Resolution Metrics for Space-Based Imagery

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Overview of Presentation

• Performance dimensions for VNIR/SWIR EO satellites
  – Spatial resolution
  – Spectral resolution
  – Temporal resolution and revisit time
  – Radiometric resolution and accuracy

• Panchromatic and MS/SS/HS Spatial Resolution
  – Implications of Discrete Image Sampling
    • What is the Meaning of “Q”?
      – The GRD versus the GSD
      – The PSF versus the Pixel Pitch (p)
    • Pathways to 1.0m, 0.5m and 0.25m GSD: Variation of D, Q, and H
    • What are the implications of oversampling?
    • What are the implications of super-resolution?
  – Spectral Imaging: the Design of Q for MSI and HSI Sensors
  – Signal-to-Noise (SNR) and Radiometry (Accuracy and Precision)
Panchromatic Spatial Resolution

Diffraction and Sampling Limitations for Point Sources

- **Diffraction-limited resolution**
  \[ GRD = 1.22 \times (\lambda/D) \times H \] (Rayleigh criterion)

- **Sampling-limited resolution**
  \[ GSD = (p/L) \times H = IFOV \times H \]

- “Q” is a property of the sensor only
  \[ Q = (\lambda \times FN)/p, \ FN = L/D \]

- **Q relates GRD and GSD**
  - \[ GRD = 1.22 \times Q \times GSD \]
  - \[ Q = 2 \] for Nyquist sampling (best resolution)
  - Choice of \( Q \) is a critical design feature
### Pathways to Hi-Res PAN: Variation of D, Q, and H

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<th>Aperture D(m)</th>
<th>(\lambda_{\text{mean}}) ((\mu\text{m}))</th>
<th>Pixel Pitch p((\mu\text{m}))</th>
<th>Focal Length L(m)</th>
<th>Q ((\lambda_{\text{mean}}\times FN/p))</th>
<th>IFOV ((\mu\text{rad}))</th>
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\[
\text{IFOV} = \frac{p}{L} = \frac{\lambda_{\text{mean}}}{(Q \times D)}; \quad \text{GSD} = \text{IFOV} \times H
\]
Improving Spatial Resolution at Fixed GSD and Q < 2.0

• **Oversampling** – increasing the effective Q by increasing line rate
  – \( LR = \left( \frac{V_{ss}}{\text{GSD}} \right) \times n \), where \( n > 1 \) (\( V_{ss} \) is the sub-satellite velocity)
  – For 1m GSD, \( LR \approx 7000 \text{ lines/sec} \)
  – Examples: EROS-B (ISR) and Pleiades (FRA)

• **Super-Resolution** – a class of techniques to enhance resolution
  – Optical SR can overcome the diffraction limits in Fourier optics
  – Geometrical SR superimposes multiple exposures of images

• **Implications for NOAA regulation**
  – Core regulatory authority is over “operational capability”
  – **Oversampling** in satellite RS systems requires a specific “operational” mode related to line rate and possibly back-scanning
  – **Super-resolution** in satellite RS is a different “operational” mode, often related to dithering a 2-D camera pointing axis
  – Licenses could explicitly limit the use of either mode to improve the ability (CDP or customer) to improve “effective” GSD licensing thresholds
• PAN systems are designed to sample the PSF in multiple pixels
• MSI/HSI systems should constrain the PSF for spectral bands to 1 pixel
  – The pixel location of a “point source of color” should be unambiguous
  – Larger pixels also produce greater SNR ($S \propto Q^2$)
• Co-boresighted PAN/MSI systems differ in IFOV and therefore GSD, but…
  – Additional utility can be derived from PAN-sharpened MSI images
  – PAN-sharpening is different from advanced spectral-spatial analysis
Implications for NOAA/NASA RS Satellites
Technology Transfer and Export Review

- Technology versus image quality
  - \( Q = (\lambda \times FN)/p = (\lambda \times L)/(D \times p) \)
  - \( p/L = \text{IFOV} = \lambda/(Q \times D) \)

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\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|}
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\text{Aperture (m)} & \lambda_{\text{mean}} (\mu m) & \text{Pixel Pitch (\mu m)} & \text{Focal Length (m)} & Q (\lambda \times FN/p) & \text{IFOV (\mu rad)} & H (\text{km}) & 350 & 400 & 450 & 500 & 550 & 600 & 650 & 700 \\
\hline
0.70 & 0.675 & 8.00 & 6.64 & 0.8 & 1.21 & & 0.42 & 0.48 & 0.54 & 0.60 & 0.66 & 0.72 & 0.78 & 0.84 \\
0.70 & 0.675 & 8.00 & 8.30 & 1 & 0.96 & & 0.34 & 0.39 & 0.43 & 0.48 & 0.53 & 0.58 & 0.63 & 0.68 \\
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GSD = IFOV x H = constant at a given H for hyperspectral
In Summary

**Definitions:**

- $GRD = 1.22 \times (\lambda/D) \times H$
- $GSD = (p/L) \times H = IFOV \times H$
- $IFOV = p/L = \lambda/(Q \times D), \ Q = (\lambda \times FN)/p$

- **Aperture constrains best possible spatial resolution for satellite imagers**
  - **Single band systems** (VNIR, SWIR, MWIR, LWIR) are optimized for spatial resolution, aliasing reduction, and SNR
  - **Best resolution attainable** for high-resolution PAN largely determined by system GRD (i.e., aperture)

- **Spectrally-resolved systems** (MSI, SSI, HSI) constrain spatial sampling to a single pixel using $Q \ll 1$
  - Effective resolution is often determined by GSD alone
  - **Instantaneous Field-of-View** (IFOV) is a useful intrinsic sensor metric
  - Regulators would be wise to use IFOV to inform export evaluation of large aperture spectrally-resolved systems (e.g., meteorological sensors)
Back-Up