EITN90 Radar and Remote Sensing Lecture 12: Space-based SAR for remote sensing

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Learning outcomes of this lecture

In this lecture we will

- Make an overview of operating space-based systems.
- Review some particularities of space-based systems.
- Make a case study of one system (TerraSAR-X).

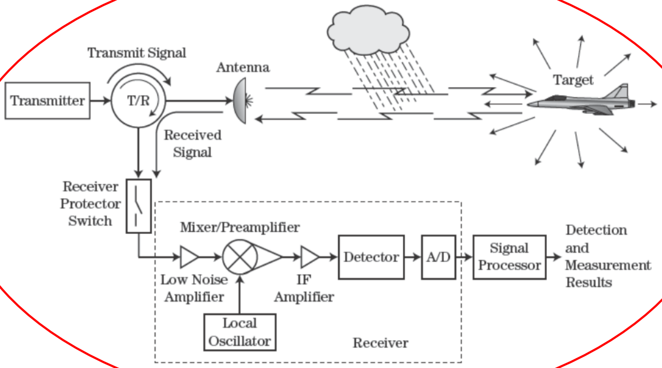


FIGURE 1-1 ■ Major elements of the radar transmission/ reception process.

Outline

1. **Historical perspective**
2. **Orbits**
3. **Design considerations for the spaceborne SAR**
4. **Special modes and capabilities**
5. **Design example: Germany's TerraSAR-X**
6. **Conclusions**

Outline

Characteristics of space-borne SAR

TABLE 10-1 ■ Characteristics and Challenges of Spaceborne SARs

- Long range; high two-way spreading loss (path loss)
- High platform velocity (large Doppler shift)
- Large antennas, some requiring distributed RF amplification and control circuitry
- Highly constrained PRF, often range-ambiguous
- Large imaged area resulting in a large data volume
- Image formation processing is usually done on the ground; system performance may be data-link-limited

- All systems in lower earth orbit (LEO), high velocity, several km/s.
- Moderate peak power, around 1–5 kW.
- Typical antenna dimensions: 10–15 m.
- First mission in 1978 (Seasat).

Timeline of various SAR missions

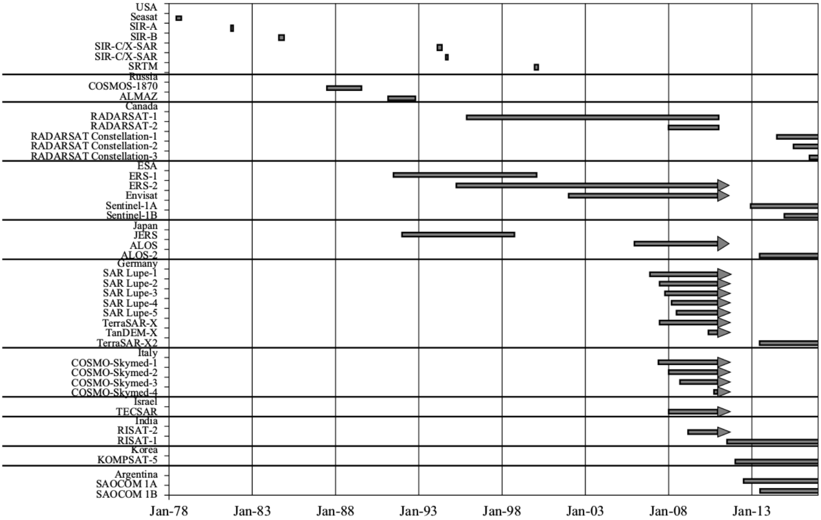


FIGURE 10-1 ■ Timeline of SAR Satellite Missions.

Examples of SAR satellites

TABLE 10-2 ■ SAR Satellite and Radar Characteristics

Parameter	Seasat	Shuttle Imaging Radar A (SIR-A)	Shuttle Imaging Radar B (SIR-B)	Shuttle Imaging Radar C (SIR-C)/ X-SAR	ERS-1 and ERS-2	ENVISAT (ASAR instrument)	JERS-1	ALOS PALSAR	Radarsat-1	Radarsat-2
Nationality	U.S.	U.S.	U.S.	U.S.	Europe	Europe	Japan	Japan	Canada	Canada
Mission dates (and duration)	1978 (105 days)	Nov. 1981 (2 days)	Oct. 1984 (8.3 days)	Apr. and Oct. 1994	ERS-1: 1991–2000 ERS-2: 1995–2011	2002–2012	1992–1998	2006–2011	Nov. 1995–2013	Dec. 2007–2013
Orbit altitude	800 km	259 km	360, 257, and 224 km	225 km	782–785 km	800 km	568 km	690 km	793– 821 km	793–821 km
Orbit inclination	108°	38°	57°	57°	98.5°	98.55°	97.7°	98.16°	98.6°	98.6°
Radar frequency	1.275 GHz (L-band)	1.275 GHz (L-band)	1.275 GHz (L-band)	1.277 GHz (L) 5.172 GHz (C) 9.677 GHz (X)	5.3 GHz (C-band)	5.331 GHz (C-band)	1.275 GHz (L-band)	1.270 GHz (L-band)	5.3 GHz (C-band)	5.405 GHz (C-band)
Antenna type	Passive array	Passive array	Passive array	AESA	Passive array	AESA	AESA	AESA	Passive array	AESA
Antenna dimensions	10.74 × 2.16 m	9.4 m × 2.16 m	10.7 m × 2.16 m	12 m × 4 m (overall)	10 m × 1 m	10 × 1.3 m	11.9 m × 2.2 m	8.8 m × 3.1 m	15 m × 1.5 m	15 m × 1.37 m
Beamwidths (Az × El)	1.26° × 6.24° (uniform wtg.)	1.27° × 6.24° (uniform wtg.)	1.26° × 6.24° (uniform wtg.)	El: 5.2–18.4°	0.29° × 5.4°	0.29° × 2.2° (uniform wtg.)	1° × 5.5°	1.36° × 3.87° (uniform wtg.)	0.19° × 1.92° (uniform wtg.)	Az: 0.21–0.63°
Swath width (in range)	100 km	50 km	20–40 km	15–90 km (L & C) 15–40 km (X)	100 km	100 km	75 km	40–70 km; 250–350 km using ScanSAR	45–170 km; 300–500 km using ScanSAR	18–170 km; 300–500 km using ScanSAR
Look angle from nadir	20°	47°	14°–56° (at 257 km alt.)	17°–63°	~20°	13°–39°	35° (typical)	9.9°–50.8°	20°–59°	9°–50°
Incidence angle at the surface	23° ±3° across the swath	50±3°	15°–65°	20°–65°	20.1°–25.9°	15°–45°	32°–38°	8°–60° (24° and 39° typ.)	20°–60°	10°–60°

(*Continues*)

Examples of SAR satellites, continued

Table 10-2 ■ (*Continued*)

Parameter	Seasat	Shuttle Imaging Radar A (SIR-A)	Shuttle Imaging Radar B (SIR-B)	Shuttle Imaging Radar C (SIR-C)/ X-SAR	ERS-1 and ERS-2	ENVISAT (ASAR instrument)	JERS-1	ALOS PALSAR	Radarsat-1	Radarsat-2
Polarization	HH	HH	HH	L & C band: HH, HV, VV, VH X band: VV	VV	HH, HV,VV, VH	HH	HH, HV,VV, VH	HH	HH, HV,VV, VH
Waveform bandwidth	19 MHz	6 MHz	12 MHz	10 and 20 MHz (L, C) 9 and 19.6 MHz (X)	15.55 MHz		15 MHz	14 and 28 MHz	11.6, 17.3, 30 MHz	12– 100 MHz
Range resolution (cross-track)	25 m (Theoretical)	40 m	58–16 m	30 m (L, C) 10 and 20 m (X)	26.3 m	30 m	18 m	7–89 m (10–30 m typ.)	5 m (min.)	3 m (min.)
Azimuth resolution (along-track)	25 m (Theoretical)	40 m	20–30 m	30 m (L, C, X)	30 m	30 m	18 m	10 m	8–100 m (30 m typical)	1–100 m (25–40 m typical)
Number of looks	4	6	4	4	4		3	2	1–16	1–4
Transmitted pulse length	33.4 μs	30.4 μs	30.4 μs	8.5–33.8 μs (L, C) 40 μs (X)	37.12 μs		35 μs	16 and 27 μs	42 μs	21 and 42 μs
PRF (Hz)	1,463–1,640	1,464–1,824		1,395–1,736 (L, C) 1,240–1,860 (X)	1,640–1,720		1,506–1,606	1,500–2,500	1,270–1,390	1,300–3,800
Transmitted peak power	1.0 kW	1.0 kW	1.12 kW	3.3 kW (X)	4.8 kW	1.395 kW	1.3 kW	2 kW	5 kW	2.4–3.7 kW
Transmit duty factor	4.9–5.5% (est.)	4.5–5.5% (est.)		5.6–6.9%	6.2%	3.5–4.5%	5.3–5.6%	2.4–6.8%	5.3–5.8%	10%
Data recorder bit rate	110 Mbits/s (on the ground)	Optical film recorder	Optical film recorder (30.4 Mbits/s on ground)	45–90 Mbits/s	105 Mbits/s	100 Mbits/s	60 Mbits/s	120 and 240 Mbits/s	74–105	400 Mbps

NASA Seasat Satellite (1978)

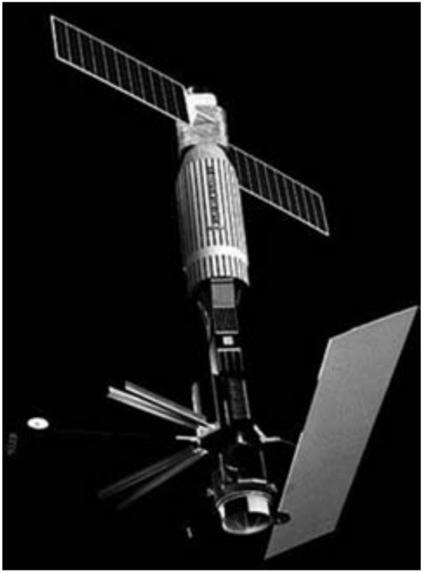
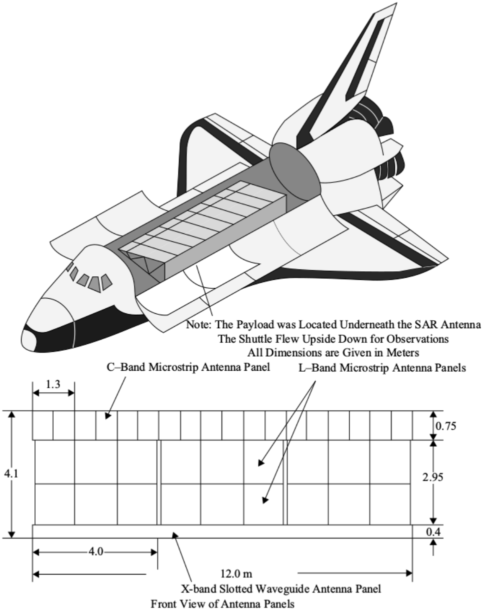


FIGURE 10-2 ■ NASA Seasat Satellite [Jet Propulsion Laboratory].

SIR-C/X-SAR (1994)

FIGURE 10-3 ■ SIR-C/X-SAR Antenna Installation, Dimensions, and Layout [eoportal.org].



ERS-2 (1995)

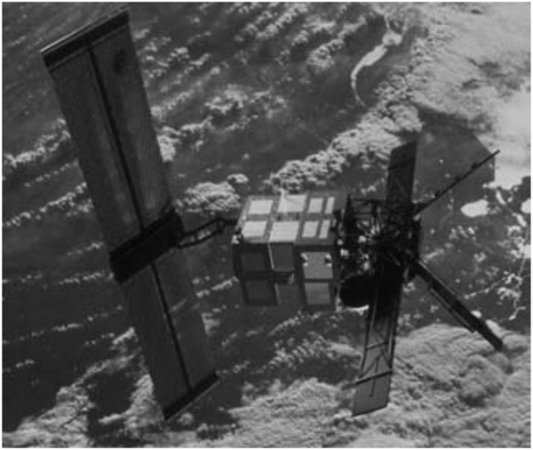


FIGURE 10-4 ■ ERS-2 Satellite. ERS-1 was Similar in Appearance. Major Components from Left to Right are the Solar Array, Spacecraft Body, SAR Antenna, and a Pair of Scatterometer Antennas. [European Space Agency].

Envisat ASAR (2002), active array

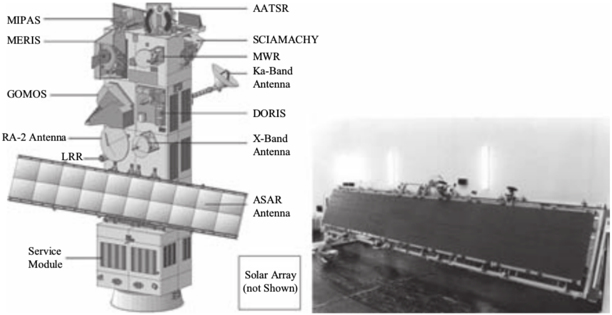
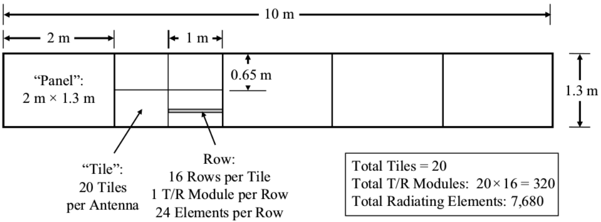


FIGURE 10-5 ■ Envisat Satellite and ASAR Antenna [European Space Agency].

FIGURE 10-6 ■ ENVISAT ASAR Antenna Layout.



JERS-1 (1992)

FIGURE 10-7 ■ JERS-1 Satellite [Jet Propulsion Laboratory].

ALOS PALSAR (2006), active array

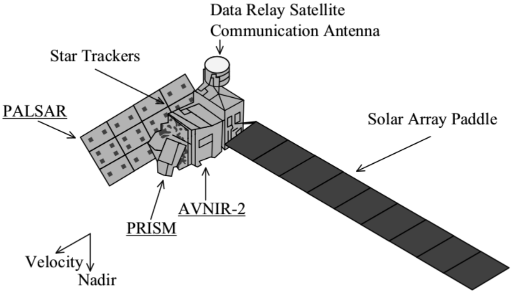
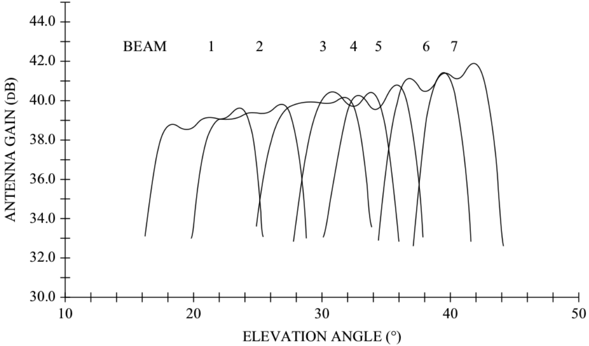


FIGURE 10-8 ■ Japanese ALOS with PALSAR [European Space Agency].

RADARSAT-1 (1995)

FIGURE 10-9 ■ RADARSAT-1 SAR Elevation Beam Patterns [18].



- Peak power 5 kW, average power 300 W.
- RF bandwidth 30 MHz.
- PRF around 1300 Hz.
- Multiple beams used to cover wider swath.

RADARSAT-2 (2007), active array

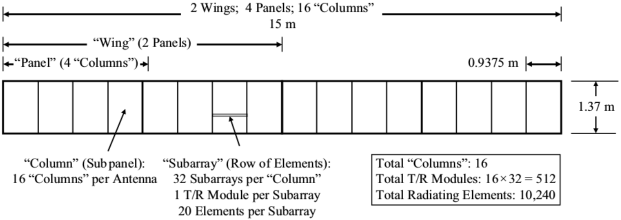


FIGURE 10-10 ■ RADARSAT-2 Antenna Layout.

- C-band 5.405 GHz.
- LFM from 12 MHz to 100 MHz.

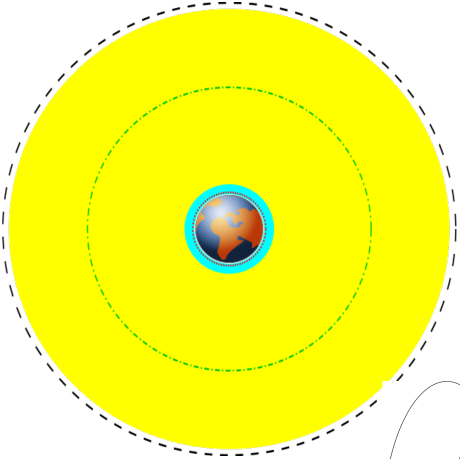
COSMO-SkyMed (2007), active array

TABLE 10-3 ■ COSMO-SkyMed Modes and Parameters [22]

Mode	Enhanced Spotlight	Himage Strip Map	PingPong Strip Map	ScanSAR Wide Region	ScanSAR Huge Region
Azimuth resolution	~1 m	~3 m	~10 m	~30 m	~100 m
Range resolution	~1 m	~3 m	~10 m	~30 m	~100 m
Azimuth frame extent	~11 km	~40 km	~30 km	~100 km	~200 km
Range swath extent	~11 km	~40 km (acq. time ~6.5 s)	30 km (acq. time ~5 s)	~100 km (acq. time ~15 s)	~200 km (acq. time ~30 s)
PRF	3,148.1 Hz to 4,116.7 Hz	2,905.9 Hz to 3,874.5 Hz	2,905.9 Hz to 3,632.4 Hz	2,905.9 Hz to 3,632.4 Hz	2,905.9 Hz to 3,632.4 Hz
Linear FM chirp duration	70 to 80 μs	35 and 40 μs	30 μs	30 to 40 μs	30 to 40 μs
LFM chirp bandwidth – minimum	185.2 MHz (187.5 MHz sampling rate)	65.64 MHz (82.50 MHz sampling rate)	14.77 MHz (18.75 MHz sampling rate)	32.74 MHz (41.25 MHz sampling rate)	8.86 MHz (11.25 MHz sampling rate)
LFM chirp bandwidth – maximum	400.0 MHz (187.5 MHz sampling rate)	138.60 MHz (176.25 MHz sampling rate)	38.37 MHz (48.75 MHz sampling rate)	86.34 MHz (108.75 MHz sampling rate)	23.74 MHz (30.0 MHz sampling rate)

Outline

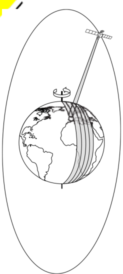
Different orbits

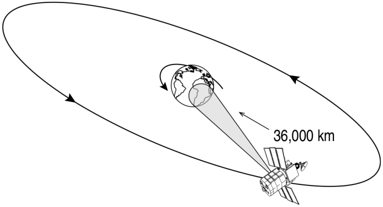


	Distance (km)
Earth surface	0
LEO	160 – 2 000
ISS	370
MEO	2 000 – 34 780
GPS	20 230
GEO	35 794
Moon	384 400

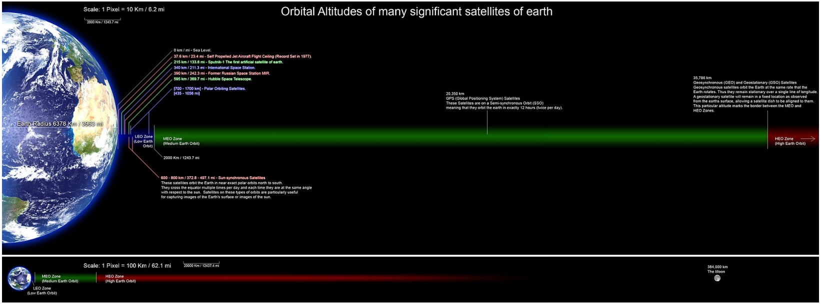
$$v_{\mathrm{sat}} = \sqrt{\frac{3.986 \cdot 10^{14}\,\mathrm{m}^3/\mathrm{s}^2}{r_{\mathrm{sat}}}}$$

$$T_{\mathrm{sat}} = \frac{2\pi r_{\mathrm{sat}}}{v_{\mathrm{sat}}}$$





Orbits to scale



By Rrakanishu - Own work, GFDL, https://commons.wikimedia.org/w/index.php?curid=4189737

Sun-synchronous circular orbit

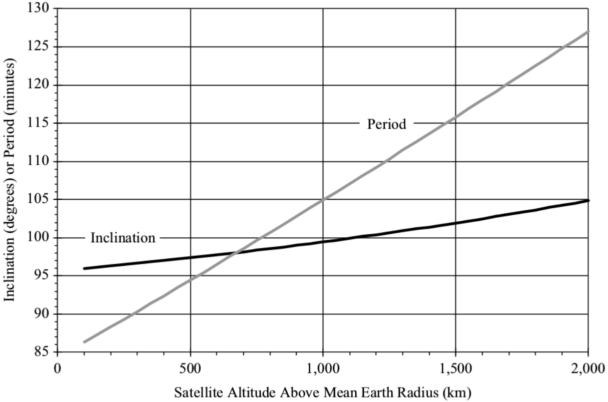


FIGURE 10-11 Period and Inclination Required for a Sun-Synchronous Circular Orbit.

A sun-synchronous orbit passes over the equator at approximately the same local solar time each day.

Typical time for propagation at 1000 km altitude:
$\frac{2 \cdot 1000 \cdot 10^3}{3 \cdot 10^8}\,\mathrm{s} = 6.7\,\mathrm{ms}.$

Doppler shift for spaceborne SAR

The high velocity of the satellite platform and Earth rotation complicates the Doppler shift

$$f_{\mathrm{d}} = \frac{2v_{\mathrm{sat}}}{\lambda} \sin\theta_{\mathrm{L}} \cos\alpha \left\{ 1 - \left(\frac{\omega_{\mathrm{e}}}{\omega_{\mathrm{sat}}} \right) [\varepsilon \cos\beta_{\mathrm{L}} + \sin i \tan\alpha + \cos i] \right\}$$

- $\theta_{\mathrm{L}} =$ look angle from nadir
- $a =$ azimuth squint angle (about the yaw axis) between the velocity vector and the target azimuth
- $\omega_{\mathrm{e}} =$ Earth's angular rotation rate
- $\omega_{\mathrm{sat}} =$ satellite angular rate $= 2\pi/P\,\mathrm{radians/sec}$ for a circular orbit
- $\varepsilon = -1$ if the radar is left-looking; $+1$ if right-looking
- $\beta_{\mathrm{L}} =$ argument of latitude (angular position of the satellite in its orbit as measured from the ascending node)
- $i =$ orbit plane inclination

Outline

1. Historical perspective
2. Orbits
3. **Design considerations for the spaceborne SAR**
4. Special modes and capabilities
5. Design example: Germany's TerraSAR-X
6. Conclusions

A linearly polarized wave passing through the ionosphere has its polarization plane rotated by interaction with the Earth's magnetic field, depending on frequency and electron content.

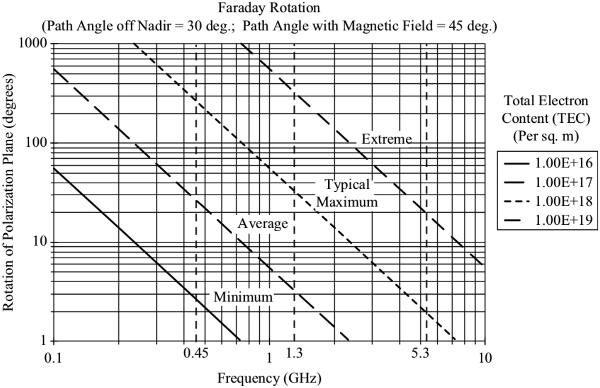


FIGURE 10-12 ■ Faraday Rotation versus Signal Frequency and Total Electron Content.

Ionospheric group delay

A wave passing through the ionosphere suffers group delay proportional to TEC/f^2, corresponding to an excess target range.

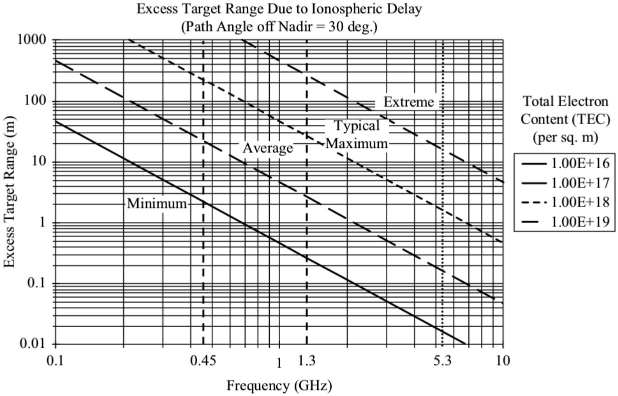


FIGURE 10-13 ■ Excess Target Range Due to Ionospheric Group Delay.

Radar frequency selection

Typically, spaceborne SARs operate in 1–10 GHz:

- Below 1 GHz ionospheric effects introduce measurement errors.
- Above 10 GHz rain attenuation can be serious.
- L-band ($\sim 1.3\,\mathrm{GHz}$, $\lambda = 23\,\mathrm{cm}$) large-scale wind waves and surface perturbations of oceans.
- C-band ($\sim 5\,\mathrm{GHz}$, $\lambda = 6\,\mathrm{cm}$) suitable for sea ice.
- X-band ($\sim 9\,\mathrm{GHz}$, $\lambda = 3\,\mathrm{cm}$) suitable for fine cross-range resolution.

Frequency band allocations

TABLE 10-4 ▪ International Frequency Allocations for Active Earth Exploration Satellites Below 100 GHz [43]. ("Radiolocation" = Radar)

Frequency Band (MHz)	Services Allocated (International Allocations)
1,215–1,240	Earth exploration satellite (active), radiolocation, radionavigation-satellite (space-to-earth and space-to-space), space research (active)
1,240–1,300	Earth exploration satellite (active), radiolocation, radionavigation-satellite (space-to-earth and space-to-space), space research (active), amateur
3,100–3,300	Radiolocation, earth exploration satellite (active), space research (active)
5,250–5,255	Earth exploration satellite (active), radiolocation, space research, mobile except aeronautical mobile
5,255–5,350	Earth exploration satellite (active), radiolocation, space research (active), mobile except aeronautical mobile
5,350–5,460	Earth exploration satellite (active), space research (active), aeronautical radionavigation, radiolocation
5,460–5,470	Radionavigation, earth exploration satellite (active), space research (active), radiolocation
5,470–5,570	Maritime radionavigation, mobile except aeronautical mobile, earth exploration satellite (active), space research (active), radiolocation
8,550–8,650	Earth exploration satellite (active), radiolocation, space research (active)
9,300–9,500 (outside the United States)	Earth exploration satellite (active), space research (active), radiolocation, radionavigation
9,500–9,800	Earth exploration satellite (active), space research (active), radiolocation, radionavigation
9,800–9,900	Radiolocation, earth exploration satellite (active), space research (active), fixed
13,250–13,400	Earth exploration satellite (active), aeronautical radionavigation, space research (active)
13,400–13,750	Earth exploration satellite (active), radiolocation, space research, standard frequency and time signal satellite (earth-to-space)
17,200–17,300	Earth exploration satellite (active), radiolocation, space research (active)
24,050–24,250	Radiolocation, amateur, earth exploration satellite (active)
35,500–36,000	Meteorological aids, earth exploration satellite (active), radiolocation, space research (active)
94,000–94,100	Earth exploration satellite (active), radiolocation, space research (active), radio astronomy

Interaction with natural surfaces

The interaction of an electromagnetic wave with a natural surface depends on several factors:

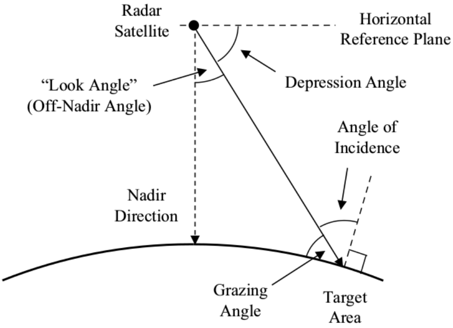
- The dielectric properties of the surface material (which may be frequency-dependent).
- The surface roughness relative to the radar wavelength.
- The orientation of complex scatterers (such as vegetation) relative to the polarization of the radar wave.
- The angle of incidence of the radar wavefront at the surface.

TABLE 10-5 ■ Penetration Depth for Various Surface Materials [45]

Material	Approximate Penetration Depth
Soil, moist (0.3 g/cm^3 water)	~$\lambda/8$ to ~$\lambda/3$
Soil, dry (0.02 g/cm^3 water)	~1 to 3λ
Sand, dry	to ~10λ
Sea ice, first year	~1 to 3λ
Sea ice, multiyear	~4 to 9λ
Snow, wet (4% liquid water)	~1 to 2λ
Snow, dry (0.2% liquid water)	~30 to 100λ

Space-borne SAR geometry

FIGURE 10-14 ■ Nomenclature for Spaceborne SAR Geometry. The Direction of Satellite Movement is Perpendicular to the Page.



Definitions of various space-borne SAR geometry parameters.

Range footprint

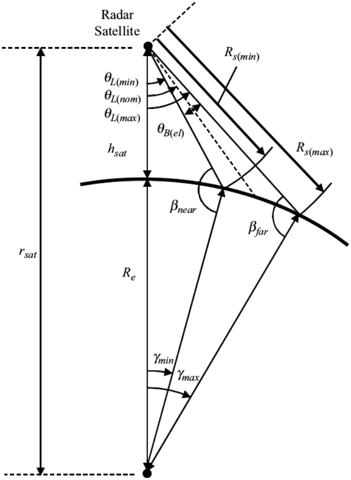


FIGURE 10-15 ■ Geometry for Range Footprint Calculation.

Unambiguous range requires

$$\mathrm{PRF} < \frac{c}{2\Delta R_{\mathrm{s}}}$$

Flat Earth approximation

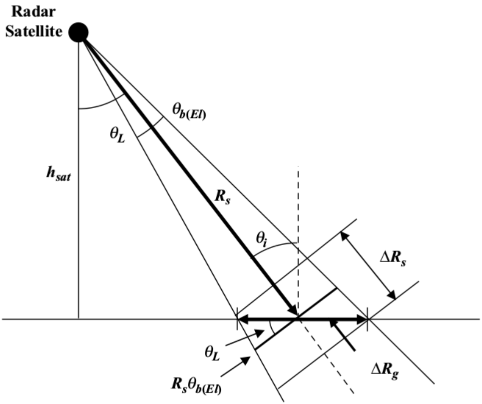
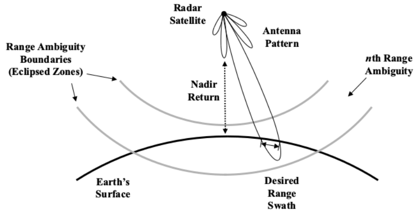


FIGURE 10-16 ■ Flat earth Approximation for Obtaining the Slant Range Extent of the Beam Footprint.

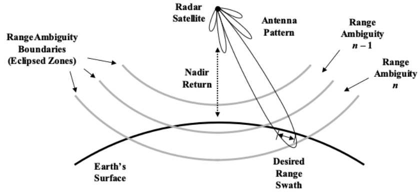
$$\Delta R_{\mathrm{g}} = R_{\mathrm{s}} \frac{2\theta_{\mathrm{b(El)}}}{\cos\theta_{\mathrm{i}}} \approx \frac{2R_{\mathrm{s}}}{\cos\theta_{\mathrm{i}}} \frac{\lambda}{H} \quad \Rightarrow \quad \mathrm{PRF} < \frac{cH}{4R_{\mathrm{s}}\lambda\tan\theta_{\mathrm{i}}}$$

Range ambiguities

FIGURE 10-17 ■ Range Ambiguities in Spaceborne SAR.



(a) Desired Range Swath and Nadir Return are in the Same Range Ambiguity. Nadir Return Cannot Interfere with Returns from the Desired Range Swath.



(b) Desired Range Swath and Nadir Return are in Different Range Ambiguities. Nadir Return May Interfere with Returns From the Desired Range Swath.

Nadir sidelobe return may interfere with the desired return.

Outline

Multilook processing

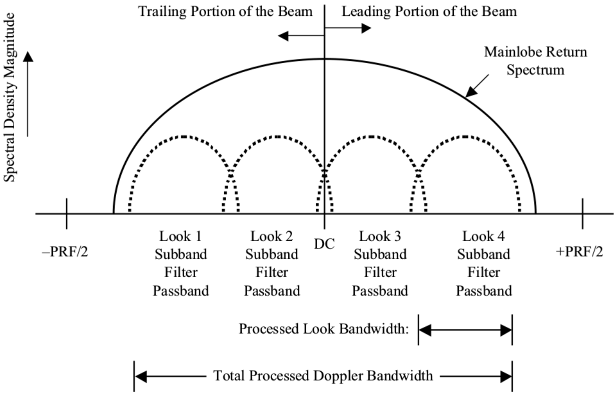


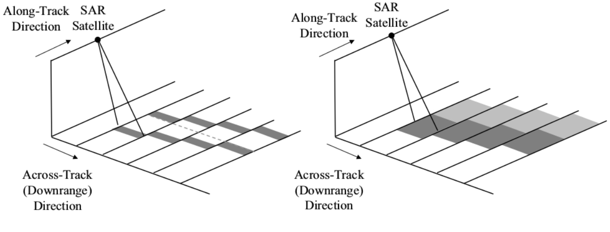
FIGURE 10-18 ■ Doppler Spectrum Filtering for Four-look Processing.

Using data from N filter banks (before azimuth compression) theoretically improves SNR by

$$\mathrm{SNR}_N = \mathrm{SNR}_1 \sqrt{N}$$

if noise dominated by speckle.

ScanSAR



(a) Data Collection Timing (b) Ground Coverage

FIGURE 10-19 ■ ScanSAR Operation.

Several target areas can be observed at coarser resolution to build a wider image.

Along-track interferometry (ATI)

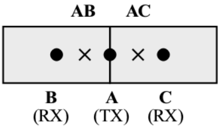


FIGURE 10-20 ■ Phase Center Relationships for a Stationary Antenna. **AB** and **AC** are the Composite Transmit-Receive Phase Centers, and the Distance Between them is B_x.

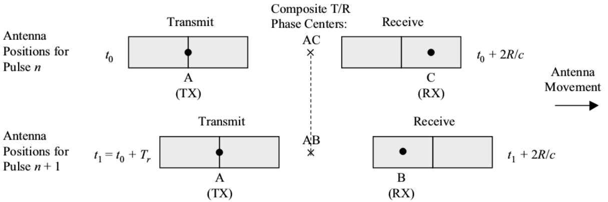


FIGURE 10-21 ■ Phase Center Relationships for a Moving Antenna. The Direction Toward the Target is Perpendicular to the Page [55].

Two images formed by two receiving sub-arrays have displaced phase center. The difference between the images provide interferometric information, typically indicating slow-moving targets like ocean currents.

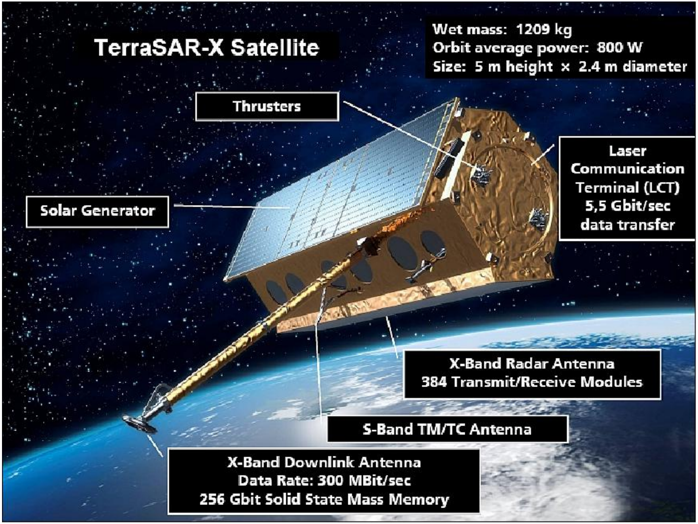
Trade-offs

TABLE 10-6 ■ Summary of Mode/Capability Trade-offs

Mode or Capability	Obtains	By Forfeiting
Block adaptive quantizer	Reduced downlink data rate or added mode capabilities using a given downlink data rate	Instantaneous dynamic range in the raw I/Q data; image SNR
Spotlight mode	Improved cross-range resolution	Continuous strip coverage
Burst mode	Reduced downlink data rate; reduced average power consumption	Cross-range resolution
Multilook imaging	Improved image quality (reduced noise and speckle)	Cross-range resolution
ScanSAR	Increased range swath width	Cross-range resolution
TOPS	Increased swath width with improved image quality (reduced scalloping)	Cross-range resolution
Along-track interferometry	Surface radial velocity measurement capability	SNR (due to receiving on half the aperture)
Multipolarization processing	Better characterization of scenes or targets	Resolution or multiple looks (i.e., image quality) assuming a data link limited system

Outline

TerraSAR-X (2007)



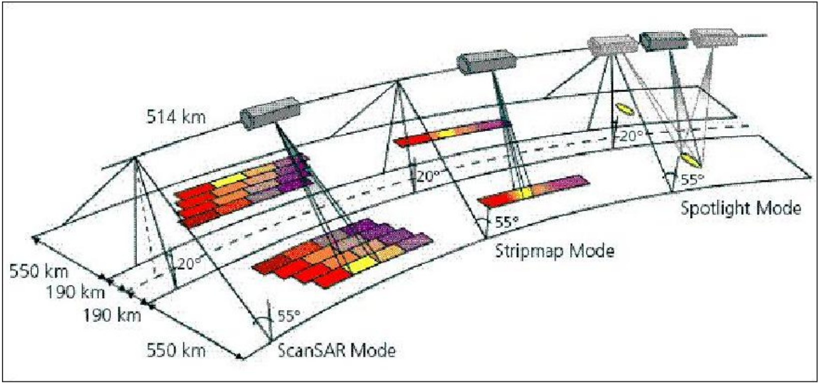
https://directory.eoportal.org/web/eoportal/satellite-missions/t/terrasar-x

Parameters

TABLE 10-7 ■ TerraSAR-X Parameter Summary

Orbit parameters	Value
Height at equator, altitude variation above GEM6	514.8 km, 505 km–533 km
Semi-major axis	6,883.513 km
Period	94.85 min
Orbits per day	$15\frac{2}{11}$
Inclination	97.44°
Eccentricity	0.001
Argument of perigee	90°
SAR instrument parameters	**Value**
Center frequency	9.65 GHz
Wavelength at center frequency	3.11 cm
Antenna aperture dimensions	4.784 m × 0.704 m
Antenna aperture area	3.368 m^2
Phase centers for beam steering (azimuth × elevation)	12 × 32
Scan angle range (azimuth, elevation)	±0.75° Az, ±19.2° El
Incidence angle access range	15°–60°
Radiated peak output power	2,260 W
Transmit duty cycle (strip map mode and spotlight mode)	18%, 20%
System noise figure	5.0 dB
Operational PRF range	3,000–6,500 Hz
Chirp bandwidth range	5–300 MHz
ADC sample resolution	8 bits I and 8 bits Q
ADC sample rates	110, 165, 330 MHz
Maximum receive duty cycles	100%, 67%, 33%
Selectable block adaptive quantizer (BAQ) compression	8 to 6, 4, 3, 2, by-pass
Mass memory size, beginning of life (BoL), end of life (EoL)	320 Gbit, 256 Gbit
Absolute timing (along-track, across-track)	3.6 ms, 63 ns (1σ)

Operational modes



Operational modes

TABLE 10-8 ■ TerraSAR-X Mode Summary [67]

Parameter/ Operational Mode	Spotlight HS Mode	Spotlight SL Mode	Experimental Spotlight	Strip Map Mode (SM)	ScanSAR Mode (SC)
Resolution, cross-track Resolution, along-track	2 m 1 m	2 m 1 m	1 m 1 m	3 m 3 m	16 m 16 m
Product coverage, (km) along-track × cross-track	5 × 10	10 × 10	5 × 10	≤1,500 × 30	≤1,500 × 100
Access range of incidence angles (full performance)	20–55° 2 × 463 km	20–55° 2 × 463 km	20–55° 2 × 463 km	20–45° 2 × 287 km	20–45° 2 × 287 km
Access range of incidence angles (data collection – reduced performance)	15–60° 2 × 622 km	15–60° 2 × 622 km	15–60° 2 × 622 km	15–60° 2 × 622 km	20–60° 2 × 577 km
Sensitivity NESZ: - typical - worst case	–23 dB –19 dB	–23 dB –19 dB	–20 dB –16 dB	–22 dB –19 dB	–21 dB –19 dB
Distributed target ambiguity ratio (DTAR)	<–17 dB	<–17 dB	<–17 dB	<–17 dB	<–17 dB
Source data rate (8/4 BAQ)	340 Mbit/s	340 Mbit/s	680 Mbit/s	580 Mbit/s	580 Mbit/s

Antenna layout

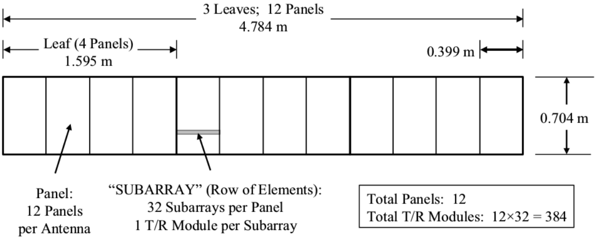


FIGURE 10-23 ■ TerraSAR-X Antenna Layout.

Full polarization selectivity (HH, HV, VH, VV). The gain is

$$G = \frac{4\pi A \eta_a}{\lambda^2} = \frac{4\pi(4.784\,\mathrm{m} \times 0.704\,\mathrm{m})}{(0.031\,\mathrm{m})^2} = 43\,791 = 46.4\,\mathrm{dB}$$

Beamwidth $\theta_3 = \frac{\lambda}{L} 50.8^\circ = 0.33^\circ$. Total peak power $2\,260\,\mathrm{W}$, or $5.8\,\mathrm{W}$ per T/R module. Duty factor around 0.2.

Look-geometry parameters

TABLE 10-9 ■ TerraSAR-X Look Geometry Parameters (Satellite Altitude = 515 km)

Angle of Incidence (Degrees)	Grazing Angle (Degrees)	Off-Nadir Look Angle (Degrees)	Slant Range (km)	Ground Range (km)
15	75	13.9	531.7	127.3
20	70	18.4	545.4	172.6
25	65	23.0	563.7	220.4
30	60	27.6	587.4	271.8
35	55	32.1	617.6	327.9
40	50	36.5	655.4	390.0
45	45	40.9	702.9	460.2
50	40	45.1	762.6	541.1
55	35	49.3	838.0	636.2
60	30	53.2	934.5	750.5

Spotlight mode received signal power

TABLE 10-10 ■ TerraSAR-X Spotlight Mode Received Signal Power Calculation

Parameter	Symbol	Value	Units	dB Value	dB Units
Numerator terms					
Transmit power (average*)	P_t	452	W	56.6	dBm
Transmit antenna gain	G_t	43,791		46.4	dBi
Receive antenna gain	G_r	43,791		46.4	dBi
Wavelength^2	λ^2	0.031	m^2	–30.1	dBsm
Target RCS	σ	10	m^2	10.0	dBsm
Denominator terms					
$(4\pi)^3$	$(4\pi)^3$	1,984		33.0	dB
(Slant range)^4	R^4	$(935{,}000)^4$	m^4	238.8	dB m^4
Losses affecting P_r (RF and beamshape losses)	L	1.00		0.0	dB
Result					
Received power (equivalent average power* at the output port of a lossless passive antenna)	P_r			–142.5	dBm

*The average transmit power is used here since our ultimate interest is in the target power after pulse compression and Doppler processing, referenced to the output of a lossless passive array.

This is the RF power available for amplification, down-conversion, pulse compression, signal processing etc.

Dwell time as function of range

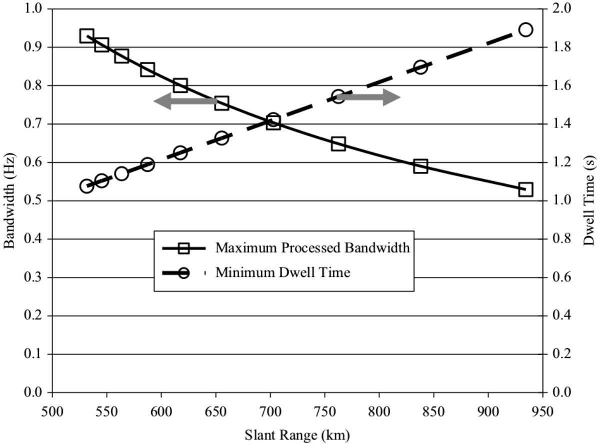


FIGURE 10-24 ■ Post-Processing Noise Bandwidth and Dwell Time as a Function of Slant Range.

Note that dwell time is increased for longer ranges, which improves the SNR.

Noise power

TABLE 10-11 ▪ TerraSAR-X Estimated Noise Power Calculation

Parameter	Symbol	Value	Units	dB Value	dB Units
Boltzmann's constant	k	1.38×10^{-23}	W/(Hz·K)	–228.6	dB W/(Hz·K)
Reference temperature	T_0	290	K	24.6	dB K
System noise bandwidth (post-processing)	B	0.5	Hz	–3.0	dB Hz
System noise figure	F	3.16		5.0	dB
Result					
Effective noise power	N			–202.0	dB W
				–172.0	dBm

Compare with $-142.5\,\mathrm{dBm}$ average received power.

Noise equivalent sigma zero (NESZ)

TABLE 10-12 ■ NESZ Calculation for TerraSAR-X at 60° Incidence Angle

Parameter	Symbol	Value	Units	dB value	dB units
Numerator terms					
Constants	8π	25.1327		14.00	dB
(Slant range)^3	R^3	$(935{,}000)^3 = 8.174 \times 10^{17}$	m^3	179.1	dB m^3
Wavelength	λ	0.031	m	–15.07	dB m
Boltzmann's constant	k	1.38×10^{-23}	W/(Hz·K)	–228.60	dB W/(Hz·K)
Reference temperature	T_0	290	K	24.62	dB K
Noise figure	F	3.16		5.0	dB
System loss	L_{sys}	1.00*		0.0	dB
Satellite velocity relative to Earth	v_{sat}	7,680	m/s	38.85	dB m/s
cos(60°)	$\cos\psi$	0.5		–3.0	dB
Denominator terms:					
Average transmit power	P_{avg}	452	W	26.55	dBW
(Aperture area)^2	A^2	$(3.368)^2$	m^4	10.55	dB m^4
(Aperture efficiency)^2	η_a^2	1*		0.0	dB
Slant range resolution	δ_r	2.0	m	3.01	dB m
Result:					
Noise-equivalent sigma zero	*NESZ*			–25.2	dB

*This calculation was done with no system loss and 100% aperture illumination efficiency for illustrative purposes.

Return power and noise summary

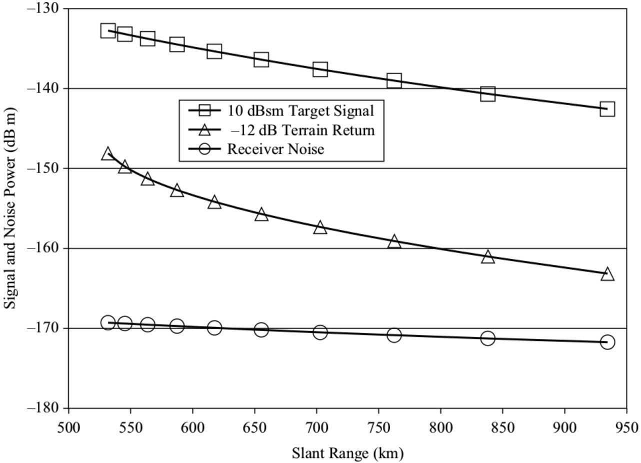
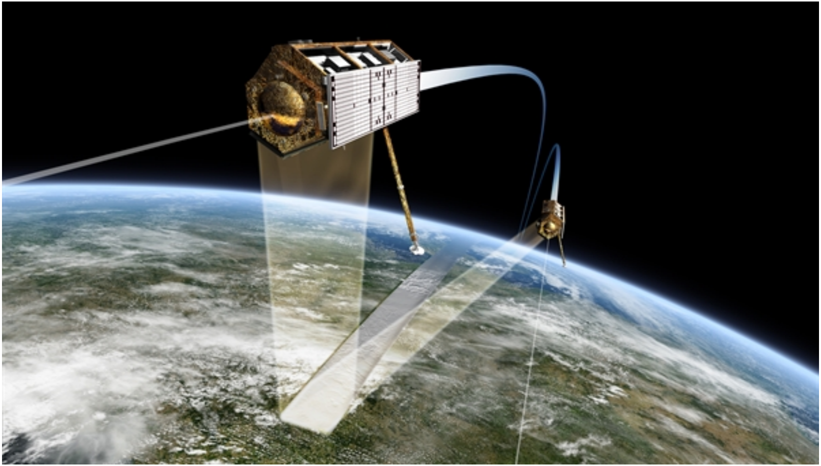


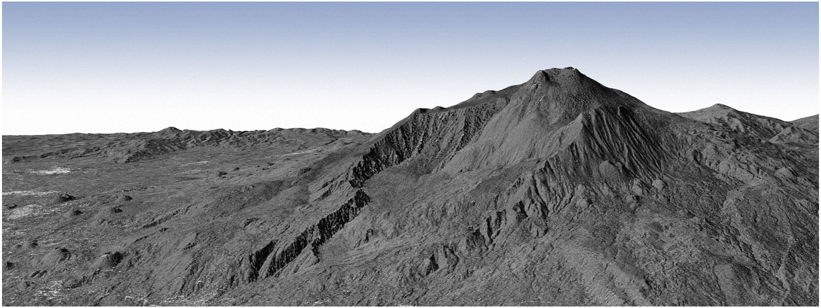
FIGURE 10-25 ■ TerraSAR-X Target, Terrain, and Noise Powers in a Resolution Cell as a Function of Slant Range in the Spotlight Mode. All Powers are Referenced to the Output Port of a Lossless Receive Antenna. The Receiver Noise Power Decreases Slightly with Increasing Range Due to the Longer Time on Target (Lower Noise Bandwidth after Processing) with Increasing Range.

Bistatic radar — TanDEM-X



Launched in 2010, flying a few hundred meters from TerraSAR-X.

TanDEM-X and TerraSAR-X: photo



Description from wikimedia: The first bistatic radar image acquired by the twin satellites TanDEM-X and TerraSAR-X shows the Italian volcano Mount Etna, on the east coast of Sicily. On the left of the image, below the flank of the volcano, the city of Catania can be seen as a collection of bright points. This image, acquired while the satellites were orbiting at a distance of only 350 metres from one another, is the world's first to be made using such a close satellite formation.

Outline

1. Historical perspective
2. Orbits
3. Design considerations for the spaceborne SAR
4. Special modes and capabilities
5. Design example: Germany's TerraSAR-X
6. **Conclusions**

Conclusions

- An overview of spaceborne SAR systems.
- Some design considerations: propagation in the ionosphere, high velocity, choice of PRF.
- Case study of TerraSAR-X.