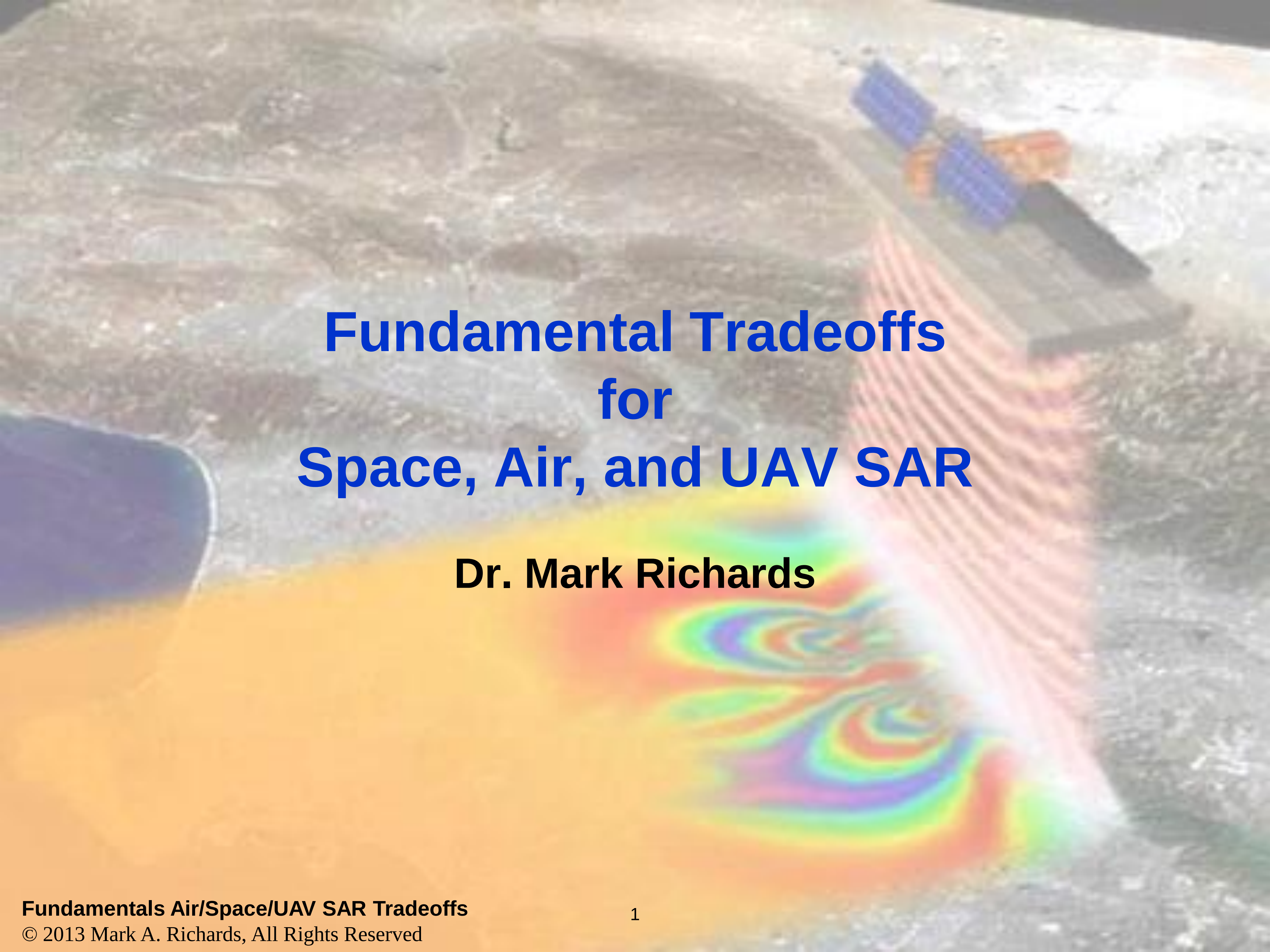

Fundamental Tradeoffs for Space, Air, and UAV SAR

Dr. Mark Richards

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Rohde & Schwarz

The expert in
test & measurement,
broadcasting,
secure communications,
radiomonitoring & radiolocation

ROHDE&SCHWARZ

Company overview

- **History**
  Established 1933 in Munich, Germany
- **Type of enterprise**
  Independent family-owned company
- **Global presence**
  In over 70 countries, approx. 60 subsidiaries
- **Net revenue**
  EUR 1.8 billion (FY 11/12, July through June)
- **Employees**
  8800 worldwide
  - 5600 in Germany
  - >400 in US
- **Success**
  A leading international supplier in all of its business fields

Business fields

Test and measurement

Radiomonitoring and radiolocation

Secure communications

High relevance to the aerospace and defense industry

Broadcasting

Services

T&M instruments for radar applications (selection)

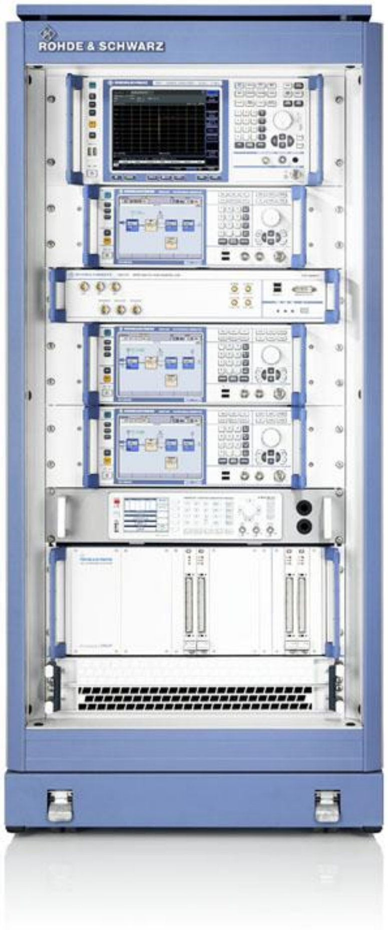
R&S®SMF100A
microwave signal generator

- Sets new standards in signal quality, speed and flexibility
- Outstanding pulse capabilities for radar component and system testing

R&S®FSW
signal and spectrum analyzer

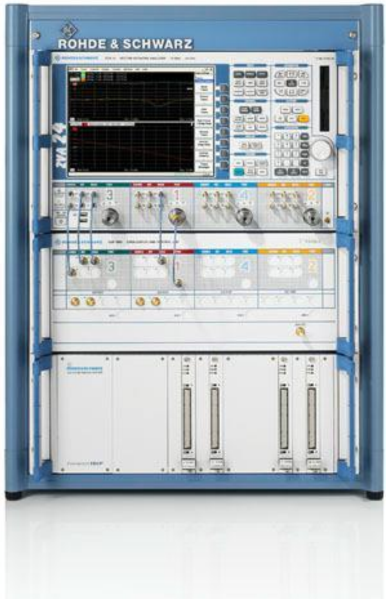
- Unprecedented low phase noise for developing receivers, transmitters and oscillators
- Comprehensive pulse analysis capabilities
- **Real-time analysis (600,000 FFT/s)**
- **320 MHz vector analysis bandwidth to 50 GHz**

Radar test systems



R&S®TS6600
radar test generator

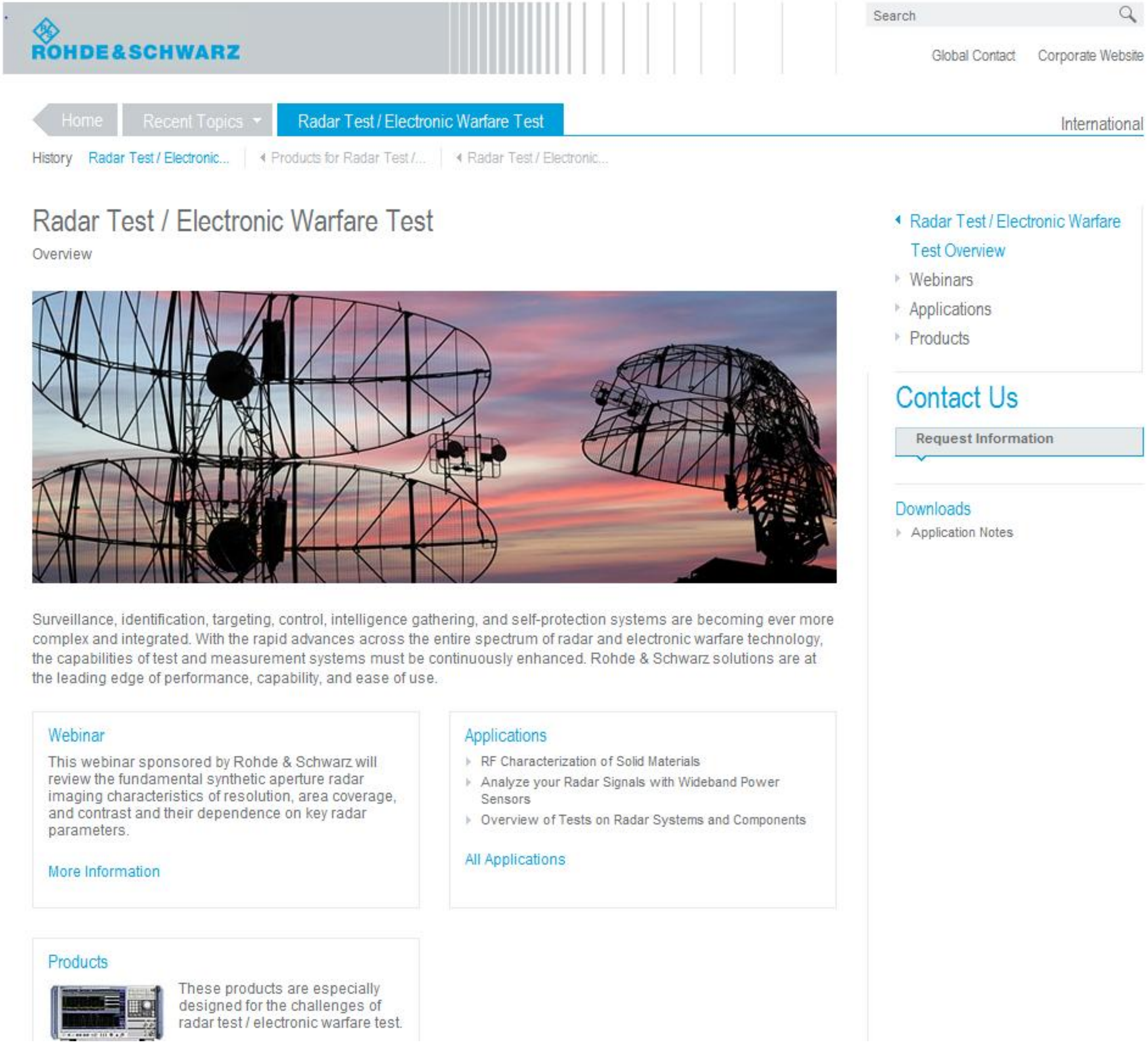
- For phase-coherent measurements on radar frontends in development, production and service



R&S®TS6710
TRM radar test system

- For automatic RF measurements on TR modules in development and production
- Very short test times,
  typ. 15 s per module (2500 values)
- Parallel device test configurations

For details, see www.rohde-schwarz.com



Radar Test / Electronic Warfare Test

Overview

Surveillance, identification, targeting, control, intelligence gathering, and self-protection systems are becoming ever more complex and integrated. With the rapid advances across the entire spectrum of radar and electronic warfare technology, the capabilities of test and measurement systems must be continuously enhanced. Rohde & Schwarz solutions are at the leading edge of performance, capability, and ease of use.

Webinar

This webinar sponsored by Rohde & Schwarz will review the fundamental synthetic aperture radar imaging characteristics of resolution, area coverage, and contrast and their dependence on key radar parameters.

More Information

Applications

- RF Characterization of Solid Materials
- Analyze your Radar Signals with Wideband Power Sensors
- Overview of Tests on Radar Systems and Components

All Applications

Products

These products are especially designed for the challenges of radar test / electronic warfare test.

What is SAR?

- **Synthetic Aperture Radar – *Imaging* radar**
- **Generate fine resolution 2D and 3D images**
- **Requires motion of the radar sensor relative to the scene to be imaged**
  - **Airborne and spaceborne platforms**

TerraSAR-X Image of Rio de Janeiro

http://www.infoterra.de/image-gallery/images.html

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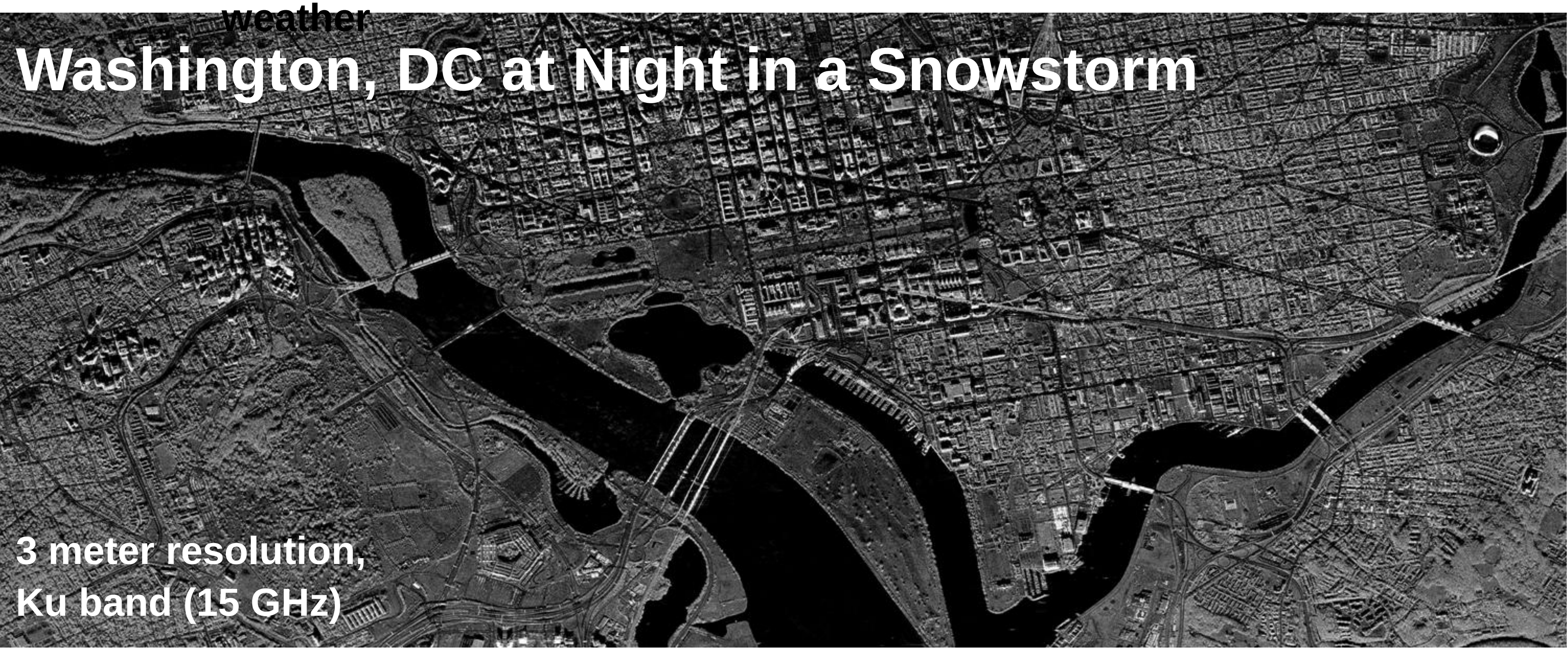
Why SAR?

- Compared to optical imagery, SAR imagery is
  - Poorer resolution -– Monochrome
  - Subject to “unusual” phenomenology such as layover and speckle
- But SAR works 24/7
  - Active system -– Microwave wavelength penetrate weather



Washington, DC at Night in a Snowstorm

3 meter resolution,
Ku band (15 GHz)

Image courtesy of Sandia National Laboratories
http://www.sandia.gov/RADAR/images/dc_big2.jpg

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Broadly Speaking, Some Sample Mission Requirements

Parameter	Earth Resources	Detection, Monitoring, Mapping	Classification, Dismount Detection
Resolution (m)	10s – 100s	1s – 10s	< 1
Swath Length (km)	10s – 100s	1s – 10s	< 10
Area Coverage (km^2/hr)	> 100,000s	1000s	10s
Standoff Range	long	medium	short
Polarization	multiple	multiple	single
Response Time	days	hours	minutes
Wavelength	L, C (X)	L, X	X, Ku, Ka

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Three SARs: Representative Stripmap Modes

Parameter	Spaceborne RADARSAT-2	Airborne E-SAR	UAV TESAR
Resolution (m)	25	2.5	1
Swath Length (km)	100	4	0.8
Area Coverage (km^2/hr)	380,000	1000	86
RF Band	C	P, L, C, X	Ku
Antenna (m)	1.5 × 15	0.5 × 1.25	0.34 × 1.25
Velocity (m/s)	7000	70	30

- *Why are they different in RF, antenna size, resolution, and area coverage?*
- *And what are some of the basic design choices that control those differences?*

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Determinants of SAR Image Characteristics

Imaging Characteristics	Primary Determinants
Phenomenology • Clutter reflectivity • Weather Penetration	EM Wave Characteristics • RF • Polarization • Incidence Angle
Resolution • Range • Cross-Range	Bandwidth • Range: Waveform • Cross-Range: Doppler
Area Coverage Rate • Swath Length • Stripmap: Velocity • Spotlight: Aperture Time	Ambiguities and Antenna Footprint • PRF • Antenna Size
Contrast, Sensitivity • Noise-equivalent σ^0 • Multiplicative noise ratio (MNR)	Range Equation for SAR • Power-Aperture^2 • RF • Resolution

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Resolution and Bandwidth

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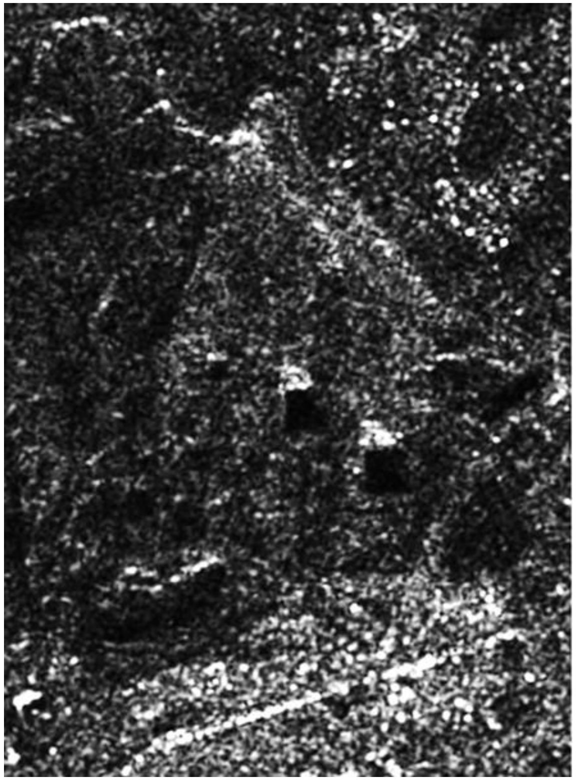
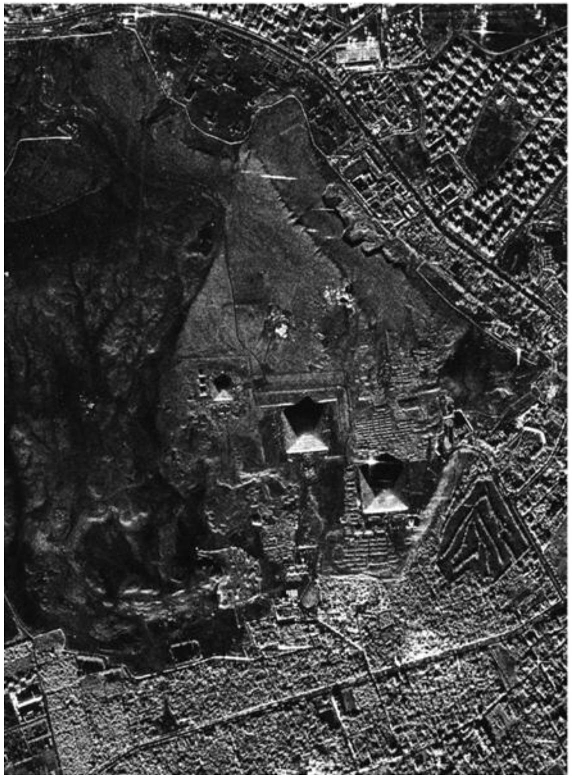
Two Spaceborne SAR Images of the Pyramids of Giza

C band, 20 m resolution



X band, 1 m resolution



- Source: “A Tutorial on Synthetic Aperture Radar”, A. Moreira et al, IEEE Geoscience & Remote Sensing Magazine, March 2013.

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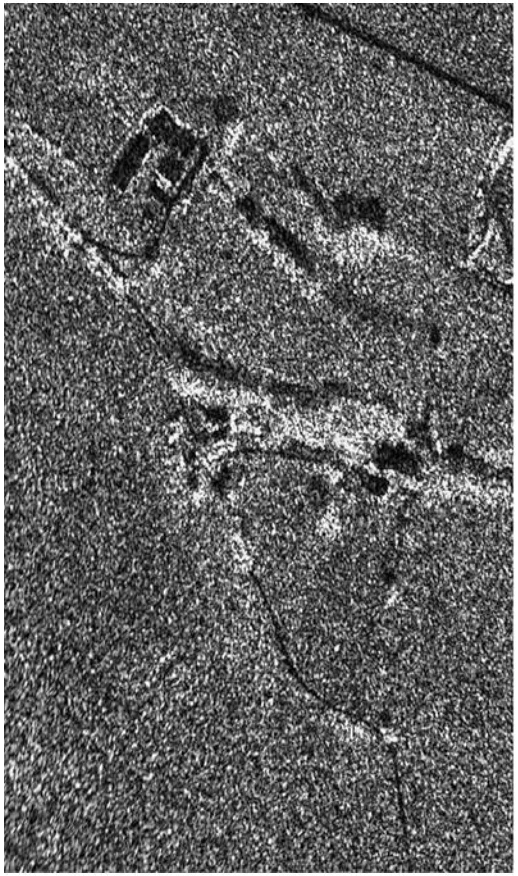
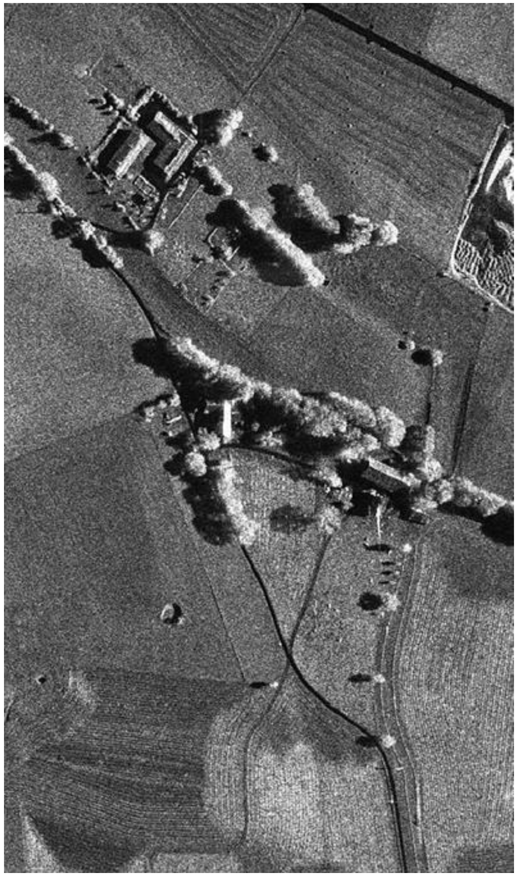
Two Airborne Images

X band, 1 m resolution



X band, 0.25 m resolution



- Source: “A Tutorial on Synthetic Aperture Radar”, A. Moreira et al, IEEE Geoscience & Remote Sensing Magazine, March 2013.

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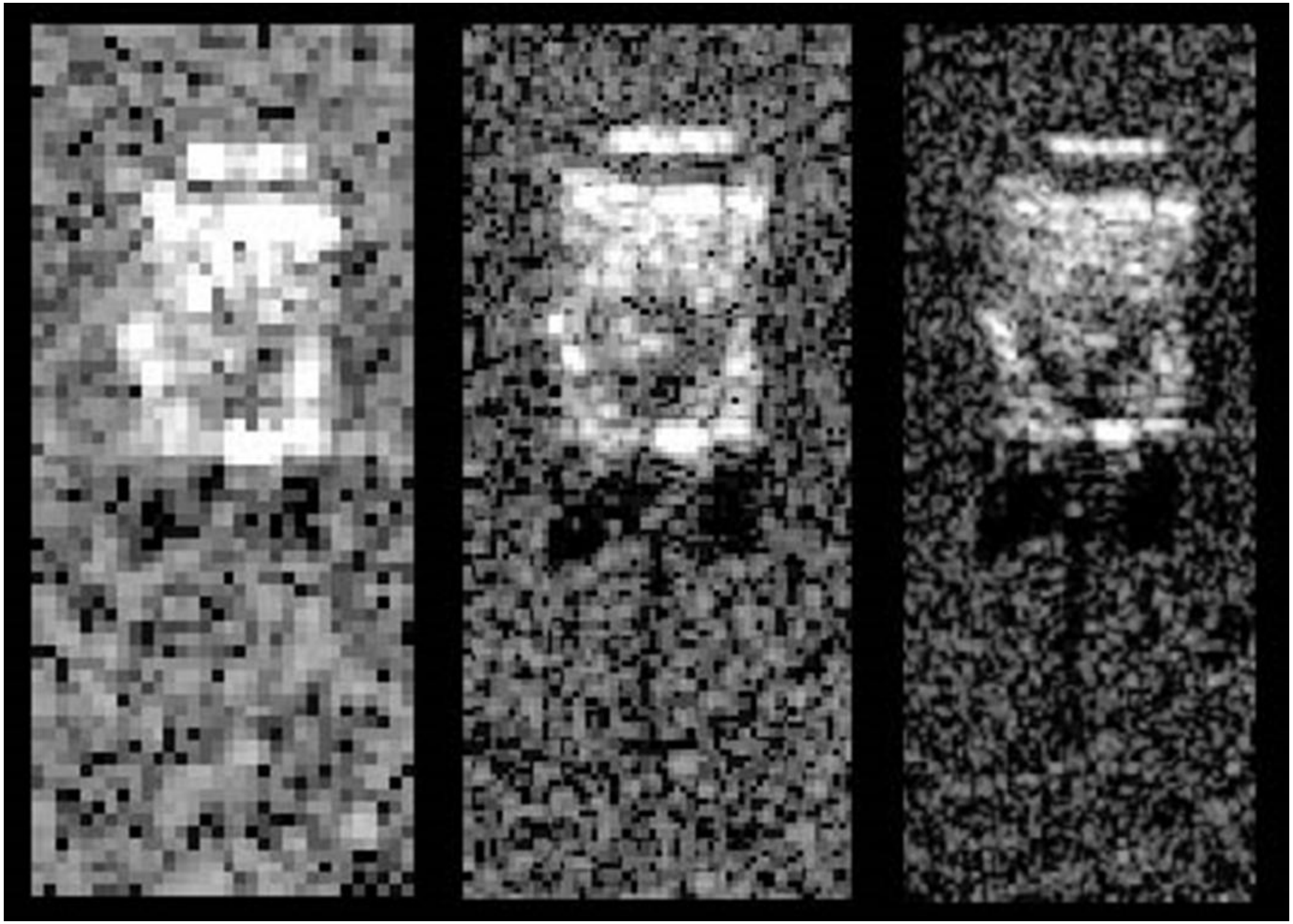
Three Levels of Fine Resolution of a Vehicle



1 foot (~ 30 cm)

6 inch (~ 15 cm)

4 inch (~ 10 cm)

Image courtesy of Sandia National Laboratory

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Range Resolution

$$\boxed{\Delta R = \frac{c}{2B} \text{ m}}$$

- c = speed of light = 3×10^8 m/s
- B = waveform bandwidth
- ΔR = range resolution

Resolution	**100 m**	**10 m**	**1 m**
Bandwidth	1.5 MHz	15 MHz	150 MHz

- **Range resolution inversely proportional to fast-time bandwidth**
- **Wideband waveforms and pulse compression used to achieve desired range resolution**
- **Typically linear FM (“chirp”)**
- **Weighting for sidelobe control requires an extra 50% bandwidth**

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Implications of Finer Range Resolution

- Finer range resolution → wider bandwidth waveforms
  - Wider bandwidth transmitters and receivers
- Wider bandwidth → higher RF to remain narrowband
- Faster A/D converters
  - Possibly fewer bits → increased quantization noise
  - Larger memories
  - Faster data links
  - Higher computing rates
- Frequency scanning losses in phase-steered array antennas
  - Possible need to adopt multi-pulse stepped frequency waveforms
- Same issues for airborne and spaceborne
- Same issues for stripmap and spotlight

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Stripmap Cross-Range Resolution

$$\Delta CR = v \cdot \Delta t = \frac{v}{B_D} \text{ m}$$

- v = platform velocity
- B_D = Doppler bandwidth
- ΔCR = cross-range resolution

Doppler Bandwidth		
Cross-Range Resolution	Airborne (100 m/s)	LEO Satellite (7500 m/s)
100 m	1 Hz	75 Hz
10 m	10 Hz	750 Hz
1 m	100 Hz	7500 Hz

- **Cross-range resolution inversely proportional to slow-time (Doppler) bandwidth**
- **Doppler bandwidth proportional to integration angle**
- **Desired cross-range resolution achieved using**
  - **Wide antenna beam or beam steering to illuminate scatterer over required angle**
  - **Matched filtering of slow-time signal**
- **Weighting for sidelobe control requires an extra 50% bandwidth**

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Implications of Finer Cross-Range Resolution in Stripmap

- Finer cross-range resolution → larger Doppler bandwidth, larger integration angle
- Larger integration angle → smaller antenna (azimuth) in stripmap SAR → reduced gain, SNR
- Larger Doppler bandwidth → Increased PRF → reduced area coverage
  - Discussed momentarily

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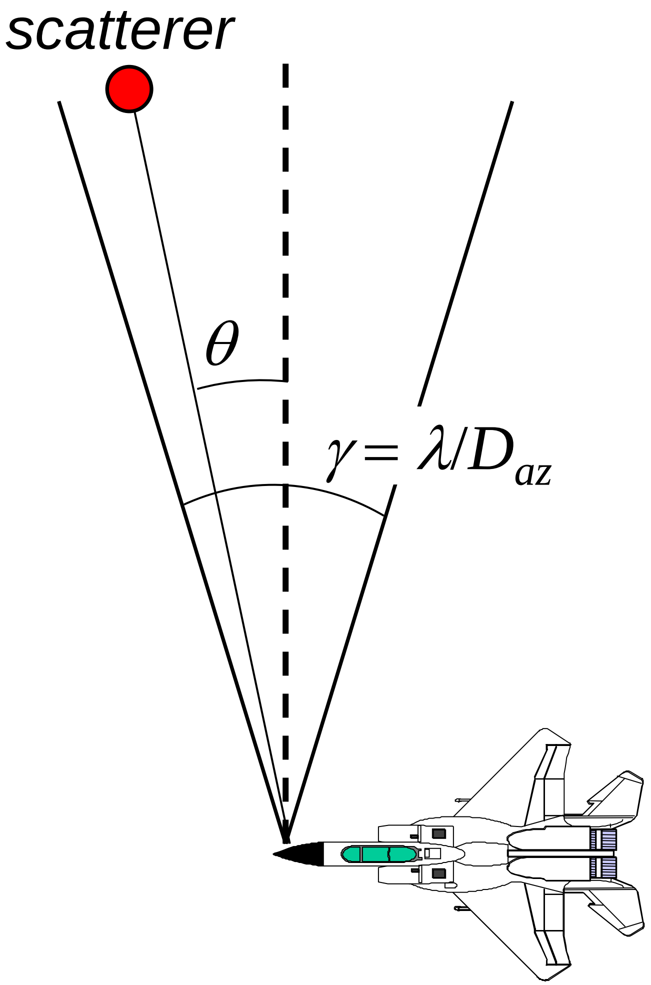
Best-Case Sidelooking Stripmap Cross-Range Resolution



- **Doppler shift of stationary scatterer:**

$$F_D = (2v/\lambda)\sin\theta$$

- **Doppler bandwidth as look angle varies over an integration angle γ:**

$$\Rightarrow B_D \approx 2v\gamma/\lambda$$

- **Max integration angle is the beamwidth** $= \lambda/D_{az}$

$$\boxed{\Rightarrow \Delta CR_{\min} = \frac{v}{B_{D_{\max}}} \approx \frac{D_{az}}{2}}$$

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Area Coverage and Ambiguities: PRF and Antenna Size

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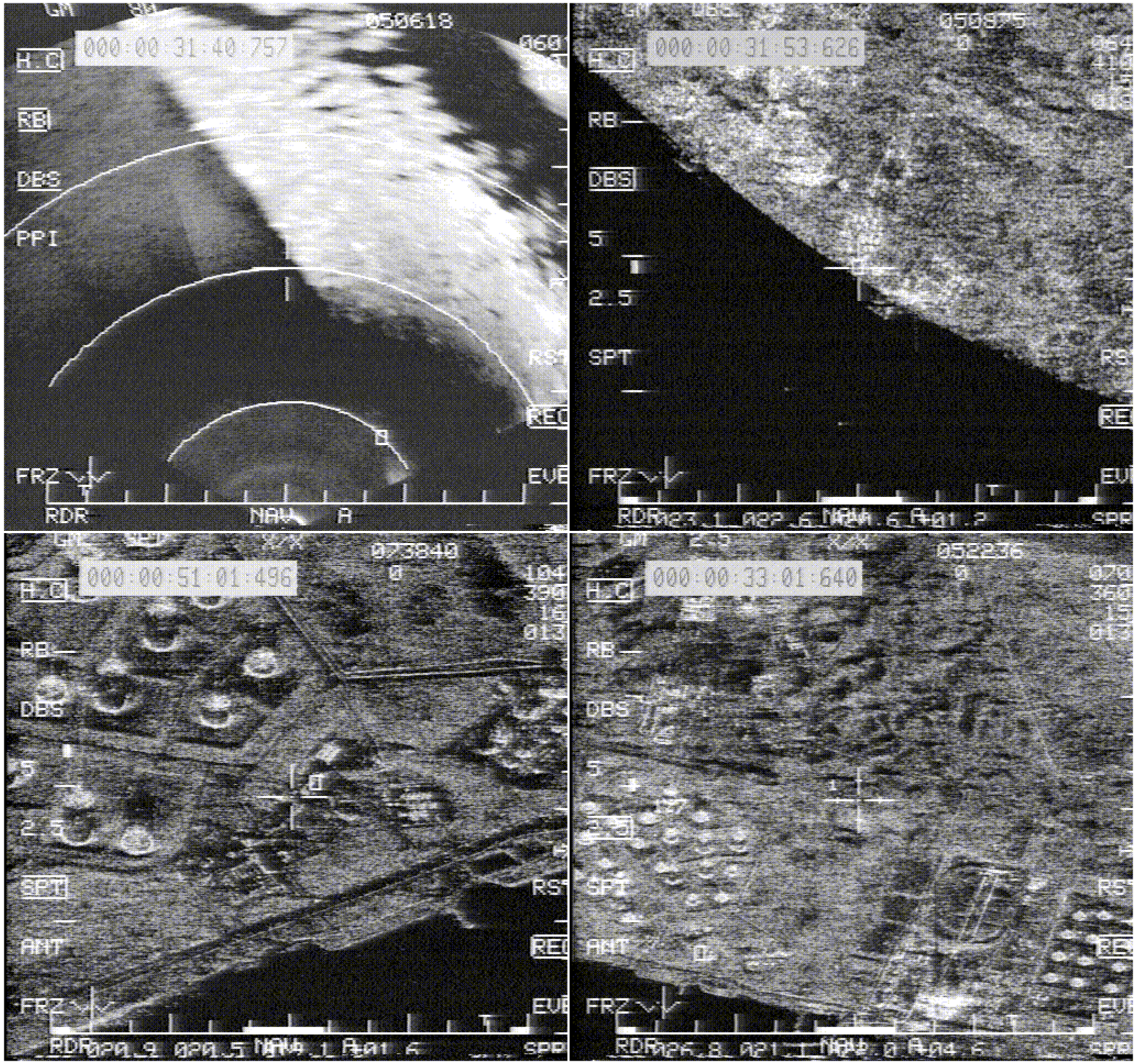
Comparison of Imaging Modes, Airborne Multi-Mode Radar Terrain Imagery

- Real Beam
  - resolution not specified

- Doppler Beam Sharpening
  - resolution not specified



Courtesy of
Westinghouse
Norden
Systems

- Spotlight SAR
  - resolution not specified

- Stripmap SAR
  - 2.5 m resolution

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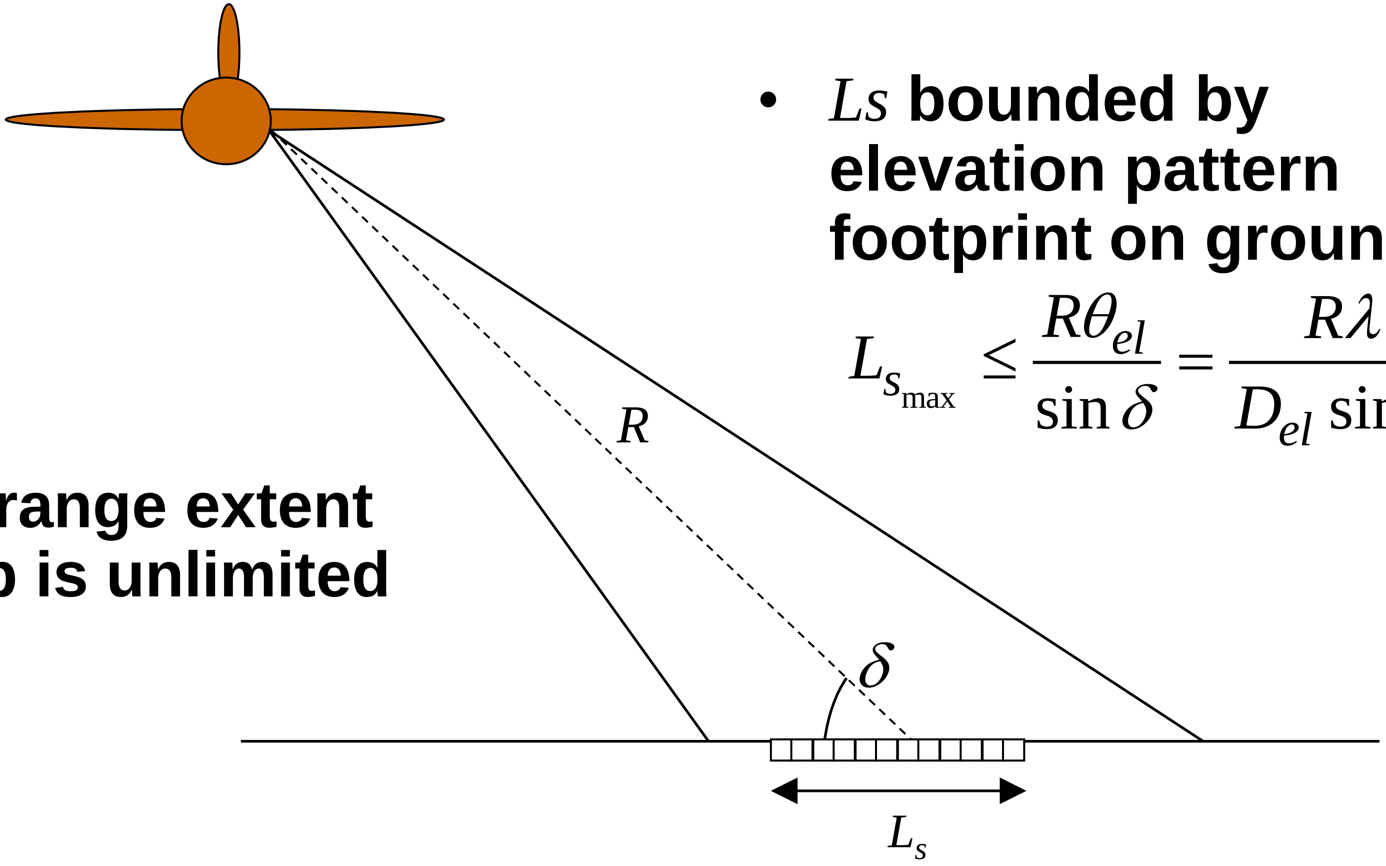
Swath Length and Mapping Rate

- **We map a strip L_s meters deep while moving forward at v m/s**
- **Area coverage rate is therefore** $\boxed{A = vL_s \quad \mathrm{m}^2/\mathrm{s}}$



- **Ls bounded by elevation pattern footprint on ground:**

$$L_{s_{\max}} \leq \frac{R\theta_{el}}{\sin\delta} = \frac{R\lambda}{D_{el}\sin\delta}$$

- **Cross-range extent of map is unlimited**

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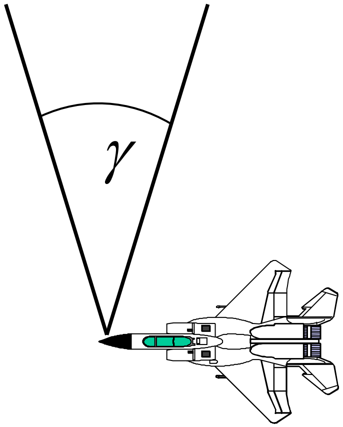
PRF is Constrained …

From below by the Doppler bandwidth

- Doppler bandwidth is

$$B_D = \frac{2v\gamma}{\lambda}$$

$$= \frac{v}{\Delta CR}$$



- Result is

$$\boxed{PRF \geq B_D = \frac{v}{\Delta CR}}$$

From above by range ambiguity and eclipsing

- Swath length establishes range ambiguity requirement

- Result is

$$\boxed{PRF \leq \frac{c}{2L_s \cos\delta}}$$

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Stripmap Range Bin Constraint & Implications

$$\frac{v}{\Delta CR} \le PRF \le \frac{c}{2L_s \cos\delta} \quad \Longrightarrow \quad \boxed{\left(\frac{L_s}{\Delta CR}\right)\cos\delta \le \frac{c}{2v}}$$

- **Left hand side is proportional to the number of range bins in the swath**
- $c/2v$ **≈ 20,000 for LEO satellites and space shuttle,**
  ≈ 300,000 to 750,000 for airborne SAR
- **Implies that increasing swath length may require increasing (degrading) cross-range resolution also**
  - **Rarely a problem in airborne SAR**
  - **could get tight in spaceborne SAR**

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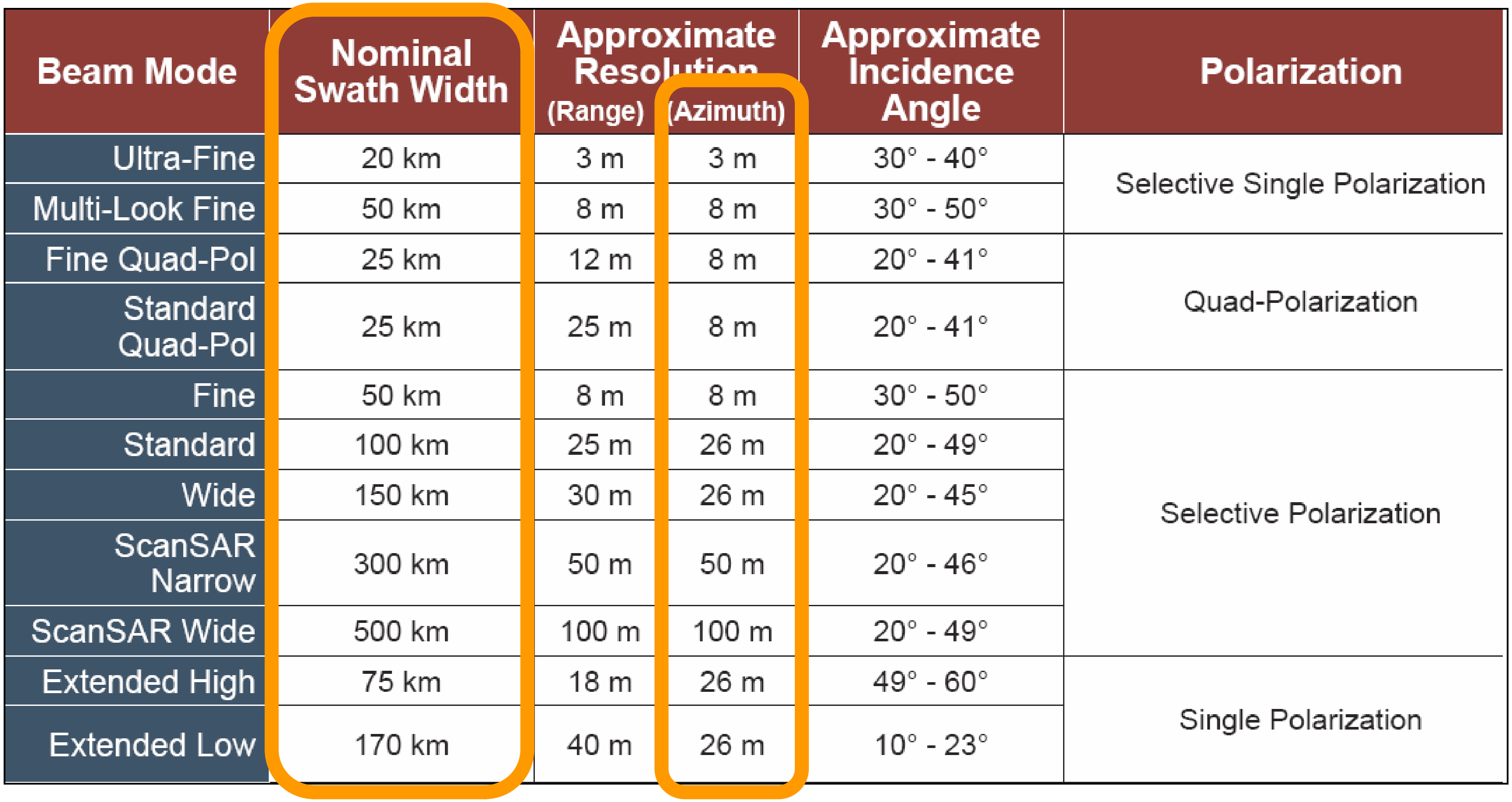
RADARSAT-2 Stripmap Modes



Beam Mode	Nominal Swath Width	Approximate Resolution		Approximate Incidence Angle	Polarization
		(Range)	(Azimuth)		
Ultra-Fine	20 km	3 m	3 m	30° - 40°	Selective Single Polarization
Multi-Look Fine	50 km	8 m	8 m	30° - 50°	
Fine Quad-Pol	25 km	12 m	8 m	20° - 41°	Quad-Polarization
Standard Quad-Pol	25 km	25 m	8 m	20° - 41°	
Fine	50 km	8 m	8 m	30° - 50°	Selective Polarization
Standard	100 km	25 m	26 m	20° - 49°	
Wide	150 km	30 m	26 m	20° - 45°	
ScanSAR Narrow	300 km	50 m	50 m	20° - 46°	
ScanSAR Wide	500 km	100 m	100 m	20° - 49°	
Extended High	75 km	18 m	26 m	49° - 60°	Single Polarization
Extended Low	170 km	40 m	26 m	10° - 23°	

http://www.asc-csa.gc.ca/eng/satellites/radarsat/radarsat-tableau.asp

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Stripmap Swath and Mapping Rate Constraints

- **If we set ΔCR to its finest stripmap value of $D_{az}/2$, the same two PRF bounds gives a stripmap swath constraint ...**

$$\boxed{L_s \le \frac{cD_{az}}{4v\cos\delta}\ \text{meters}}$$

- **… which, using $A = vL_s$, in turn gives a stripmap mapping rate constraint:**

$$\boxed{A \le \frac{cD_{az}}{4\cos\delta}\ \mathrm{m}^2/\mathrm{s}}$$

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Implications of Stripmap Swath and Mapping Rate Constraints

$$\boxed{L_s \le \frac{cD_{az}}{4v\cos\delta}\ \text{meters}} \qquad \boxed{A \le \frac{cD_{az}}{4\cos\delta}\ \text{m}^2/\text{s}}$$

- **Deeper swath requires wider antenna**
- **Faster platform requires wider antenna for a given swath length**
- **Higher mapping rate requires wider antenna**
- **Wider antenna implies**
  - **Greater gain, SNR: good for contrast**
  - **Larger and heavier**
- **Recall finer resolution required narrower antenna → Conflict between mapping rate and cross-range resolution**
  - **Seen in the 4-mode airborne images and in the RADARSAT modes**

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Antenna Area Constraint & Implications

- **If also swath length set to antenna footprint bound,**

$$L_s = R\lambda / D_{el} \sin\delta$$

- **Result is the antenna area constraint:**

$$\boxed{D_{az} D_{el} \geq \frac{4 v \lambda R}{c \tan\delta}}$$

- **Faster platform requires larger antenna area**
- **Longer-range platform requires larger antenna area**
- **Both show that larger antennas needed for spaceborne than for airborne SAR**
- **Lower RF also requires larger antenna area**
  - **RADARSAT: C band,1.5×15 m = 22.5 m^2 antenna**
  - **TerraSAR-X: X band, 0.8×4.8 m = 3.84 m^2 antenna**

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Contrast and Sensitivity

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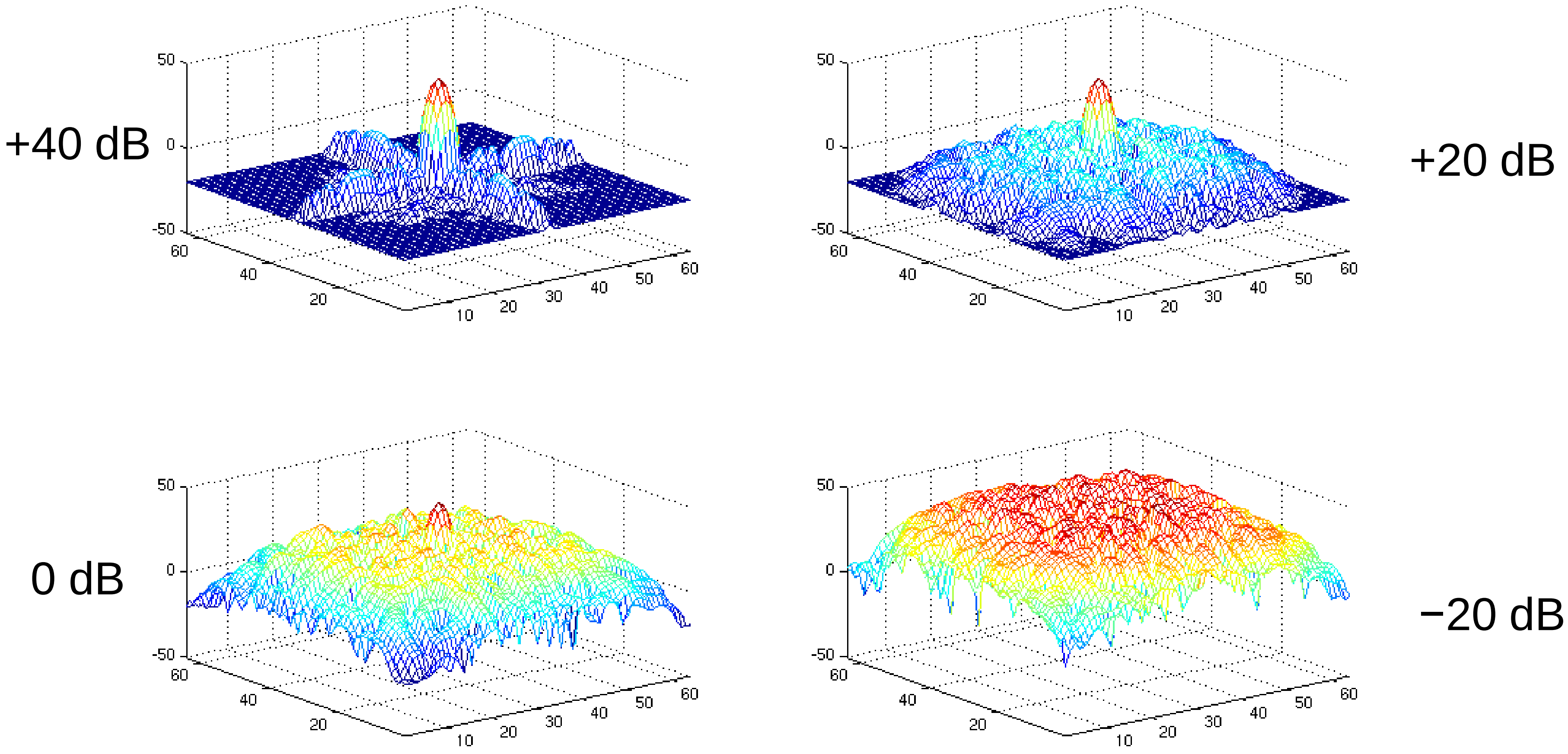
Effect of Additive Noise on Simulated Point Scatterer Image



- **SNR listed is on single sample**
- **32x32 signal gives 30 dB compression gain**

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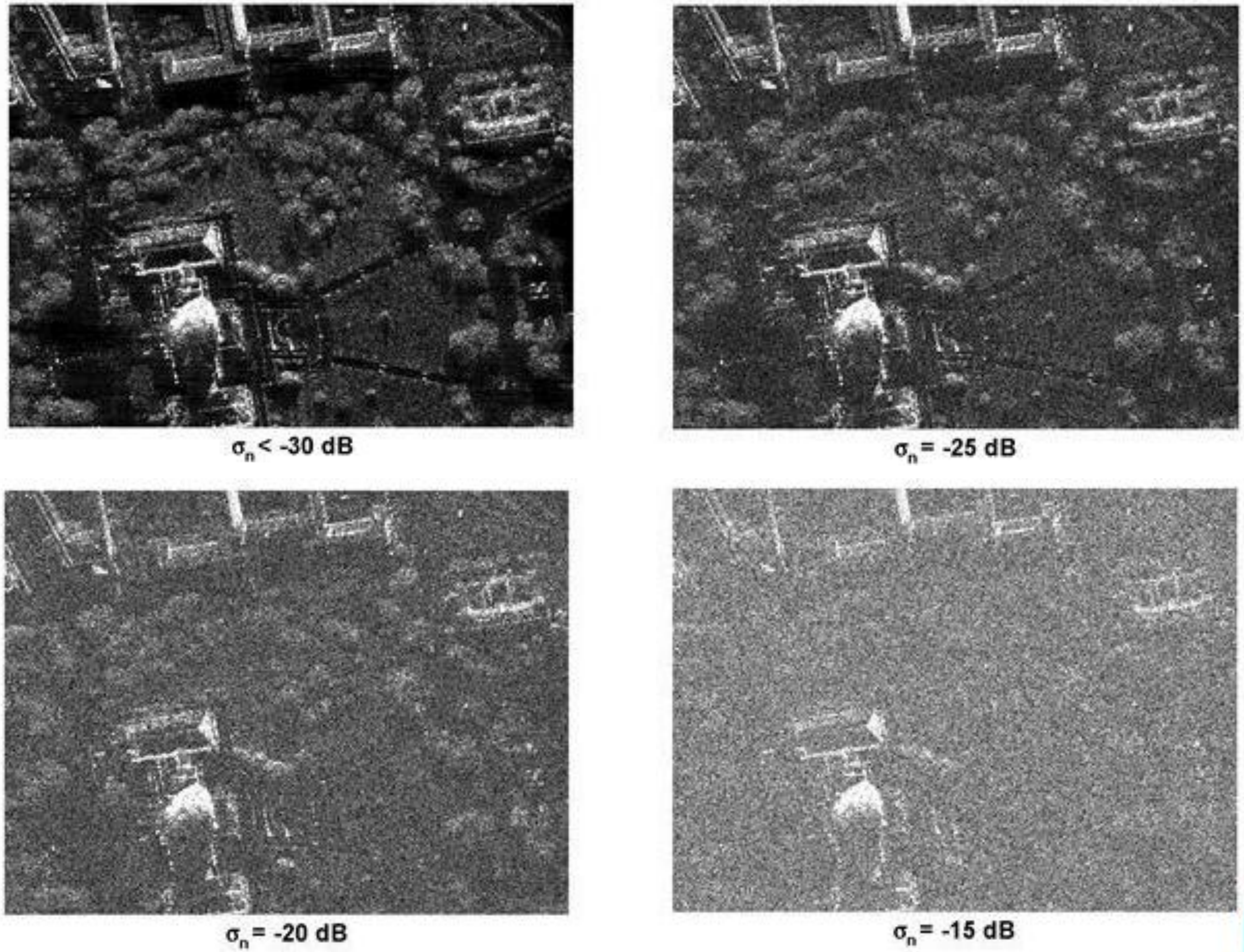
SNR Affects SAR Image Contrast

- **Rising noise floor fills in shadow regions**
  - **reduces image contrast and dynamic range**
- **No impact on spatial resolution**

Example SAR Image Sensitivities
U. S. Capitol Building



$\sigma_n < -30$ dB

$\sigma_n = -25$ dB

$\sigma_n = -20$ dB

$\sigma_n = -15$ dB

Images courtesy of Sandia National Laboratories
http://www.sandia.gov/radar/images

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How Do We Improve SNR, CNR in a SAR?

- **Look at the radar range equation**
  - **But specialize it to highlight the role of resolution**
- **Typical results are**

Point Target-to-Noise

$$SNR = \frac{1}{8\pi k T_0 F L} \cdot \frac{P_{av} A_e^2}{v \lambda R^3} \cdot \frac{\sigma}{\Delta CR}$$

Clutter-to-Noise

$$CNR = \frac{1}{8\pi k T_0 F L} \cdot \frac{P_{av} A_e^2}{v \lambda R^3} \cdot \sigma^0 \Delta R$$

P_{avg} = average transmitted power
A_e = effective antenna aperture
λ = wavelength
σ = RCS of point target
σ^0 = area reflectivity of clutter

R = range
k = Boltzmann's constant
T_0 = standard temperature
F = noise figure of receiver
L = loss factors

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SNR, CNR Dependence in SAR

Point Target-to-Noise

$$SNR = \frac{1}{8\pi kT_0FL} \cdot \frac{P_{av}A_e^2}{v\lambda R^3} \cdot \frac{\sigma}{\Delta CR}$$

Clutter-to-Noise

$$CNR = \frac{1}{8\pi kT_0FL} \cdot \frac{P_{av}A_e^2}{v\lambda R^3} \cdot \sigma^0 \Delta R$$

- **SNR, CNR both increase with average power, aperture size, and frequency; decrease with velocity**
  - **so higher frequencies better for a given aperture size**
  - **spaceborne at a disadvantage (for fixed average power)**
- **Point target SNR increases with finer cross-range resolution, but independent of range resolution**
- **Clutter-to-noise CNR decreases with finer range resolution, but independent of cross-range resolution**

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Noise-Equivalent Sigma-Zero (NESZ)

- NESZ is a measure of the clutter reflectivity that will produce CNR = 1 (0 dB)
  - CNR > 3 dB for adequate quality image
- Used as a measure of minimum σ^0 that can be imaged successfully
  - lower values of NESZ signify greater sensitivity

$$\boxed{\mathrm{NESZ} = \sigma_n = 8\pi k T_0 F L \cdot \frac{\lambda v \Delta R}{P_{av} A_e^2 R^3}}$$

- NESZ better (smaller) at higher frequency, slower platform, finer range resolution
- NESZ independent of cross-range resolution

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Computational Rates, Data Rates, and Computing Power Efficiency

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ROM SAR FLOPS & Data Rate Requirements

- **Computational rate can be estimated based on number of samples**

$$\boxed{CR \approx O\left(\frac{2\lambda Rc}{\Delta CR \cdot \Delta R^2}\right) \propto \frac{R}{\Delta^3}}$$

- **Raw data rate:**

$$\boxed{R_{in} = 25B = 12.5c/\Delta R \ \text{bps}}$$

  - **2.5× oversampling, ~10 bits/sample, no compression, no buffering**
- **Examples:**
  - **SIR-B: R = 225 km, 1.28 GHz, 25 m resolution:**
    - ~2 Gflops, ~150 Mbps
  - **LEO Surveillance: R = 770 km, 10 GHz, 3 m resolution:**
    - ~500 Gflops, ~1.25 Gbps
- **Extra channels increases proportionally**

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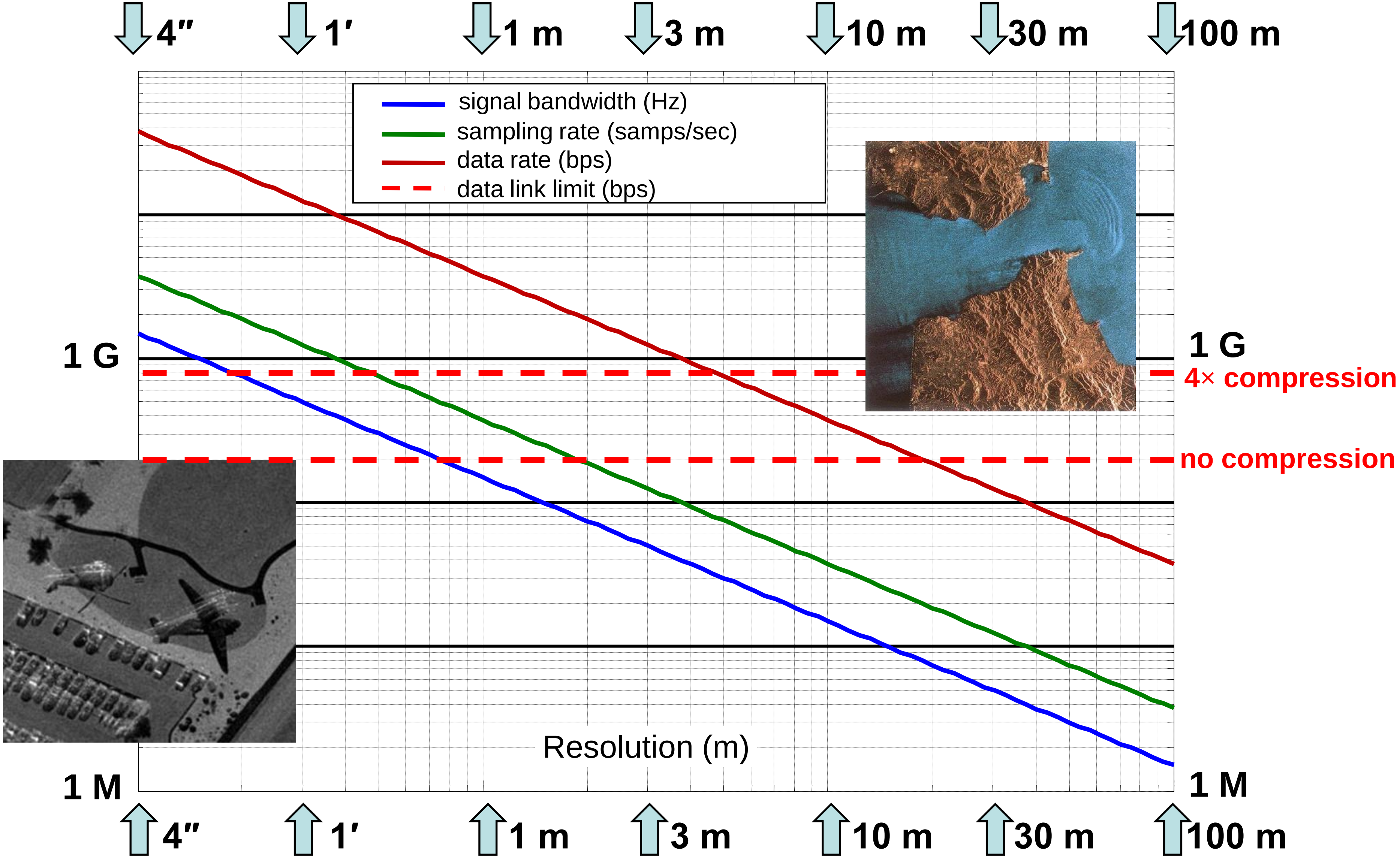
SAR Input Data Rates



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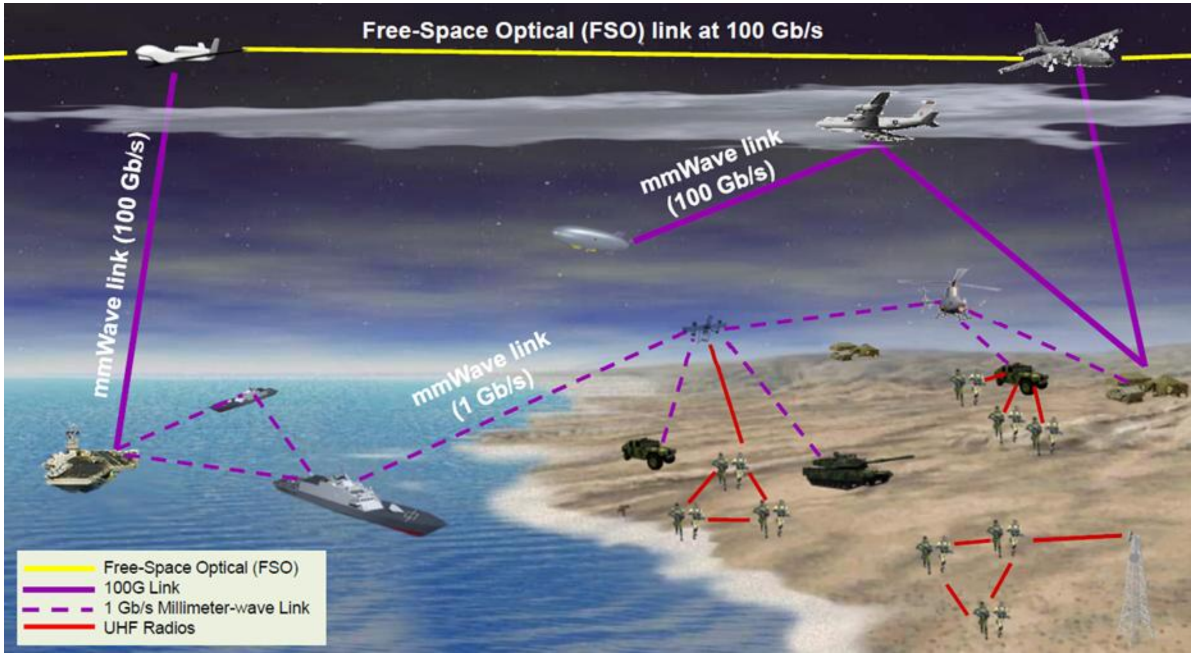
Link Capacity

- **Current State of the Art:**
  - **NASA Tracking and Data Relay Satellite (TDRSS)**
    - up to 300 Mbps
  - **DoD Common Data Link (CDL)**
    - ~200 Mbps per channel
- **Data compression helps by ~4×**

L3 Communications AT2740-3 Airborne Data Link

- **Future link?**
  - **DARPA “Backbone” program working on high capacity tactical data links**
  - **100 Gbps free space optical**
  - **1 and 100 Gbps millimeter wave**
  - **CDL power and weight**



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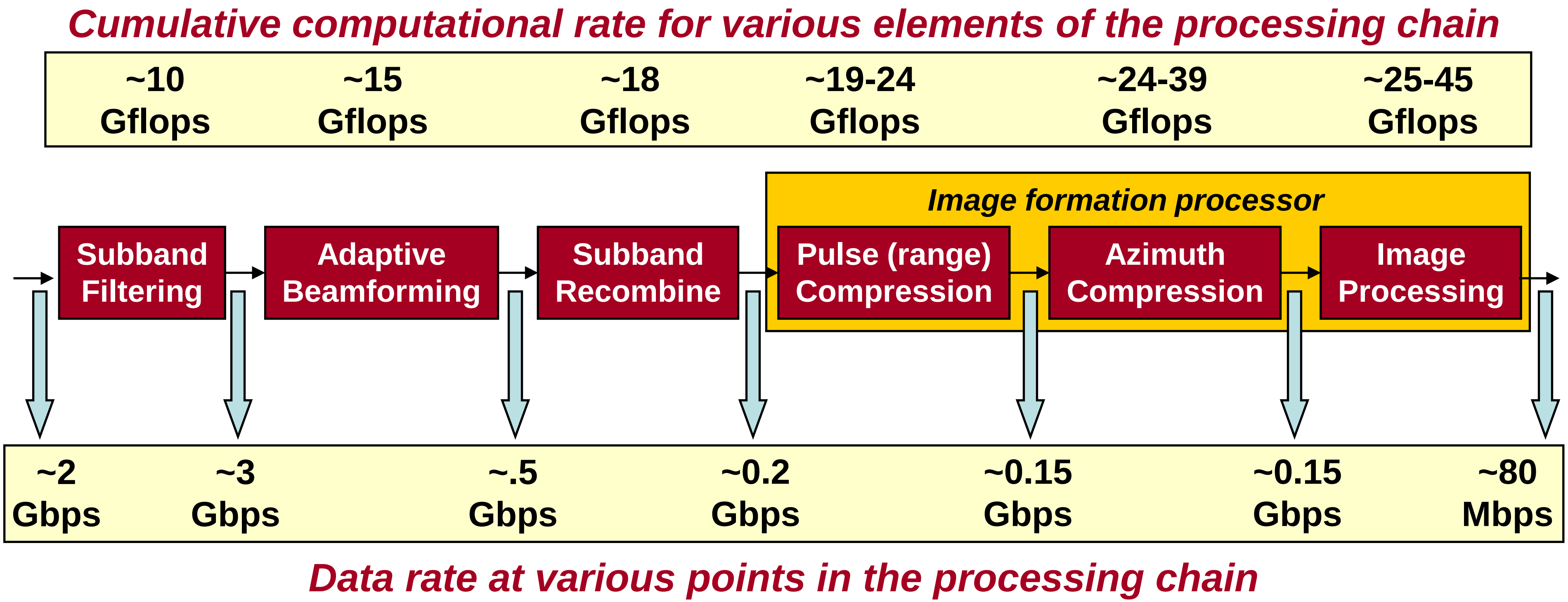
Limited Link Capacity Pushes Heavy Processing Onboard

- **Notional LEO surveillance system with interference cancellation**
- **~4:1 data compression; ~16:1 on imagery**


Cumulative computational rate for various elements of the processing chain

~10 Gflops | **~15 Gflops** | **~18 Gflops** | **~19-24 Gflops** | **~24-39 Gflops** | **~25-45 Gflops**

Image formation processor

Subband Filtering → **Adaptive Beamforming** → **Subband Recombine** → **Pulse (range) Compression** → **Azimuth Compression** → **Image Processing**

~2 Gbps | **~3 Gbps** | **~.5 Gbps** | **~0.2 Gbps** | **~0.15 Gbps** | **~0.15 Gbps** | **~80 Mbps**

Data rate at various points in the processing chain

- ***With only a 200 Mbps link, subbanding, adaptive beamforming, and recombine must be onboard → 18 Gflops onboard***
- ***2 Gbps link would allow offloading of all processing***

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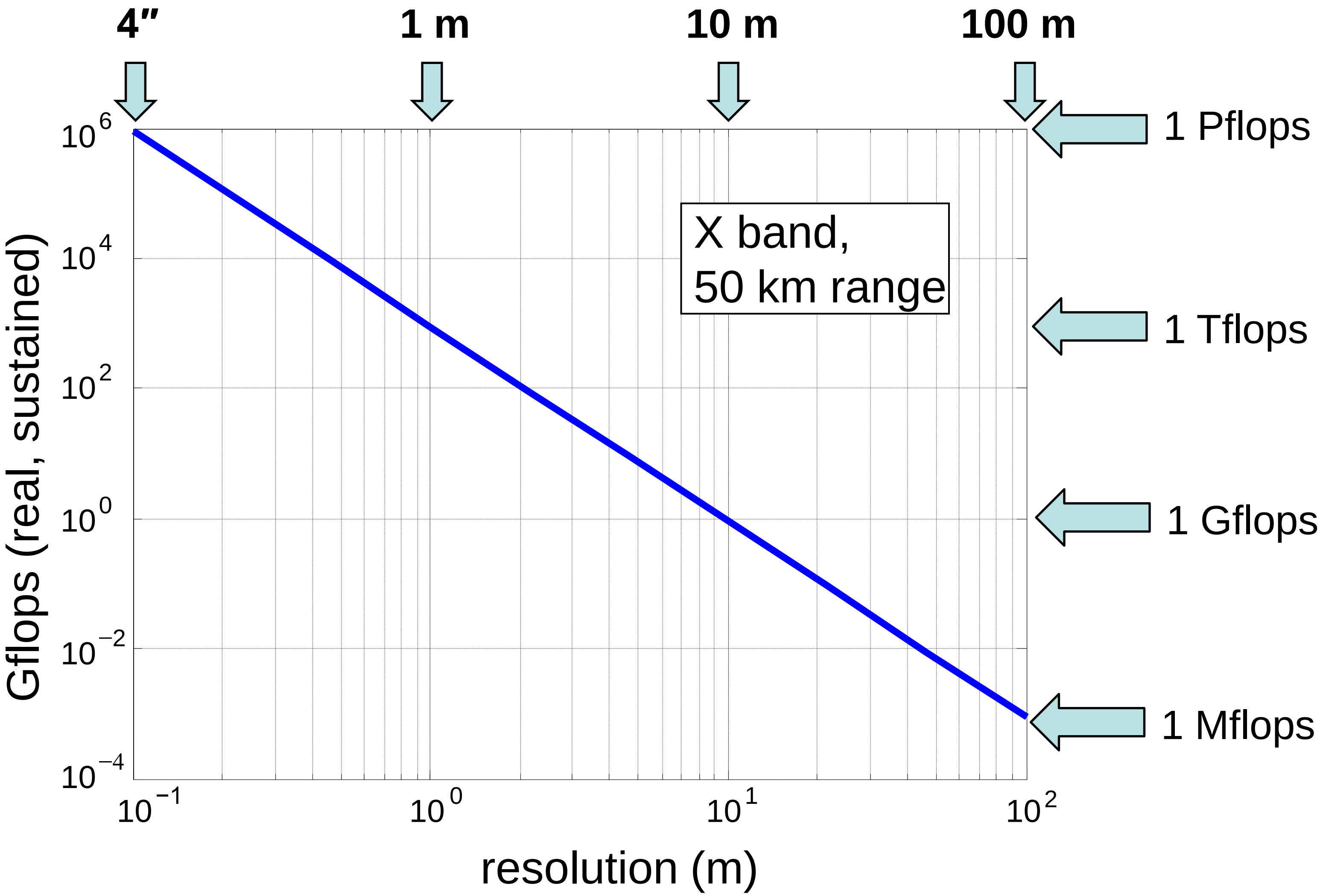
Processing Load Grows Rapidly with Finer Resolution

- **X band (10 GHz), 50 km range, real (not complex) flops**



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Improvements in Computational Efficiency Needed

- **Current practice baseline for general-purpose microprocessors: ~2 Gflops/W**

Platform	Widebody Aircraft	Mid-Size Aircraft	Global Hawk UAV	Reaper UAV	A160T Hummingbird
SAR WAMI, 10 km scene	3×	12×	19.3×	19.3×	28.4×
SAR WAMI, 5 km scene	0.5×	2×	3.2×	3.2×	4.8×
Advanced BF and STAP	0.4×	1.5×	2.4×	2.4×	3.5×

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Summary

- There is a fundamental conflict between area coverage and resolution, driven by Doppler bandwidth and swath length and their effects on PRF
- Spaceborne SAR
  - Long range, high velocity
  - Wide antennas
  - Large viewing area with relatively constant incidence angle
  - Moderate resolution, large area coverage
- Airborne SAR
  - Short range, low velocity
  - Small antennas
  - Fine resolution, small area coverage, shallower incidence
  - Motion compensation needed
- Data link limits → increased onboard processing → computing power efficiency barriers

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Some Issues Not Considered

- RF & polarization
  - Weather effects
  - Size and weight of antenna, components
  - Phenomenology
- Multiplicative noise
  - Range and cross-range ambiguities
  - Integrated sidelobe ratio
  - Quantization noise
- Motion compensation
  - Primarily airborne
- Spotlight SAR

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