Explain the terms: FOV, GFOV, GSI
• Explain: whiskbroom and pushbroom scanners
• How is at-sensor radiance converted to DNs, give example DNs
$s_b(x, y; \lambda)$

$\text{PSF}_{\text{net}}(x, y; \lambda)$

$e_b(x, y; \lambda)$

$n(x, y; \lambda)$

$\text{PSF}_{\text{net}}(x, y; \lambda)$ is the system point spread function for band centered in $\lambda$
Coordinate System

- The coordinates \((x,y)\) and all parameters are assumed to be in image space.
- Conversion factors
  
  - Ground distance = image distance / magnification
    = image distance \(\times \) \(H/f\)
  
  - Ground velocity = image velocity / magnification
    = image velocity \(\times \) \(H/f\)
Spatial Response

• The spectral signal is convolved with the sensor spatial response

\[ e_b(x, y; \lambda) = \int_{\alpha_{\min}}^{\alpha_{\max}} \int_{\beta_{\min}}^{\beta_{\max}} \text{PSF}_{\text{net}}(x - \alpha, y - \beta; \lambda)s_b(\alpha, \beta; \lambda)d\alpha d\beta \]

where the spatial response of an imaging system is now called the Point Spread Function (PSF). Assumes LSI imaging system.

• The net sensor PSF is a convolution of individual responses from:
  – optics \( \text{PSF}_{\text{opt}} \)
  – image motion \( \text{PSF}_{\text{IM}} \)
  – detector \( \text{PSF}_{\text{det}} \) (defines the geometrical GIFOV)
  – electronics \( \text{PSF}_{\text{el}}(x, y) \)

\[ \text{PSF}_{\text{net}}(x, y) = \text{PSF}_{\text{opt}} * \text{PSF}_{\text{IM}} * \text{PSF}_{\text{det}} * \text{PSF}_{\text{el}}(x, y) \]
Spatial Response:
Larger than GIFOV

The area on the ground that a pixel represents
The area on the ground that actually contributes to the observed signal, that is, the support
\[ \text{PSF}_{\text{net}}(x,y; \lambda) \]

- The total system response to a spatial “impulse” signal
- Larger than geometric GIFOV
  - time integration smear (cross-track for whiskbrooms, in-track for pushbrooms)
  - optics blur
  - electronic filters (cross-track for whiskbrooms; not common for pushbrooms)
  - detector electron diffusion, charge transfer inefficiency (pushbrooms)
- The net spatial response is the convolution of all these factors, converted to a common spatial coordinate system
Illustration of PSF

from Wikipedia
Optical PSF $\rightarrow$ $\text{PSF}_{\text{opt}}$

Valid for an optical system with no degradation other than diffraction.
Optical PSF $\rightarrow$ PSF$_{\text{opt}}$

- PSF$_{\text{opt}}$ is given by

$$PSF(r') = \left[2 \frac{J_1(r')}{r'}\right]^2$$

where $J_1$ is a Bessel function of the first kind and the normalized radius is given by

$$r' = \frac{\pi D}{\lambda f} r = \frac{\pi r}{\lambda N},$$

where $D$ = aperture diameter, $\lambda$ = wavelength of light, $f$ = focal length, $N$ = f-number, and $r$ is the radius to the first dark ring (Airi Disk) is

$$r = 1.22 \left[\frac{\lambda f}{D}\right] = 1.22 \lambda N,$$

where $N$ is the optics f-number given by the ratio of the optical focal length $f$ divided by the aperture stop diameter.
Detector PSF $\rightarrow$ PSF$_{det}$

$$PSF_{det}(x, y) = \text{rect}(x/w)\text{rect}(y/w)$$
Image Motion $\rightarrow$ PSF$_{IM}$

where $s$ is the spatial smear of the image in the focal plane

whiskbroom scanner: $PSF_{IM}(x, y) = \text{rect}(x/s)$

pushbroom scanner: $PSF_{IM}(x, y) = \text{rect}(y/s)$

where $s$ is the spatial smear of the image in the focal plane

whiskbroom scanner: $s = \text{scan velocity} \times \text{integration time}$

pushbroom scanner: $s = \text{platform velocity} \times \text{integration time}$
MODIS: $\text{PSF}_{\text{det}} \ast \text{PSF}_{\text{IM}}$

50% overlapping of neighboring pixels!
Electronics PSF $\rightarrow$ $\text{PSF}_{el}$

- Detectors signal is filtered to reduce noise.
  - AVHRR, MSS, TM and ETM+ whiskbroom scanners use a low-pass Butterworth type filter
  - Pushbroom scanners have no filters but introduce PSF due to intrinsic properties

- Time domain $\rightarrow$ Equivalent to a spatial dependence

*whiskbroom scanner:* $x = \text{scan velocity} \times \text{sample time interval}$

*pushbroom scanner:* $y = \text{platform velocity} \times \text{sample time interval}$
Net PSF $\rightarrow$ $\text{PSF}_{\text{net}}$

$\text{PSF}_{\text{net}}(x, y) = \text{PSF}_{\text{opt}} \ast \text{PSF}_{\text{IM}} \ast \text{PSF}_{\text{det}} \ast \text{PSF}_{\text{el}} (x, y)$
PSF Properties

• The net sensor PSF is wider than the GIFOV because of
  – PSF_{opt} in both directions
  – PSF_{IM}
    • cross-track for whiskbroom scanners
    • in-track for pushbroom scanners
  – PSF_{el} cross-track for whiskbroom scanners

• Reasonable assumption in many cases is that the PSF is separable in the cross-track and intrack directions

\[ \text{PSF}_{\text{net}}(x, y) = \text{PSF}_i(x) \text{PSF}_c(y) \]
PSF for AVHRR and MSS

in track

cross track
PSF for SPOT and TM
PSF for MODIS and ALI
• PSF is normalized to same GSI
• For AVHRR and MSS, the amount of sensor blur is about twice as great in the cross-track direction than in the in-track direction
• Cross-track response is considerably broader than that of the detector.
• Effective GIFOV of RS systems is larger than the quoted geometric GIFOV
Visualizing imaging system effect using simulation
Simulation of the effect of GSI and GIFOV on visual image quality.

Upper: undersampled conditions, GSI > GIFOV

Lower: GSI = GIFOV
Imaging Simulation

• Example: simulation of Landsat TM imaging
  – Model TM spatial response components (at a common scale)
TM Spatial Response Components

- Optics
- Optics and GIFOV
- Optics, GIFOV and Electronics
High resolution aerial photography

scanned aerial photograph, GSI = 2m

rotated and trim to align with TM orbit and scan direction
Imaging Simulation (cont.)

Apply each component of the spatial response and downsample to 30m
Comparison with Real TM taken 4 months later
Quiz

• How does sensor modify spatial response of scene
• What are the components of the PSFnet.
• What is optical PSF, detector PSF, image motion PSF
• Explain the MODIS design
• What contributes to electronics PSF
• What happens increasing GSI or GIFOV
• Compare effective GIFOV and geometric GIFOV
Measurement of Sensor PSF

• Laboratory tests
  – Point sources $\rightarrow$ PSF
  – Lines sources $\rightarrow$ Line Spread Function (LSF)-1D
  – Edge sources $\rightarrow$ Edge Spread Function (ESF)-1D

• From data itself
  – Subpixel line and edge sources
  – Spatial domain representation of spatial response
  – Fourier transform domain representation is discussed in Chapter 6.
Mathematical Relations

\[ LSF_c(x) = \int_{-\infty}^{\infty} PSF(x, y)dy \]

\[ LSF_i(y) = \int_{-\infty}^{\infty} PSF(x, y)dy \]

\[ ESF_c(x) = \int_{-\infty}^{x} LSF_c(\alpha \alpha)\,d \]

\[ LSF_c(x) = \frac{d \, ESF_c(x)}{dx} \]

\[ ESF_i(y) = \int_{-\infty}^{y} LSF_i(\alpha \alpha)\,d \]

\[ LSF_c(y) = \frac{d \, ESF_i(y)}{dy} \]
Mathematical Relations

\[
\text{PSF}(x,y) \xrightarrow{\text{one-sided 1-D integration}} \text{ESF}_x(x) \xrightarrow{\text{one-sided 1-D integration}} \text{LSF}_x(x)
\]
• The line or edge response is measured rather than point response
• Measure PSF, ESF and LSF using man-made targets such as mirrors or geometric patterns or targets of opportunity such as bridges
• Specular mirrors as subpixel targets, flat mirror detected in the 80m GIFOV of the first landsat MSS
• Phased array of effective point sources was used to measure the TM PSF
• Each point produces an independent, sampled PSF image
# Measurement of sensor spatial response

<table>
<thead>
<tr>
<th>sensor</th>
<th>target type</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADAR System 1000</td>
<td>edge</td>
<td>Blonski et al., 2002</td>
</tr>
<tr>
<td>ALI</td>
<td>agriculture field berms</td>
<td>Schowengerdt, 2002</td>
</tr>
<tr>
<td>ETM+</td>
<td>bridge</td>
<td>Storey, 2001</td>
</tr>
<tr>
<td>HYDICE</td>
<td>bridge</td>
<td>Schowengerdt et al., 1996</td>
</tr>
<tr>
<td>Hyperion</td>
<td>ice shelf edge, bridge</td>
<td>Nelson and Barry, 2001</td>
</tr>
<tr>
<td>IKONOS</td>
<td>edge</td>
<td>Blonski et al., 2002</td>
</tr>
<tr>
<td></td>
<td>parking lot stripes</td>
<td>Xu and Schowengerdt, 2003</td>
</tr>
<tr>
<td></td>
<td>edge</td>
<td>Ryan et al., 2005</td>
</tr>
<tr>
<td></td>
<td>line</td>
<td>Helder et al., 2004</td>
</tr>
<tr>
<td>MODIS</td>
<td>higher-resolution imagery</td>
<td>Rojas et al., 2002</td>
</tr>
<tr>
<td>MSS</td>
<td>higher-resolution imagery</td>
<td>Schowengerdt and Slater, 1972</td>
</tr>
<tr>
<td>OrbView-3</td>
<td>edge</td>
<td>Kohm, 2004</td>
</tr>
<tr>
<td>QuickBird</td>
<td>phased-array of mirrors, edge</td>
<td>Helder et al., 2004</td>
</tr>
<tr>
<td>simulated</td>
<td>non-specific</td>
<td>Delvit et al., 2004</td>
</tr>
<tr>
<td>SPOT4 (simulated)</td>
<td>point source array</td>
<td>Robinet et al., 1991</td>
</tr>
<tr>
<td>SPOT5</td>
<td>edge, spotlight</td>
<td>Leger et al., 2003</td>
</tr>
<tr>
<td>TM</td>
<td>bridge, higher-resolution imagery</td>
<td>Schowengerdt et al., 1985</td>
</tr>
<tr>
<td></td>
<td>phased-array of subpixel targets</td>
<td>Rauchmiller and Schowengerdt, 1988</td>
</tr>
</tbody>
</table>
**ALI LSF measurement**

- The berm crop canopy forms a linear, high-contrast subpixel feature used to measure the MSS band LSF in the in-and cross-track directions.
- Several transects were extracted, registered, and averaged in both cases to reduce noise.
- If target is too narrow, result is not good due to low signal level.
- If target is too wide, the estimated LSF will be broadened by the target itself.
Experimental Measurement

**Cross-track and in-track band 3 LSFs**

**transect used to extract subpixel samples for the in-track LSF**

**transect used to extract subpixel samples for the cross-track LSF**
Exercise

• With angle of 13.08 deg between a line target and sensor scan direction, as in Fig. 3-18, how is the effective subpixel sample interval calculated for the extracted profiles.

• Derive equation 3-44 starting with equation 3-40.

• Calculate the convolution of a square sensor GIFOV and a square wave radiance target, either by integration using equation 3-2 or by a graphical approach. Allow the GIFOV to be ½, 1 and 2 times the width of a single bar in the pattern and discuss the results in terms of sample-scene phase.
Effect of Target Size

Ratio = Target size/LSF width
QuickBird LSF measurement

- Trade-off using man-made targets and targets-of-opportunity that are already present on the ground
- Abundant man-made features in urban areas are good candidates
- White painted stripes in an asphalt vehicle parking lot are used to measure the QuickBird LSF
- Individual parking stripes are only about 1/7 GIFOV in width, but high contrast with background to yield good signal level
- Spacing is a non-integer number of pixels, each stripe is imaged with a different sample-scene phase.
- Length is several pixels, allowing averaging of several rows or columns
Estimation from data itself:
QuickBird, Tucson Bargain Center, Nov. 4, 2002
TABLE 3-2. Parking lot stripe parameters relevant to QuickBird image analysis.

<table>
<thead>
<tr>
<th>parameter</th>
<th>size</th>
<th></th>
<th>pixels (resampled)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>inches</td>
<td>meters</td>
<td>in-track</td>
</tr>
<tr>
<td>width</td>
<td>4</td>
<td>0.102</td>
<td>0.148</td>
</tr>
<tr>
<td>spacing</td>
<td>120</td>
<td>3.05</td>
<td>4.42</td>
</tr>
<tr>
<td>length</td>
<td>240</td>
<td>6.10</td>
<td>8.84</td>
</tr>
</tbody>
</table>

**cross-track pixel data**

**interleaved subpixel data**

**cross-track and in-track pan band LSFs**
Method Description (Helder ‘03)

• Edge Method (MTF-Modulation Transfer Function estimation method)
  – Sub-pixel edge locations were found by Fermi function fit.
  – A least-square error line was calculated through the edge locations.
  – Savitzky-Golay Helder-Choi filtering was applied on each line
  – The filtered profile was differentiated to obtain LSF
  – MTF calculated by applying Fourier transform to LSF.

Fig 1. Edge Method
• Pulse method
  – A pulse input is given to an imaging system.
  – Output of the system is the resulting image.
  – Edge detection and SGHC filtering was applied to get output profile.
  – Take Fourier transform of the input and output.
  – MTF is calculated by dividing output by input.

![Figure 2. Pulse method]
• Parametric Edge Detection
  – A model based parametric method was applied to detect sub-pixel edge locations.
  – The Fermi function was chosen to fit this function to the ESF for improved edge angle estimation.
  – Sub-pixel edge locations were calculated on each line by finding best fitting curve’s value ‘b’.

\[ f(x) = \frac{a}{\exp\left(\frac{(x-b)}{c}\right) - 1} + d \]

Figure 3. Parametric edge detection
Signal Amplification

- The electronic signal produced by the detectors is amplified

\[ a_b = \text{gain}_b \times e_b(x, y) + \text{offset}_b. \]

- Some sensors have multiple gain settings, e.g. SPOT HRV (Chavez, 1989) and ETM thermal band, to increase signal level for dark objects

*Linear amplification characteristics*
Landsat ETM+
Sampling and Quantization

- The amplified signal is sampled in time (during scan) and quantized into Digital Numbers (DNs)

\[ DN_{pb} = \text{int}[a_b] = \text{int}[\text{gain}_b \times e_b(x, y) + \text{offset}_b] \]

- Quantization is a low-level noise superimposed on the data values
  - For Q bits/pixel quantization there are $2^Q$ integer DNs over the range $[0...2^Q-1]$

- Radiometric resolution
  - $2^{-Q}x$ dynamic-range-in-radiance
Radiometric Resolution:
(a) 1-bit,
(b) 4-bits,
(c) 8 bits

Figure 4.20: Comparison of radiometric resolutions. The same image is displayed with (a) 2, (b) 16, and (c) 256 gray levels, which corresponds to 1-, 4-, and 8-bit radiometric resolutions. Since the human eye does not reliably distinguish more than about 30 gray levels, there is little apparent loss of image quality in the 4-bit image.

Source: © Natural Resources Canada.
Effective Sensor Model

- Total measured signal at pixel p in band b

\[ DN_{pb} = int \left[ K_b \iiint L_\lambda(x, y) d\lambda dx dy + \text{offset}_b \right] \]

- where
  - \( DN_{pb} \) is the Digital Number at pixel p in band b
  - \( L_\lambda(x,y) \) is the at-sensor spectral radiance from scene location (x,y)
  - \( K_b \) is a gain coefficient for band b that includes sensor gain, detector spectral responsivity and spectral filter transmittance
  - \( \text{offset}_b \) is the sensor offset coefficient for band b
  - the gain and offset are effective quantities, averaged over an effective spectral band
Gain-Offset Model

• The three integrals are over:
  – the effective spectral response range of band b (spectral resolution)
  – the effective spatial response range in-track and crosstrack (spatial resolution)

• Assume a **band- and space-integrated** at-sensor radiance \( L_{pb} \) at pixel p, band b. Then,

\[
DN_{pb} = K_b L_{pb} + offset_b
\]

  – DNs are **linearly proportional** to the total at-sensor radiance
  – Ignores radiometric quantization and nonuniform response within spectral bands and the GIFOV
  – Simplifies modeling and radiometric calibration of the sensor
Sensor Calibration (DNs to radiance)

• Relating the digital number (DN) to radiance.
  – Linear relationship with radiance ($L_\lambda$)
  – $L_\lambda = \text{Gain (DN)} + \text{Offset}$
  – Gains and offsets provided in metadata with distribution of data
Callibration Coefficients for LANDSAT TM

TABLE II
L5 TM PRELAUNCH GAIN/BIAS COEFFICIENTS [8]

<table>
<thead>
<tr>
<th>Band</th>
<th>Prelaunch Gain</th>
<th>Prelaunch Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.555</td>
<td>1.8331</td>
</tr>
<tr>
<td>2</td>
<td>0.786</td>
<td>1.6896</td>
</tr>
<tr>
<td>3</td>
<td>1.02</td>
<td>1.8850</td>
</tr>
<tr>
<td>4</td>
<td>1.082</td>
<td>2.2373</td>
</tr>
<tr>
<td>5</td>
<td>7.875</td>
<td>3.2893</td>
</tr>
<tr>
<td>7</td>
<td>14.77</td>
<td>3.2117</td>
</tr>
</tbody>
</table>
Scene Calibration: 
Radiance to Reflectance (inverse problem)

Measured Radiance  
Estimated Reflectance using ATREM
Geometric Distortions

• Previous discussion focused on sensor characteristics that affected the radiometric quality of the imagery

• Here we focus on where are we looking?
  – Geometric characteristics of the imagery
    • Orbit
    • Platform attitude
    • Scanner properties
    • Earth rotation and shape
Sources of Distortion

• All remote sensing images are distorted relative to a map
  – platform motion, especially airborne sensors
  – scanning distortion of the Ground Sample Interval (GSI)
  – topography
Sensor attitude

- The angle(s) of an aerospace vehicle with respect to a reference such as the horizon
- Small changes in sensor attitude can result in large changes in the viewed location on the ground
- Expressed by three angles: roll, pitch and yaw.
  - Usually recorded with the image data
Figure 5.17 Geometric distortions due to aircraft orientation. Gray boundaries represent nominal coverage; black boundaries represent actual coverage.
Geometric Modification of Remotely Sensed Data
Caused by Changes in Platform Altitude and Attitude

a. Change in Altitude
   x-axis

   Direction of flight
   Roll
   rotation about x-axis angle ω
   up/down

   Pitch
   rotation about y-axis angle φ

   Yaw
   rotation about z-axis angle κ

   Frame of imagery
   aircraft flies straight but fuselage is crabbed into wind

b. Change in Attitude

   Nominal
   Decrease in altitude creates larger-scale image
   Increase in altitude creates smaller-scale image

   compression
   expansion
   compression
   expansion

   Nose down compression fore
   Expansion fore
   Expansion aft
   Compression aft
   Tail down

   Wing up and down motion

(Jensen 2000)
# Angle Between Adjacent Pixels

**TABLE 3-3.** The angle between two adjacent pixels for a number of sensors. AVHRR and Landsat are not pointable; all the other sensors are pointable.

<table>
<thead>
<tr>
<th>system</th>
<th>altitude (km)</th>
<th>in-track $GSI$ (m)</th>
<th>angle (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVHRR</td>
<td>850</td>
<td>800</td>
<td>0.941</td>
</tr>
<tr>
<td>Landsat-4,-5 TM (multispectral)</td>
<td>705</td>
<td>30</td>
<td>0.0425</td>
</tr>
<tr>
<td>SPOT-1 to -4 (multispectral)</td>
<td>822</td>
<td>20</td>
<td>0.0243</td>
</tr>
<tr>
<td>Landsat-7 ETM+ (panchromatic)</td>
<td>705</td>
<td>15</td>
<td>0.0213</td>
</tr>
<tr>
<td>SPOT-5 (multispectral)</td>
<td>822</td>
<td>10</td>
<td>0.0122</td>
</tr>
<tr>
<td>SPOT-5 (panchromatic)</td>
<td>822</td>
<td>5</td>
<td>0.00608</td>
</tr>
<tr>
<td>OrbView-3 (panchromatic)</td>
<td>470</td>
<td>1</td>
<td>0.00213</td>
</tr>
<tr>
<td>IKONOS (panchromatic)</td>
<td>680</td>
<td>1</td>
<td>0.00147</td>
</tr>
<tr>
<td>QuickBird (panchromatic)</td>
<td>450</td>
<td>0.6</td>
<td>0.00133</td>
</tr>
</tbody>
</table>
Sensor Attitude (more)

• Satellite Sensors: it is assumed to be a slow varying function of time

\[ \alpha = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + \ldots \]

• Airborne Sensors: subject to large changes from wind and turbulence.
  – Gyro-stabilized platform is needed to avoid severe image distortions
Distortion caused by airplane motion (ASAS airborne sensor)

Note changes in geometric patterns (changes in attitude) and radiometric differences (non-Lambertian surfaces) due to changes in view angle.
Example: Recent Campaign in PR
With some corrections
Scanner Models

• Scanner induced distortions can be easily modeled as a function of time
  – As long as they are consistent throughout an image
• Whiskbroom scanners have more inherent distortions than pushbroom
  – Whiskbroom: moving crosstrack
  – Pushbroom: fixed crosstrack geometry
  – Pre-flight calibration is possible
TABLE 3-4. Examples of sensor-specific internal distortions. The reader is cautioned that some measurements of distortion were made from ground-processed imagery, and that a careful reading of the indicated reference is required before assuming the errors apply to all of the imagery from a given sensor. For example, the inter-focal plane misregistration in TM is given for early data; later data were found to be registered to within 0.5 pixel because of improved ground processing (Wrigley et al., 1985).

<table>
<thead>
<tr>
<th>sensor</th>
<th>source</th>
<th>effect on imagery</th>
<th>maximum error</th>
<th>reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSS</td>
<td>non-unity aspect ratio sampling</td>
<td>cross-track versus in-track scale differential</td>
<td>1.41:1</td>
<td>USGS/NOAA, 1984</td>
</tr>
<tr>
<td></td>
<td>nonlinear scan mirror velocity</td>
<td>nonlinear cross-track distortion</td>
<td>±6 pixels</td>
<td>Anuta, 1973; Steiner and Kirby, 1976</td>
</tr>
<tr>
<td></td>
<td>detector offset</td>
<td>band-to-band misregistration</td>
<td>2 pixels between bands</td>
<td>Tilton et al., 1985</td>
</tr>
<tr>
<td>TM</td>
<td>focal plane offset</td>
<td>misregistration between visible (bands 1–4) and IR (bands 5–7)</td>
<td>-1.25 pixels</td>
<td>Bernstein et al., 1984; Desachy et al., 1985; Walker et al., 1984</td>
</tr>
<tr>
<td>SPOT</td>
<td>detector element misalignment</td>
<td>in-track and cross-track pixel-to-pixel positional error</td>
<td>±0.2 pixels</td>
<td>Westin, 1992</td>
</tr>
</tbody>
</table>
Line and Whiskbroom Scan Geometry

• Flat Earth

\[ \text{flat earth: } \frac{GSI_f(\theta)}{GSI(0)} = \left[ \frac{1}{\cos(\theta)} \right]^2 \]

• Spherical Earth: Large IFOV

\[ \text{spherical earth: } \frac{GSI_e(\theta)}{GSI(0)} = \frac{[H + r_e(1 - \cos \phi)]}{H \cos(\theta) \cos(\theta + \phi)} \]

– where \( \phi \) is the geocentric angle

\[ \phi = \arcsin \left\{ \left[ \frac{(r_e + H)}{r_e} \right] \sin(\theta) \right\} - \theta \]
Scanning Distortion: line and whiskbroom scanners
Bow-tie distortion in AVHRR data (Fig. 3-23)
More on Scan Distortion

Vertical Aerial Photography Perspective Geometry

Across-track Scanner Geometry with One-Dimensional Relief Displacement and Tangential Scale Distortion

Significant geometric compression at edges of scan line

(Jensen 2000)
Pushbroom Scan Geometry

• For flat earth

\[ GSI_f = w \times \frac{H}{f} \]

• Spherical earth

\[ IFOV(\theta)/IFOV(0) = [\cos(\theta)]^2 \]

\[ GSI_e(\theta)/GSI(0) = \frac{[H + r_e(1 - \cos\phi)]\cos(\theta)}{H\cos(\theta + \phi)} \]
Pushbroom Scan Geometry
Earth Model

• Earth geometric properties are independent of the sensor but they affect the acquisition process via the orbital motion of the satellite.
  – Earth is not an exact sphere
    • Ellipsoid Equation
      \[
      \frac{p_x^2 + p_y^2}{r_{eq}^2} + \frac{p_z^2}{r_q^2} = 1
      \]
      where \((p_x, p_y, p_z)\) are the geocentric coordinates of any point \(P\) in the surface of the earth, \(r_{eq}\) and \(r_q\) are the equatorial and polar radius respectively.
    • \(r_p < r_{eq}\)
Earth Model

- Geodetic Latitude
  \[ \varphi = \arcsin\left(\frac{p_z}{r}\right) \]

- Geodetic longitude
  \[ \lambda = \arctan\left(\frac{p_y}{p_x}\right) \]

- Eccentricity
  \[ \varepsilon = \frac{r_{eq}^2 - r_p^2}{r_{eq}^2} \]
Earth Model

- Earth rotates at a constant speed $\omega_e$
- Velocity at the surface is given by
  $$\nu_0 = \omega_e r_e \cos \varphi$$
- For polar orbiting satellites
  $$\nu_e = \nu_0 \cos(i)$$
  where $i$ is the orbit inclination angle
  - LANDSAT, 9.1° w.r.t. the poles
    $$\nu_e = 0.98769 \ \nu_0$$

$s$, $g$, and $p$ form the fundamental observation triangle
Pixels in a Landsat Thematic Mapper dataset \textit{prior} to correcting for Earth rotation effects

Landsat satellite line of flight

Earth rotates west to east

Entire scan consisting of 16 lines offset to correct for Earth rotation effects

Usually padded with null values (e.g., $BV_{i,j,k} = 0$)

\textit{continued}

(Jensen 2000)
# Earth Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>equatorial radius</td>
<td>6,378.137 km</td>
</tr>
<tr>
<td>polar radius</td>
<td>6,356.752 km</td>
</tr>
<tr>
<td>equatorial circumference</td>
<td>40,075.02 km</td>
</tr>
<tr>
<td>polar circumference</td>
<td>39,940.65 km</td>
</tr>
<tr>
<td>eccentricity</td>
<td>0.00669</td>
</tr>
<tr>
<td>angular velocity</td>
<td>$7.2722052 \times 10^{-5}$ rad/sec</td>
</tr>
</tbody>
</table>
Satellite Orbits

• Standard orbits depend on altitude
  – LEO – low earth orbiting satellite ➔ Few hundreds of miles
  – Geosynchronous ➔ Some 20,000 miles
LEO Satellites

• Sun-synchronous
  – They cross the equator at the same local time,
  – Maintain a constant solar-illumination angle for observations.

• Ascending and descending node orbits
  – Ascending → South to north
    • NASA Aqua 1:30 PM – ascending mode
  – Descending → North to south (most common)
    • NASA Terra 10:30 AM – descending mode
LANDSAT 7

Descending: day, Ascending at night
Topographic Relief (cont.)

- ground point at $A$ actually appears to come from $A_0$ because of topography
Relief Displacement
Topographic Relief

- Image offset proportional to elevation above base plane, or “datum”
- Stereo pair of images can be used to find elevation (see book for more info)
- Imagery corrected for topographic distortion is called “orthographic”
FIGURE 3-34. Geometry of stereo imaging. The distance between the image points $a_1$ and $c_1$ in frame 1 is not equal to the distance between the image points $a_2$ and $c_2$ in frame 2 because of the elevation difference between ground points A and C and the different view points of the two frames. The distance between the two view points (called "camera stations" in aerial photography) is called the "base" $B$ of the stereopair.
• Image parallaxes of ground points A and C are,

\[ p_a = a_1 - a_2 = \frac{fB}{H-Z_A} \]

\[ p_c = c_1 - c_2 = \frac{fB}{H-Z_C} \]

• H and Z are measured relative to the datum plane, image coordinates, a1, a2, c1 and c2 are measured relative to optical center (principal point) of the respective image

\[ \Delta Z = \Delta p \frac{H^2}{fB} = \Delta p \times \frac{H}{f} \times \frac{H}{B} = \frac{\Delta p/m}{B/H}. \]
Summary

• This chapter presents how the sensor and acquisition process modifies the signal of interest in remote sensing.
  – The sensor affects the spatial and radiometric quality of the signal.

• Important aspects
  – Spatial features weighted by sensor PSF.
  – Spectral radiance weighted by sensor spectral response
  – Imaging is an affine transform of the radiance
  – Geometric distortions arise from internal sensor and external platform and topographic factors
Quiz

• Explain PSF, LSF and ESF. How are they related?
• What are optical PSF, detector PSF, image motion PSF.
• How are LSF and ESF measured?
• How is at sensor signal amplified, sampled and quantized.
• Is the sensor model linear? Explain.
• What is sensor calibration.
• What is geometric distortion.
• What is sensor attitude. Explain.
• Explain scanner models and their geometry
• How does earth geometry affect sensor acquisition.
• What is topographic distortion. How is it measured.