2. Fundamentals and Specialties of Synthetic Aperture Radar (SAR)

Vorlesung: **Hochauflösende Radarsysteme**

WS 2007/08,

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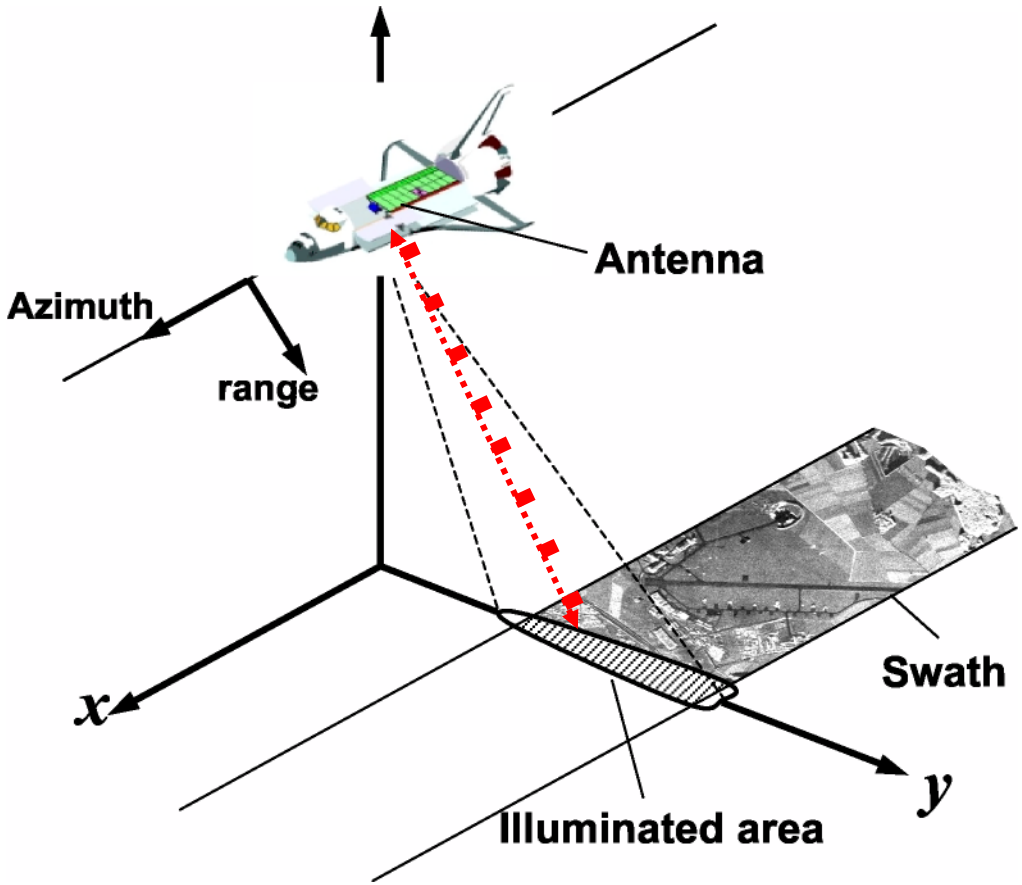
Bandwidth, B; Puls Length, τ_P; Range Resolution, δ_{rg}

$$B = \frac{1}{\tau_P}, \qquad \delta_{rg} = \frac{c\tau_P}{2} = \frac{c}{2B}$$

τ_P	100 nsec	20 nsec	10 nsec	3,3 nsec	2 nsec	1nsec	333 psec
B	10 MHz	50 MHz	100 MHz	300MHz	500MHz	1GHz	3GHZ
δ_{rg}	15 m	3,0 m	1,5 m	0,5 m	30 cm	15 cm	5 cm

Quellenangabe

Side-Looking Imaging Geometry



$$\frac{S}{N} = \frac{P_{ave} G^2 \lambda^2 \sigma \, T_D}{(4\pi)^3 r^4 (k T_0 F) L_{tot}}$$

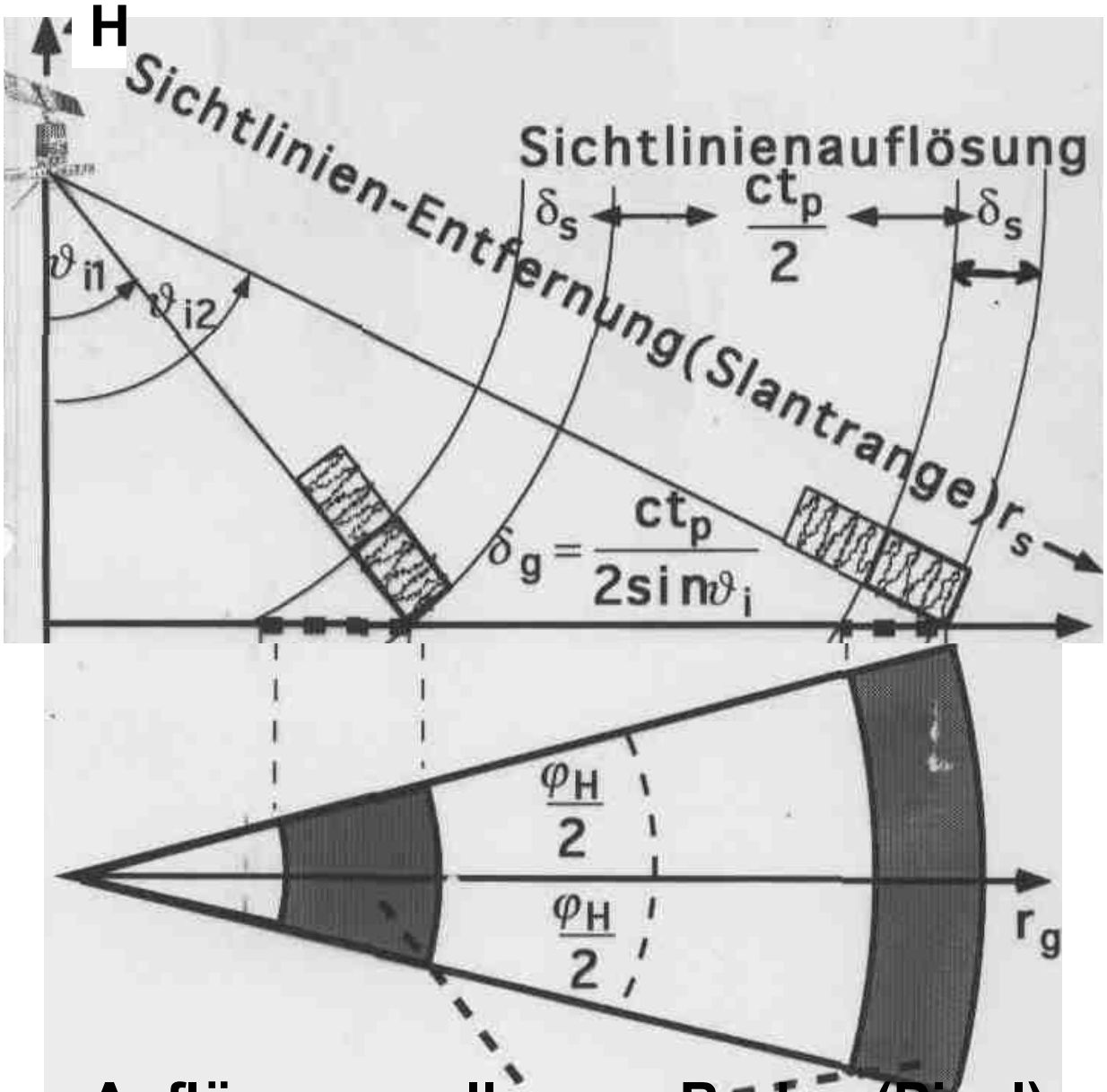
$$\frac{S}{N} = \frac{P_{ave} G^2 \lambda^2 \sigma_0 \Delta_d \delta_{rg} \, T_D}{(4\pi)^3 r^4 (k T_0 F) L_{tot}}$$

$$\Delta_d = \frac{\lambda}{d} r$$

$$\frac{S}{N} = \frac{P_{ave} G^2 \lambda^3 \sigma_0 \delta_{rg} \, T_D}{(4\pi)^3 r^3 (k T_0 F) d L_{tot}}$$

Quellenangabe

Auflösungsgeometrie



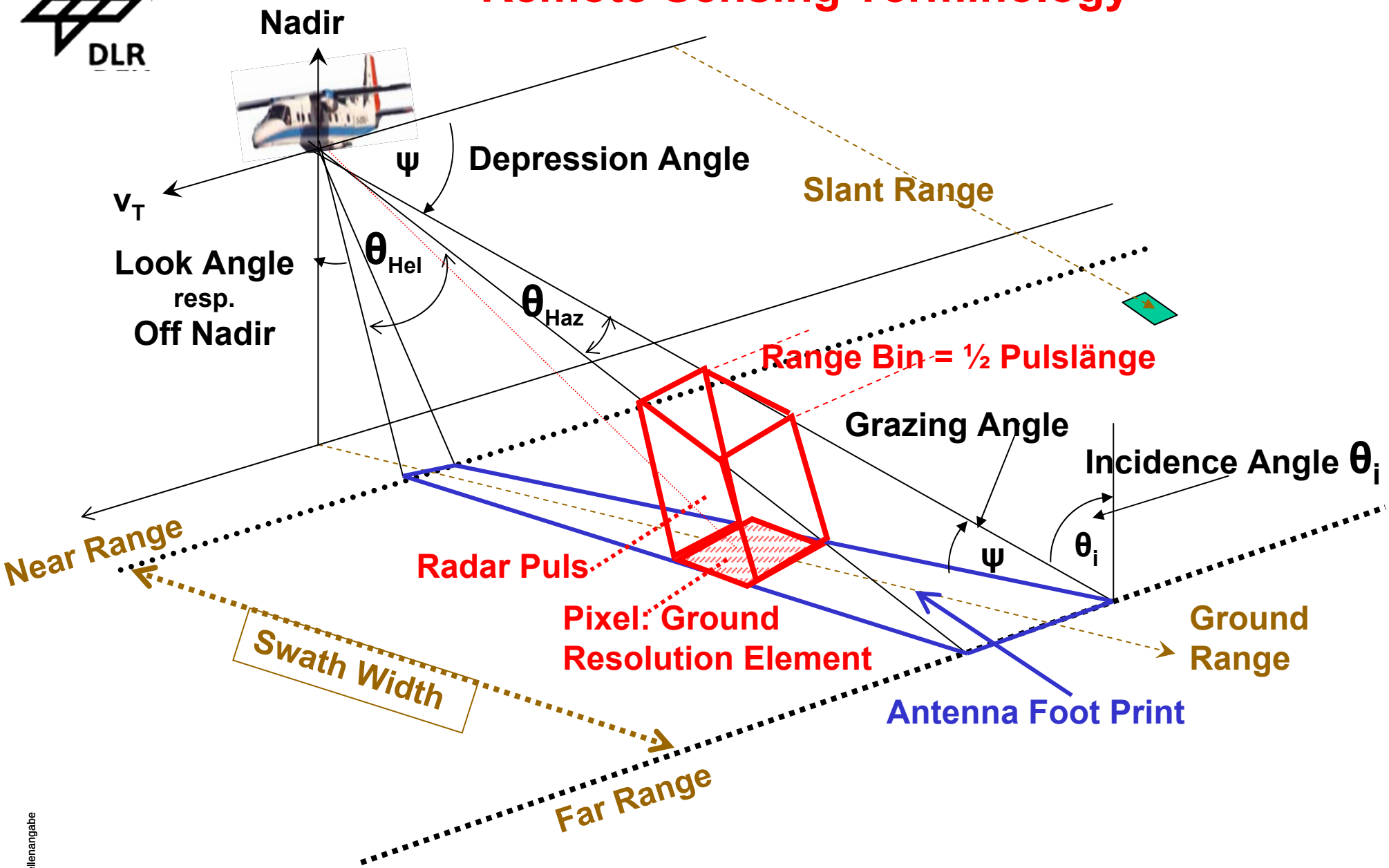
Boden-Entfernung

Ground Range (r_g)

Auflösungszellen am Boden (Pixel)

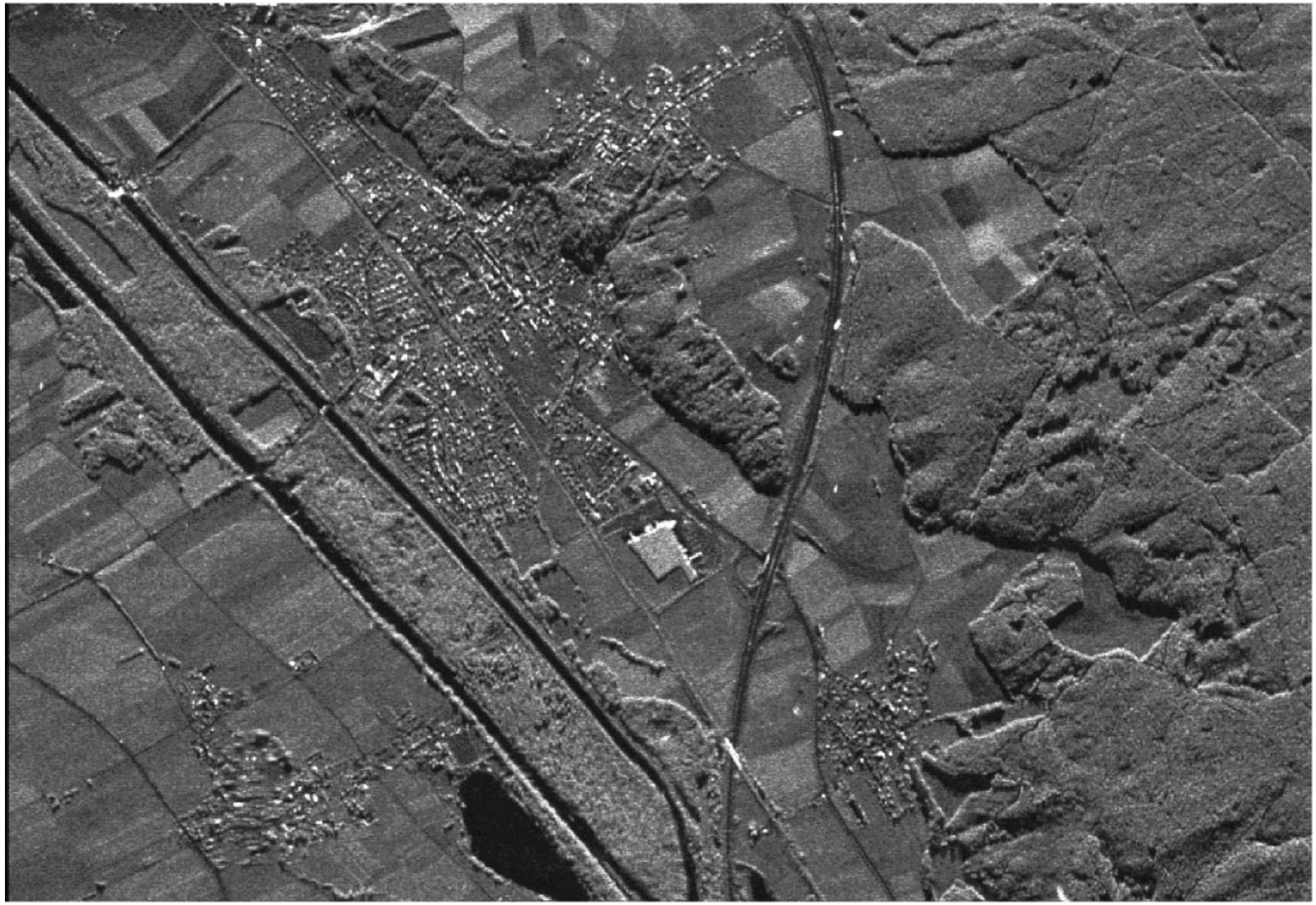
Quellenangabe

Remote Sensing Terminology



Quellenangabe

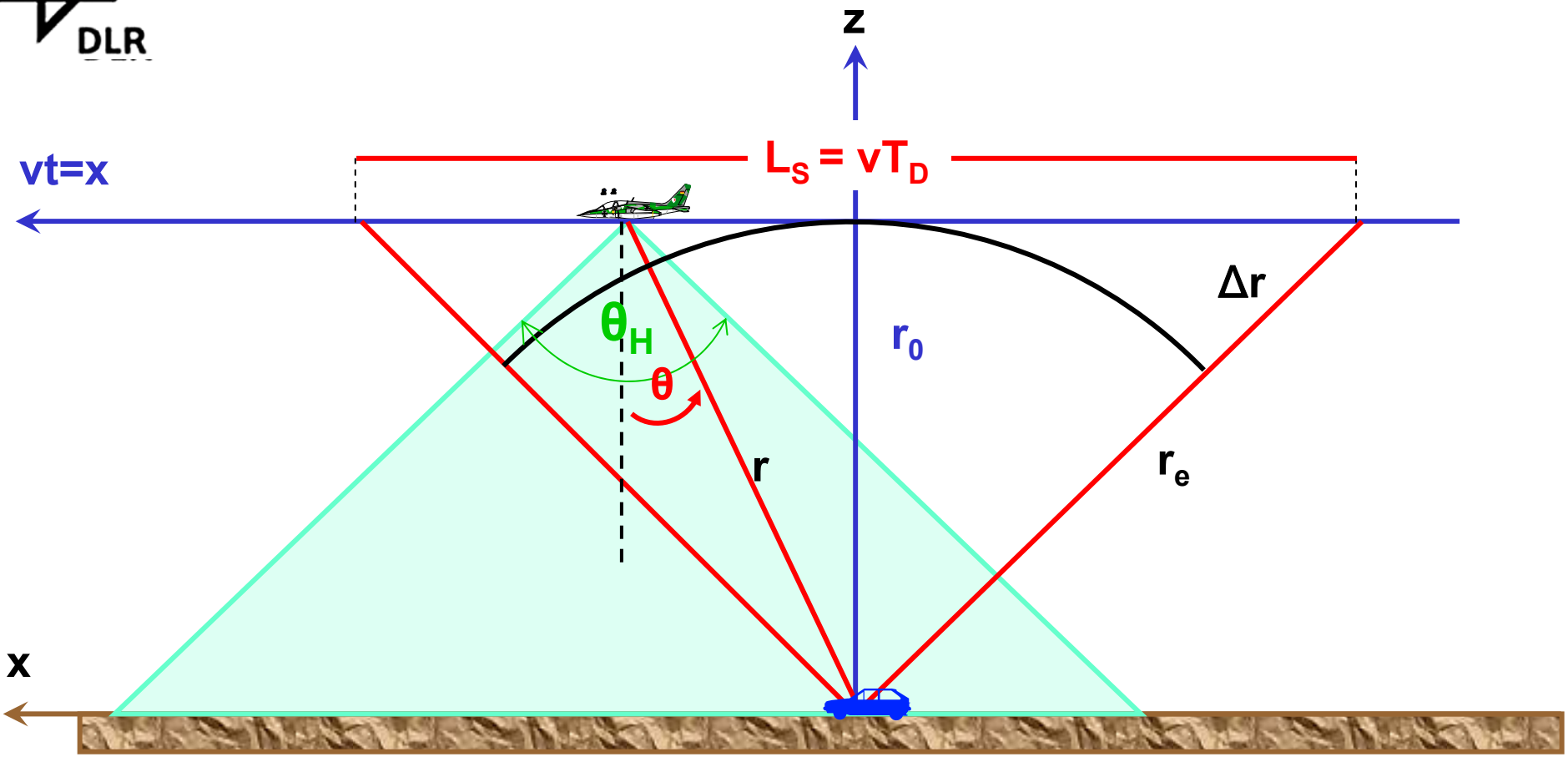
E-SAR image (X-band) processed in real-time, 3 x 3 m resolution, 6 looks



Quellenangabe

The Basic Principle of SAR

Two dimensional SAR Scheme,



Received Doppler Frequency: $f_D = \frac{2v}{\lambda} \sin \vartheta(t) \approx \frac{2v}{\lambda} \vartheta(t)$

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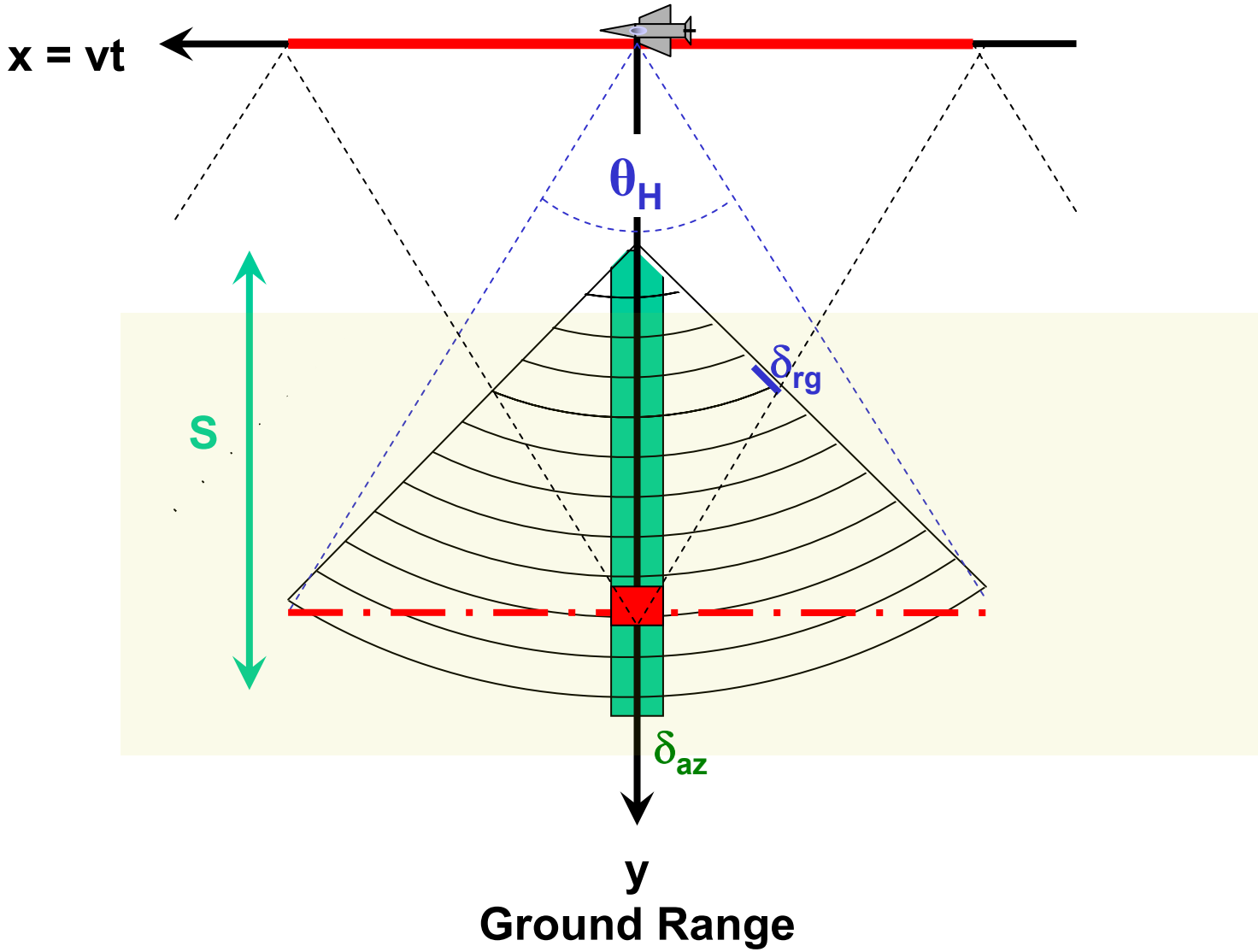
SAR Foot Print Scheme



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Beam Forming with Fixed Filter $B_{fix} = \Delta f_D$

$$\Delta f_D \approx \frac{2v}{\lambda}\Delta\vartheta(t) = \frac{2v}{\lambda}\frac{\Delta x}{r} \quad \Rightarrow \quad \delta_{xDB} = \frac{\lambda}{2v} r \Delta f_D$$

Corresponding Synthetic Aperture: $L_{sDB} = \dfrac{2v}{\Delta f_D}$

$1/B_{min} \leq T_{max}$ = Time necessary to shift f_D through the whole Filter Bandwidth

$$\frac{\Delta f_D}{\Delta T} = \frac{2v}{\lambda r}\frac{\Delta x}{\Delta T} = \frac{2v^2}{\lambda r}$$

$B_{min} = \Delta f_D$ and $T_{max} = \Delta T$

$$\boxed{\delta_{xDB} = \sqrt{\frac{r}{2\lambda}}}$$

Optimum Resolution obtainable by use of a fixed Filter

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Geometric SAR Azimuth Resolution

- **Length of the synthetic aperture ($\Theta_a \leq 30°$)**

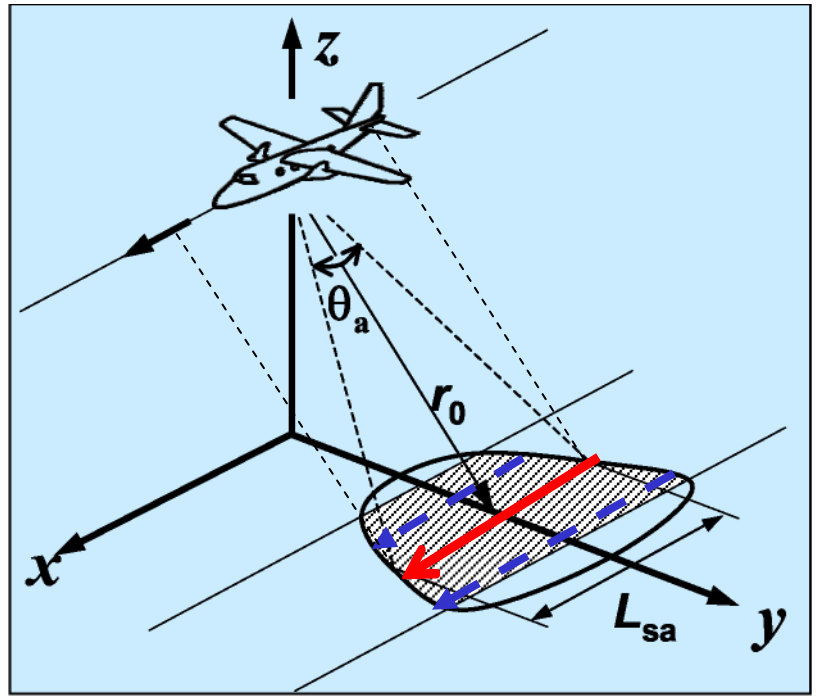
$$L_{sa} = \Theta_a \cdot r_0 = \frac{\lambda}{d_a} \cdot r_0$$

- **Beam Width of the Synthetic Antenna:**

$$\Theta_{sa} = d_a / 2r_0$$

Azimuth resolution

$$\delta_{sa} = d_a / 2$$



Synthetic Antenna Length = Ground Strip

Azimuth Resolution = Half Antenna Length in Azimuth

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Tracking Filter leads to Matched Transmit Receive System

allows Use of Total Dwell Time T_D & Largest Synthetic Aperture L_S

SAR

$$L_S = vT_D = \frac{v}{B} \rightarrow \delta_{\mathrm{az}} = \frac{\lambda r}{2L_S}$$

General Valid Relations (for $\theta_H \leq 30°$)

$\theta_H = \lambda/d$ and $L = \theta_H r$

$$\boxed{\delta_{az} = \frac{d}{2}}$$

Optimum Theoretical Azimuth Resolution for Focussed SAR

(Strip Map Mode)

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Synthetic Apertur Radar
Basically Coherent Scatterometer

with

Very High Sophisticated Data Evaluation and Processing

Basis: Construction of Very Large Antenna along a flight path by means of Data Processing

Unfocussed SAR:

neglects inherent Phase Differences with respect to a fixed Point

Azimuth Resolution (unfocussed)

$$\delta_{azunfoc} = \tfrac{1}{2}\sqrt{\lambda R}$$

Focussed SAR:

Resolution independent of Wavelength & Distance

Azimuth Resolution

$$\delta_{az} = d/2$$

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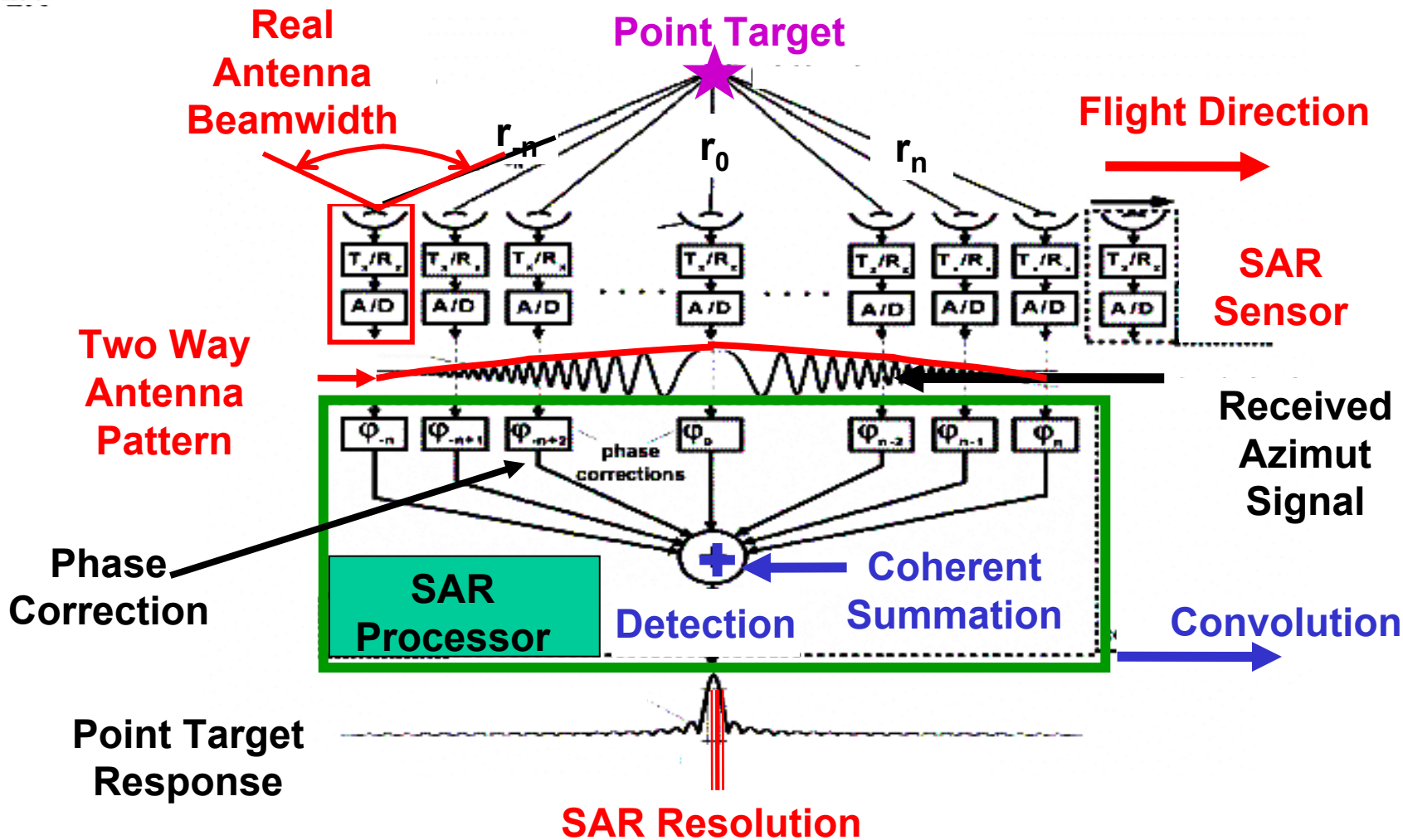
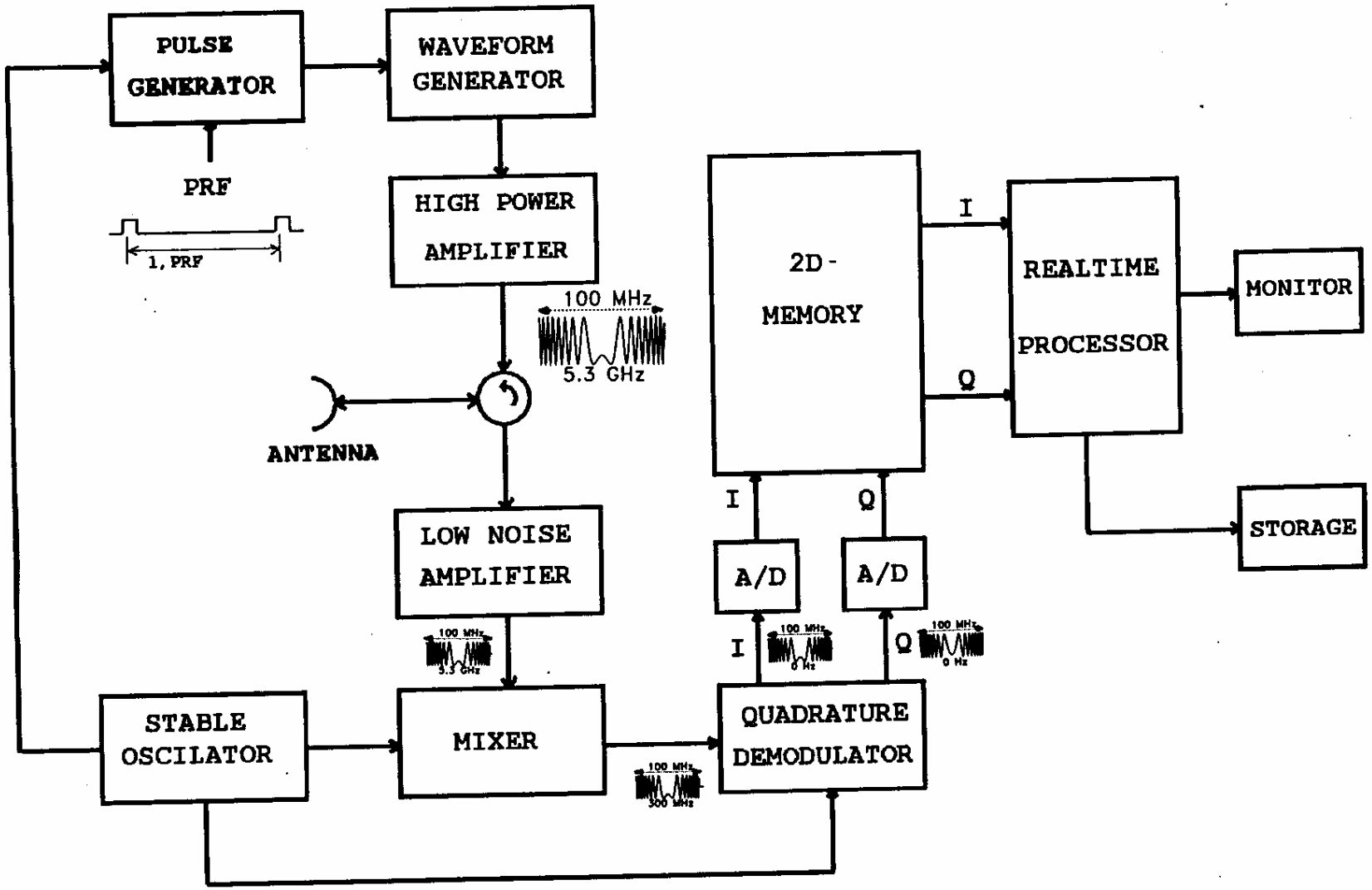
The Antenna: System Determining Element for SAR



SAR is an Antenna

SAR Block Diagramm



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SAR Range Equation

Normal Radar Equation (Hall)

$$\frac{S}{N} = \frac{P_{ave} G^2 \lambda^2 \sigma T_D}{(4\pi)^3 r^4 (kT_0 F) L_{tot}}$$

$$T_D = \frac{\lambda r}{2\delta_{az} v}$$

SAR Radar Equation Point Target

$$\frac{S}{N} = \frac{P_{ave} G^2 \lambda^3 \sigma}{(4\pi)^3 r^3 (kT_0 F) 2v\delta_{az} L_{tot}}$$

$$\sigma = \sigma_o \delta_{az} \delta_{rge}$$

SAR Radar Equation Area Target

$$\frac{S}{N} = \frac{P_{ave} G^2 \lambda^3 \sigma_0 \delta_{rge}}{(4\pi)^3 r^3 (kT_0 F) 2v L_{tot}}$$

All SAR Design Equations contain Antenna Parameter!!

Point Target Signal/Noise (S/N)	$S/N = \frac{P_{ave} A^2 \sigma}{(4\pi)\lambda^2 R^3 (kT_0F) 2v\delta_{az}}$
Pulse Repetition Frequency (PRF)	$2v/D \leq (PRF) \leq c/2R_{max}$
Optimum Range Resolution(δ_{rg})	$\delta_{rg} = c/2B = c\tau_p/2$
Optimum Azimuth Resolution(δ_{az})	$\delta_{az} = D/2$
Swath width(S)	$S = c\ D/4v$
Synthetic Aperture Length(L)	$L = \lambda R/D$
Along Track Pixel Number(N_{az})	$N_{az} = R\lambda/2\delta_{az} = L/\delta_{az}$
Across Track Pixel Number(N_{rg})	$N_{rg} = S/\delta_{rg}$
Data Rate(DR)	$DR = N_{rg}\ PRF$
Pixel(Sample) Rate(Q)	$Q = nvS/\delta_{az}\delta_{rg}$

A = Antenna Area, B = Bandwidth, D = Antenna Length, kT_0F = Noise Charakteristic,
n = Number of Looks, P_{ave} = Mean Power, R_{max} = Maximum Distance SAR-Pixel,
v = Platform Velocity, λ = Wavelength, σ = Radar Cross Section, τ_p = Pulse Length,

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SAR – RAR Comparision

Type	Point Target (S/N =SNR)	Area Target (C/N = CNR)	Contrast (S/C = SCR)
RAR	$(SNR)_{RAR} = \frac{P_{ave} G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 (kT_0 F) B \tau_P (PRF) L_{tot}}$	$(SNR)_{RAR} = \frac{P_{ave} G^2 \lambda^3 \sigma_0 \delta_{rg}}{(4\pi)^3 R^3 (kT_0 F)(PRF) L_{tot}}$	$(S/N)_{RAR} = \frac{\sigma d}{\sigma_0 r \lambda B \tau_P \delta_{rg}}$
SAR	$(SNR)_{SAR} = \frac{P_{ave} G^2 \lambda^2 \sigma}{(4\pi)^3 R^3 (kT_0 F) 2v \delta_{az} L_{tot}}$	$(SNR)_{SAR} = \frac{P_{ave} G^2 \lambda^3 \sigma_0 \delta_{rg}}{(4\pi)^3 R^3 (kT_0 F) 2v L_{tot}}$	$(S/N)_{SAR} = \frac{\sigma}{\sigma_0 \delta_{rg} \delta az}$
Im-prove-ment	$\frac{(SNR)_{SAR}}{(SNR)_{RAR}} = \frac{B \tau_P (PRF) \lambda r}{\delta_{rg} 2v}$	$\frac{(SNR)_{SAR}}{(SNR)_{RAR}} = \frac{(PRF) d}{2v}$	$\frac{(SCR)_{SAR}}{(SCR)_{RAR}} = \frac{B \tau_P r \lambda}{\delta_{\alpha\zeta} d}$

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Pulse Repetition Frequency

Pulse Repetition Frequency (PRF)

Dominating Factor in SAR Design

Principal Limitations:

- ★ Azimuth & Range Ambiguities
- ★ Swath Coverage- & Extension Requirements
- ★ Forbidden PRF Bands due to
  - Altitude Line Echo (ALE)
  - Altitude Variations
  - Earth Curvature & Orbit Excentricities

Lower Limit: $2vd^{-1} < PRF$

Transmitter must be pulsed before platform moves ½ the Antenna Length d

Upper Limit

defined by Range Ambiguity Requirements

Impulse needs for crossing the Swath along r_{gmax} the Time $t_{gmax} = c\,(2\,r_{gmax})^{-1}$

$$2\frac{v}{d} \leq PRF \leq \frac{c}{2r_{g\,max}}$$

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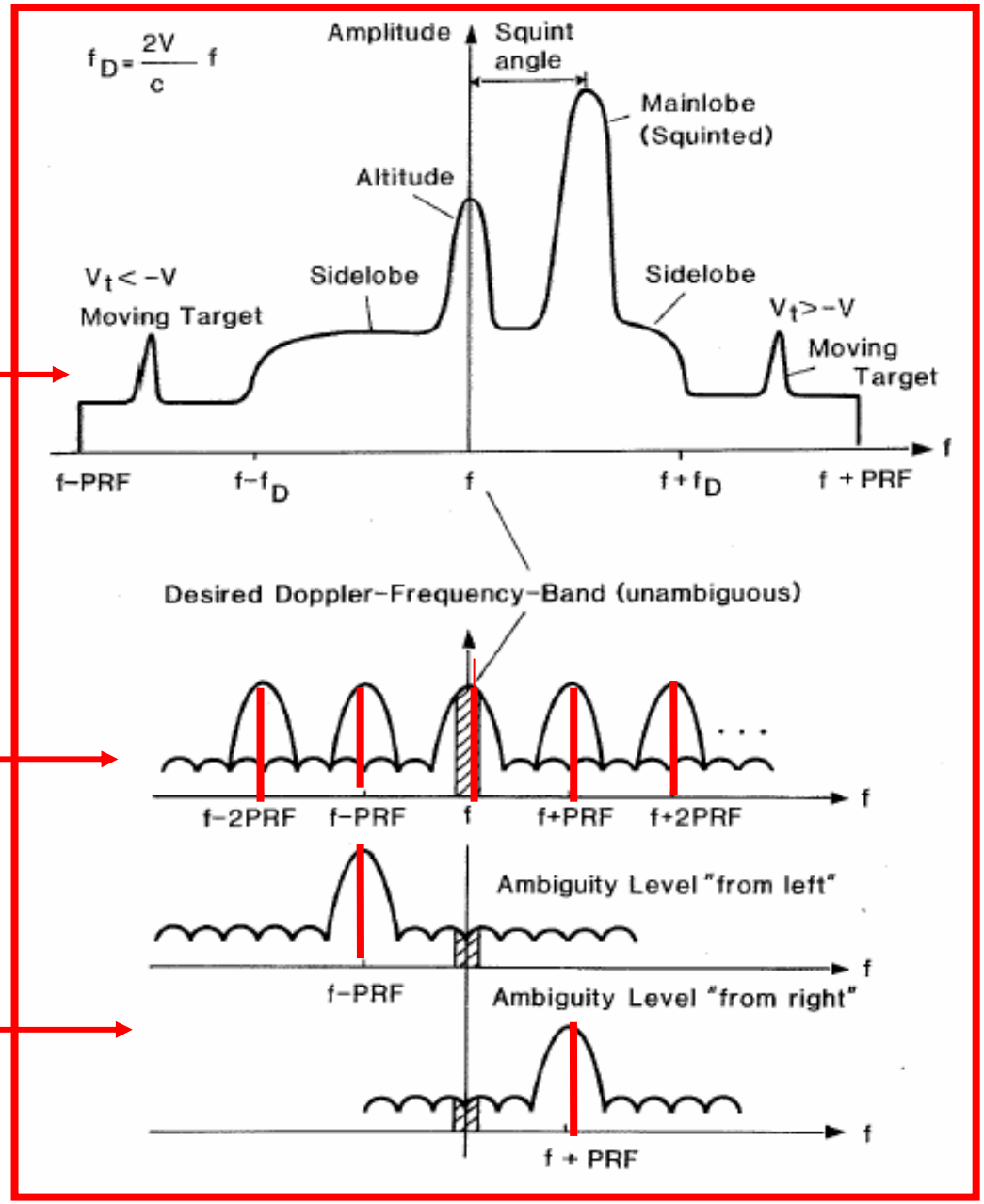
Pulse Spectrum Scheme
Moving Pulse Doppler Radar

Single Spectral Line Fine Structure

Pulse Spectrum with Ambiguities

Single Spectral Lines



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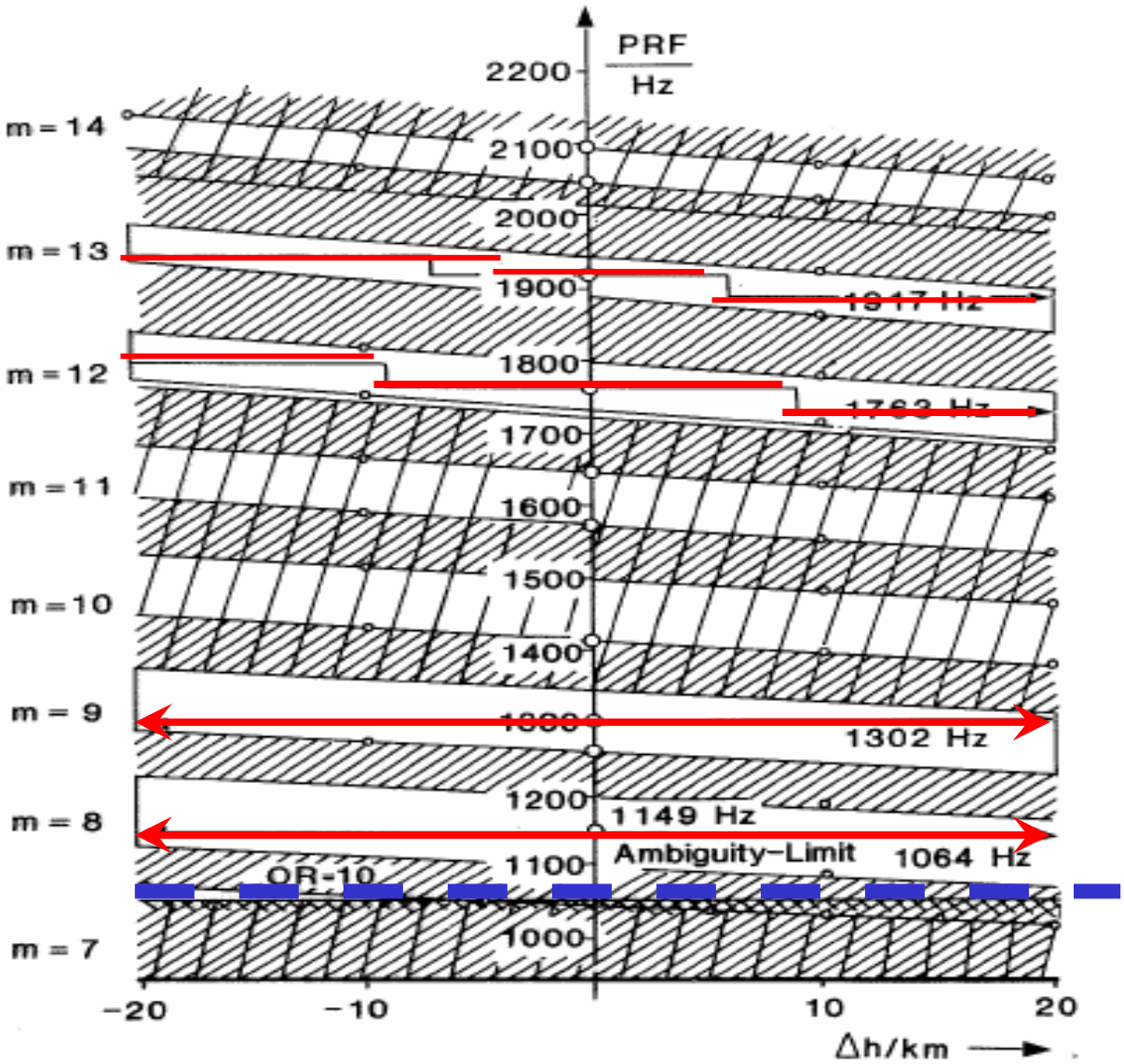
PRF Limitations due to Altitude Variations
Allowed PRF Bands for X-Band Satellite



m = Number of allowed Range Ambiguities

Ambiguity Limit 1064 HZ

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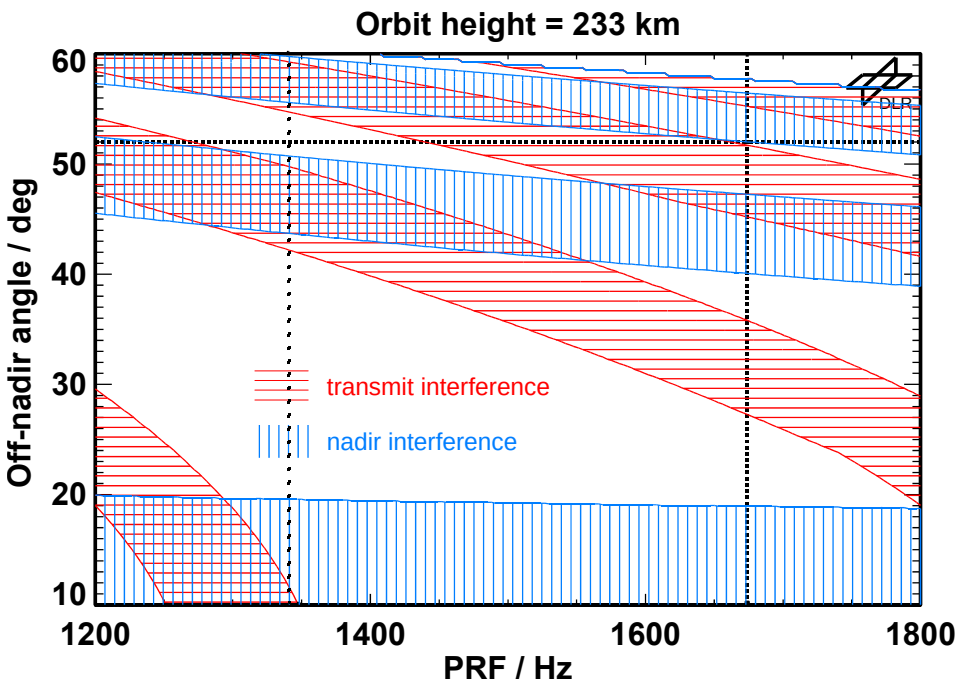
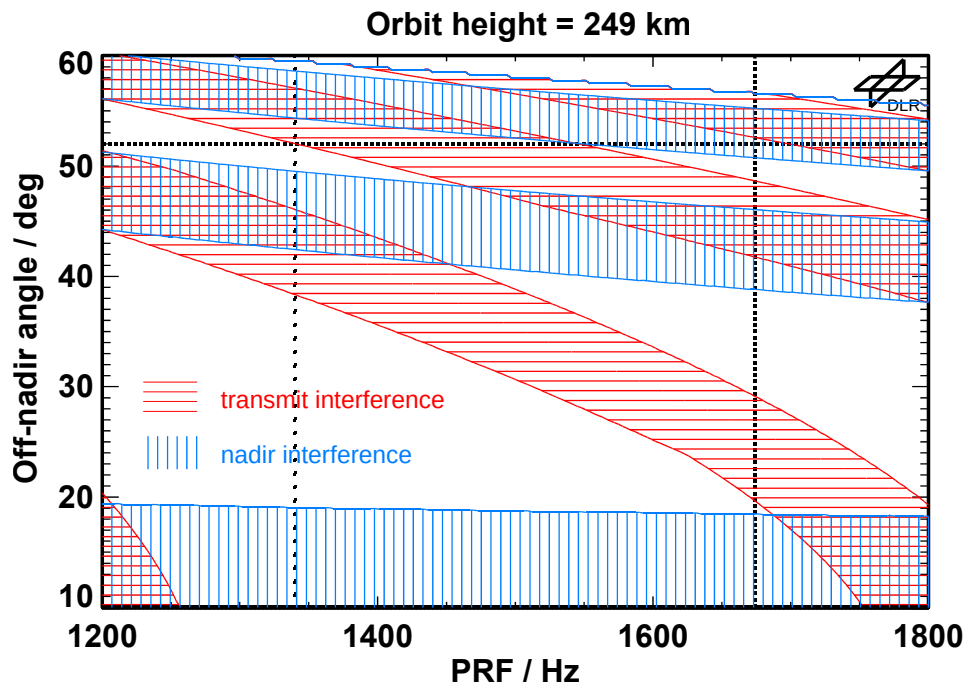
PRF choice for X-SAR/SRTM
Transmit & Nadir Interference Limitations





Objective: **A fixed combination of PRF and Off-nadir angle**

- **takes into account the historical development and restrictions,**
- **avoid transmit and preferably nadir interferences and**
- **yield a good interferometric performance.**

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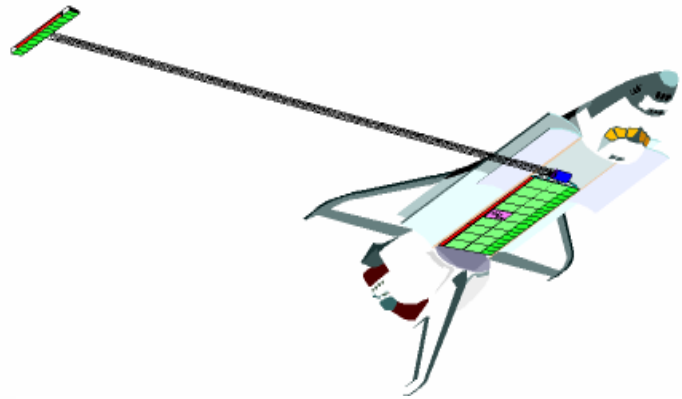
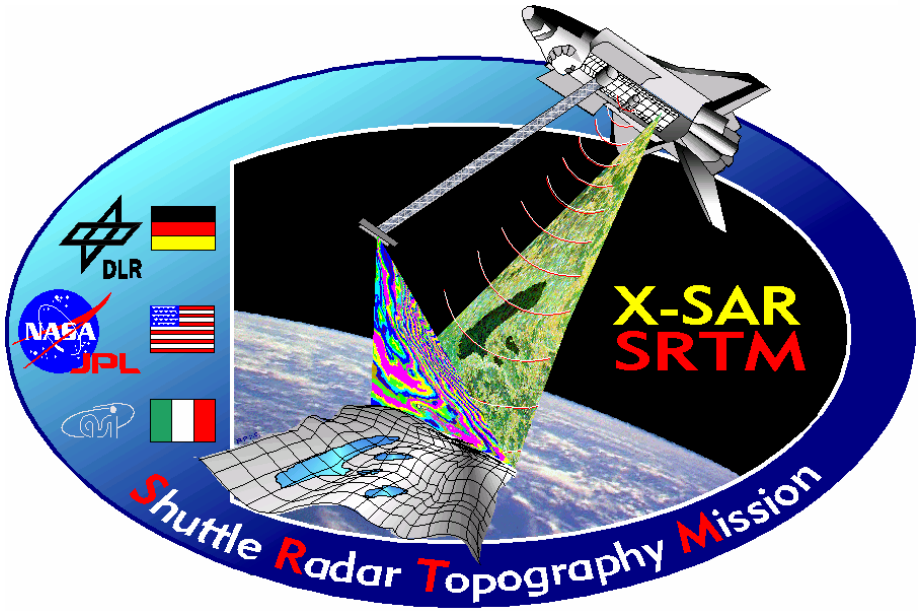
System Parameters of the X-SAR Instrument

- Orbit height from 233 km to 249 km (coverage requirement of C-Radar)
- PRF limited to eleven fixed values ranging from 1240 Hz up to 1736 Hz
- Off-nadir angle > 51° to avoid interference with Attitude and Orbit Determination Avionics (AODA)





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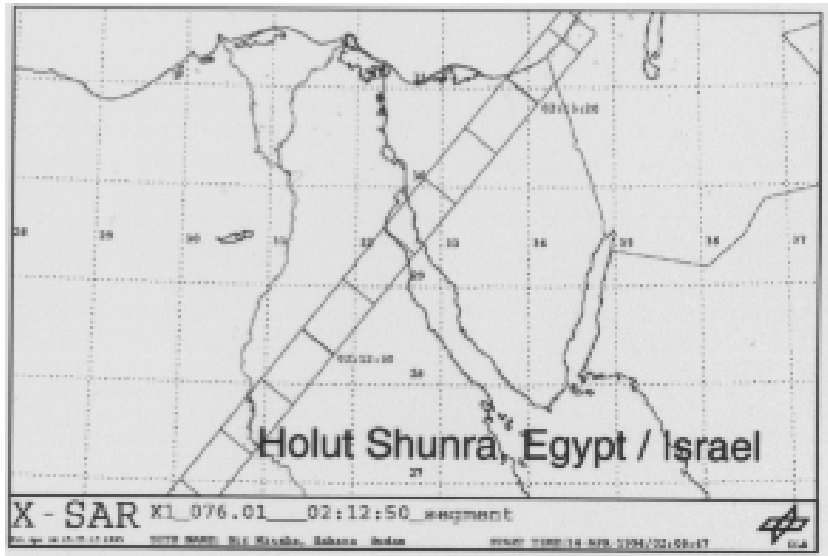
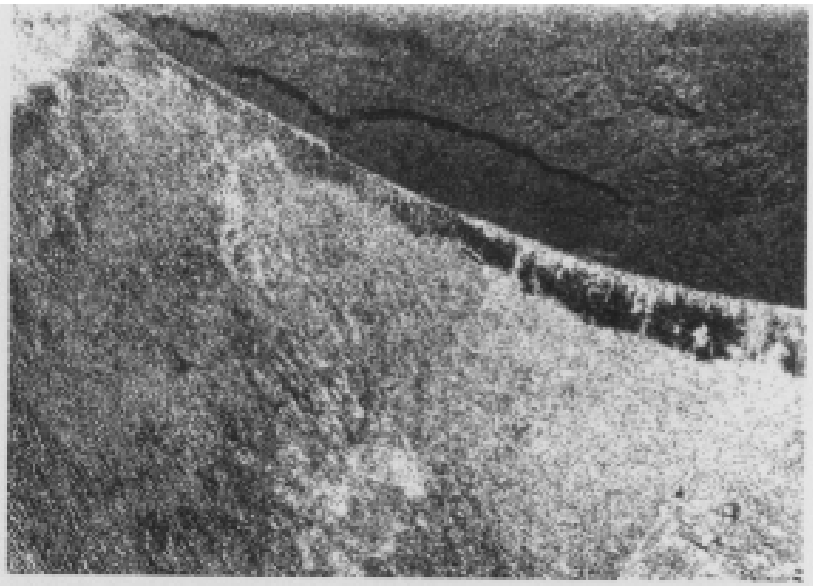
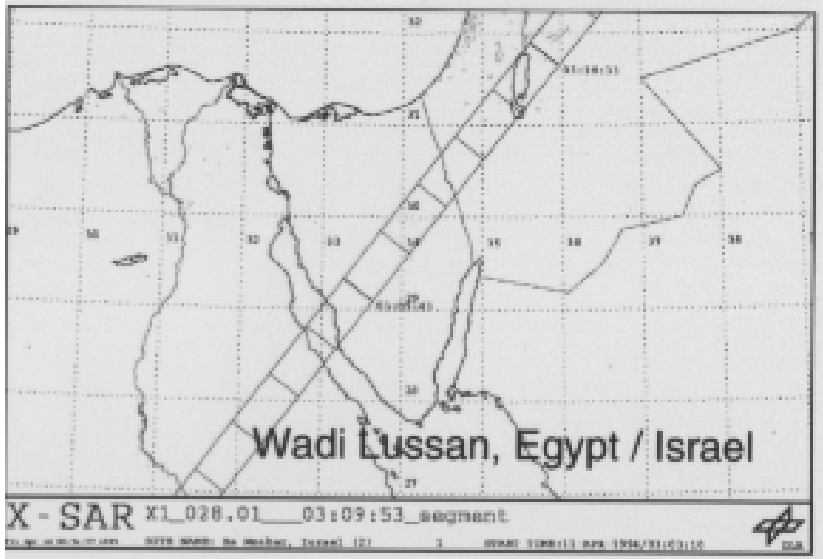
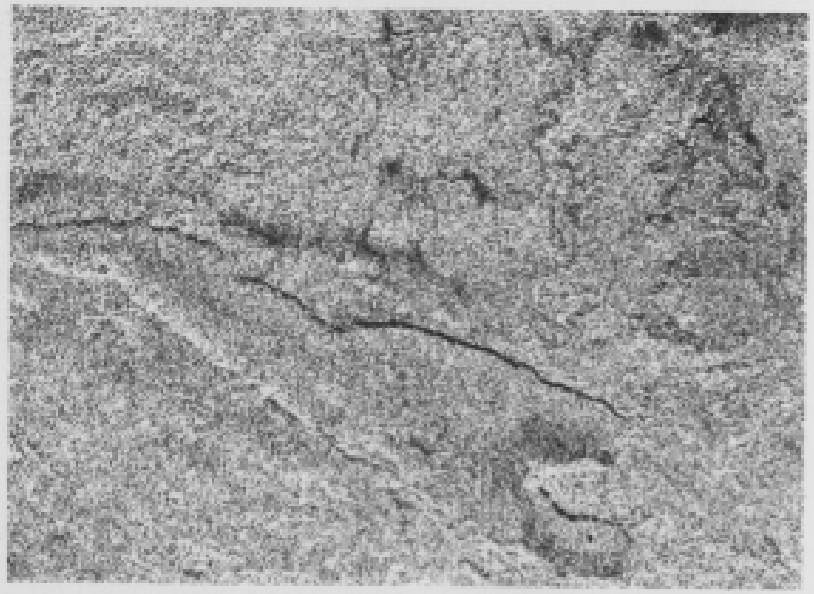
Ambiguities

X-SAR Ambiguities









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Airport Zürich Klothen with & without Ambiguities caused by 6,8° Antenna Squint Angle

Ambiguities

E-SAR, X-VV, θ_{HH}= 12°, v = 70 msec^{-1}

Near Range 2805m, Far Range 5355m

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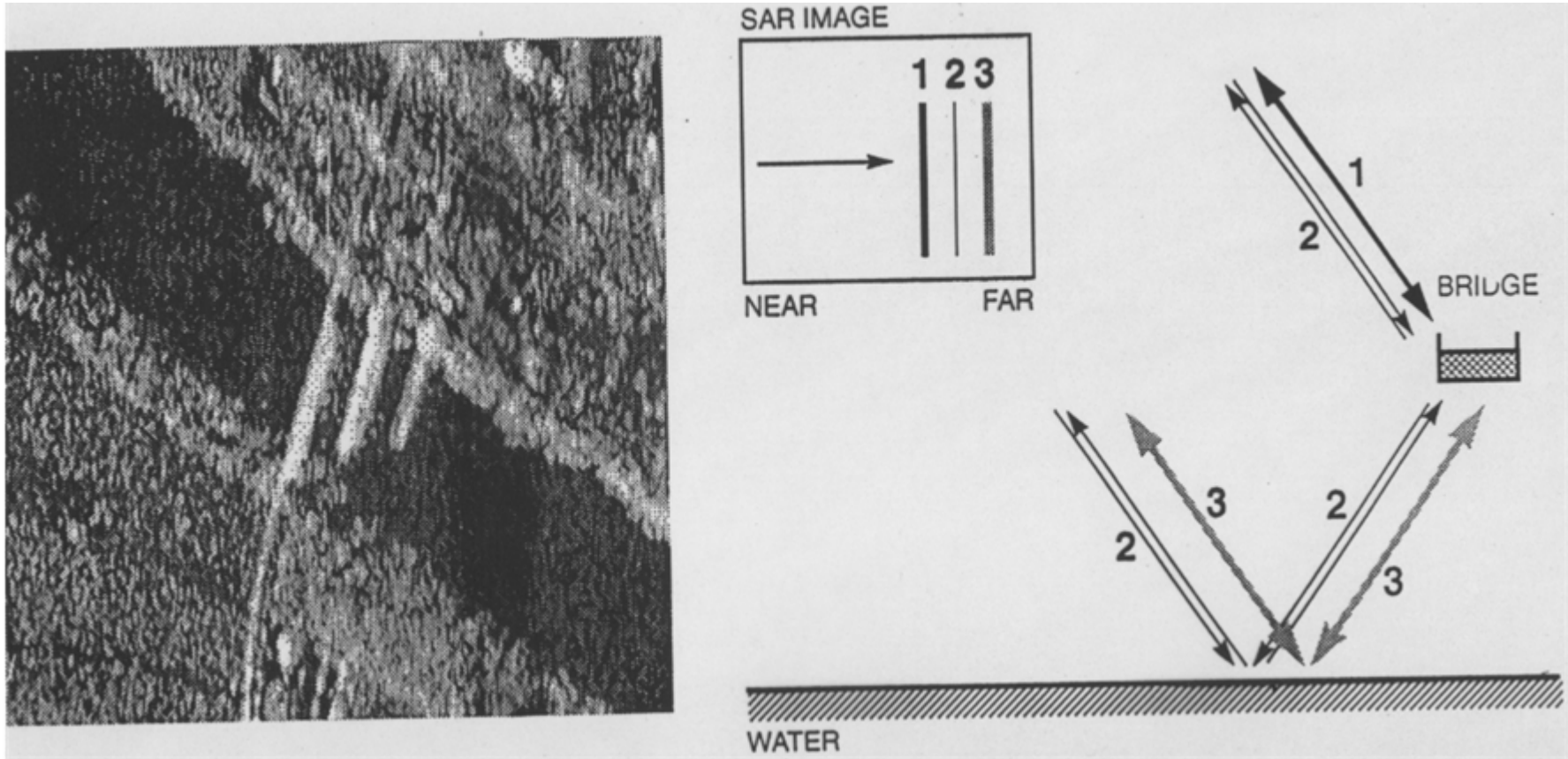
Ambiguities due to Multipath Reflection (Bridge)



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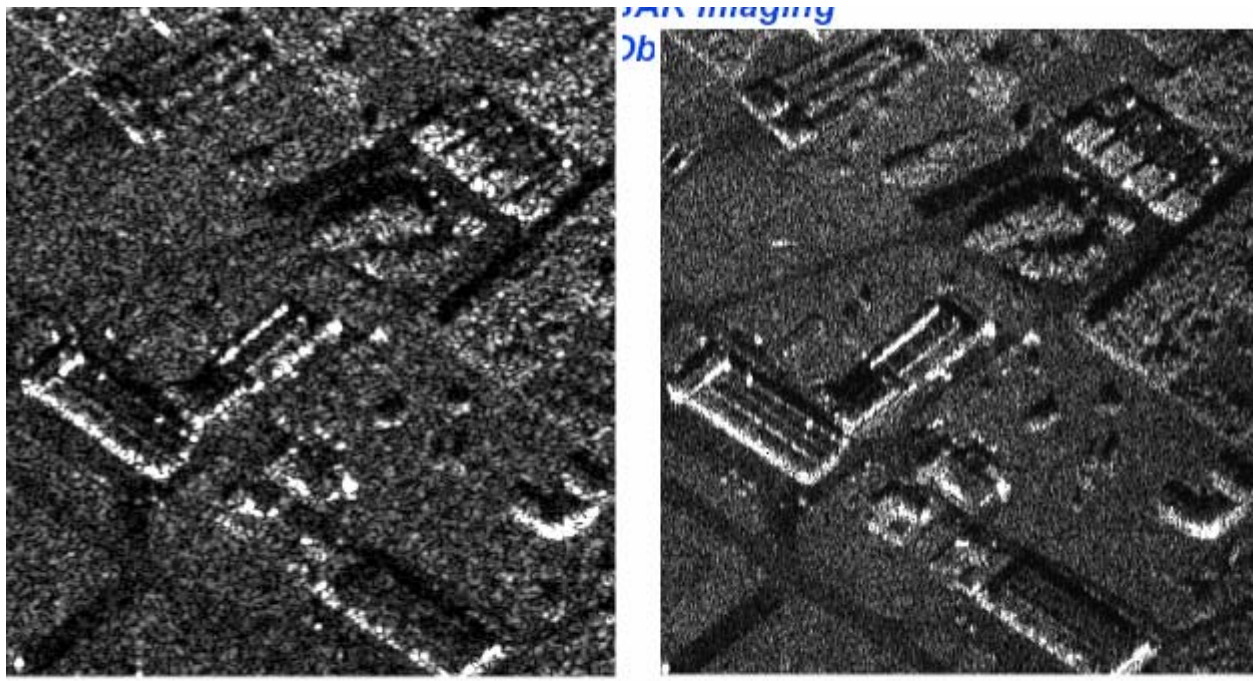

Stripmap image
3 m azimuth resolution

Spotlight image
0.46 m azimuth resolution

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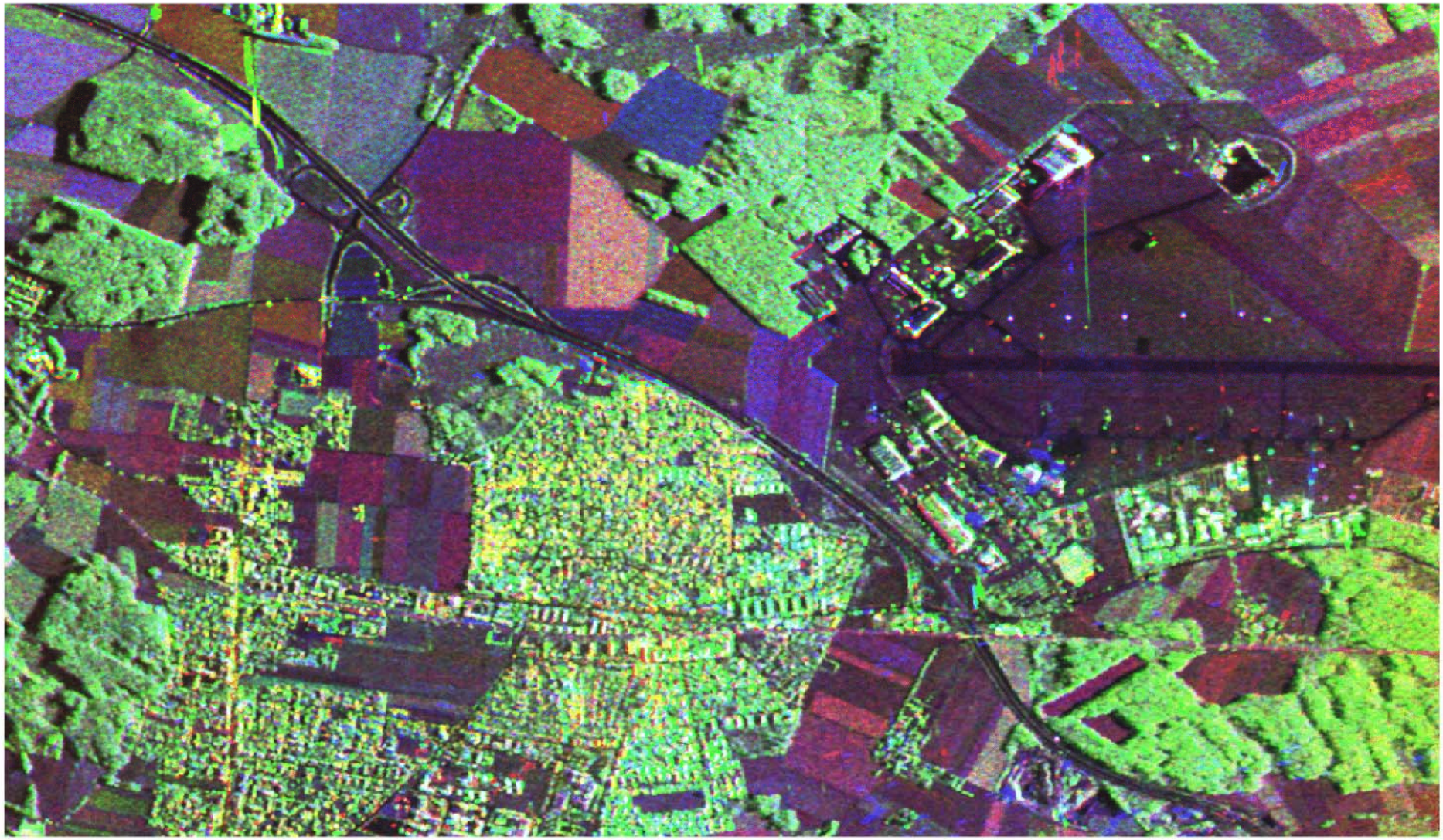
Multi-Frequency E-SAR-Image (L, C, and X-band)



L-band, HH C-band, HH X-band, VV

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Processing Principles

Coherence

If phases φ of waves random & (directly or in effect) uniformly distributed

$0 \leq \varphi \leq 2\pi$ ➔ incoherent.

If phase relations between waves are constant ➔coherent

Correlation $$C = \frac{\left\langle (E_1(t)E_2^*(t)) \right\rangle}{\sqrt{\left\langle E_1(t)E_1^*(t) \right\rangle \left\langle E_2(t)E_2^*(t) \right\rangle}}$$ $-1 \leq C \leq +1$

E_1 and E_2 vary in conformity ➔ C=1, E_1 and E_2 vary in opposition ➔ C=-1

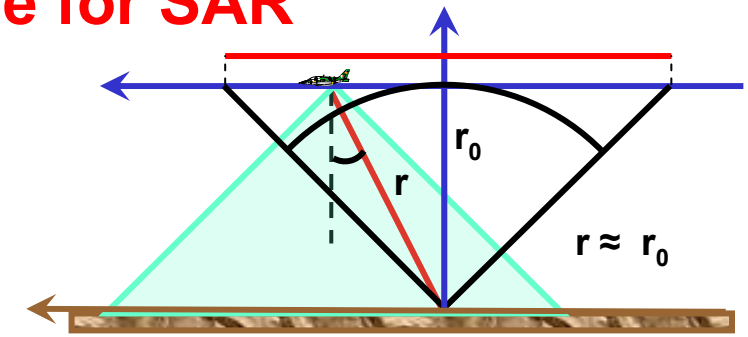
Coherence: $$\gamma = |C| = \left| \frac{\left\langle (E_1(t)E_2^*(t)) \right\rangle}{\sqrt{\left\langle E_1(t)E_1^*(t) \right\rangle \left\langle E_2(t)E_2^*(t) \right\rangle}} \right|$$ $0 \leq \gamma \leq 1$

γ = 0 means ➔ incoherence, γ = 1 ➔ complete coherence

Continous transition from pure coherence to pure incoherence

SAR Processing Basics

Phase Information is decisive for SAR



$$r^2 = r_0^2 + (vt)^2 \quad ==> \quad (r - r_0) \approx \frac{(vt)^2}{2r_0}$$

$$r \approx r_o + \frac{(vt)^2}{2r_0}$$

Two Way Phase: $\varphi = \frac{2\pi}{\lambda}\left(r_0 + \frac{v^2 t^2}{r_0}\right) \quad => \quad \omega_D = 2\pi f_D = \frac{d\varphi}{dt} = 4\pi \frac{v^2}{\lambda r_0} t$

x

Transmitted: $V_T = V_1 \sin\omega t$ ➔ Received: $V_r = V_2 \sin(\omega t + \omega_D t)$

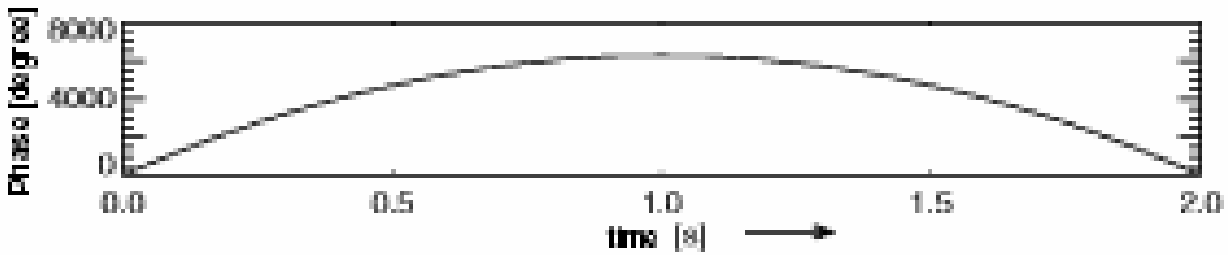
Linear Frequency Modulation

Chirp Steepness: $\frac{2v^2}{\lambda r_0}$

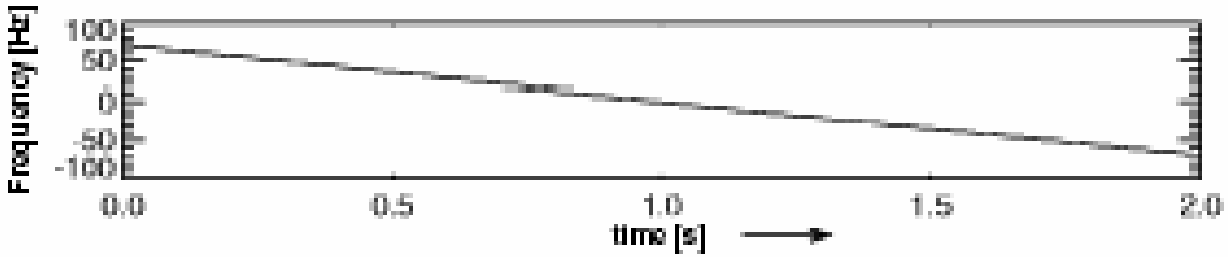
Bandwidth Required: $B_{f_D} = \frac{2v^2}{\lambda r_0} T_D = \frac{2v}{\delta_{az}}$

Azimuth Signal

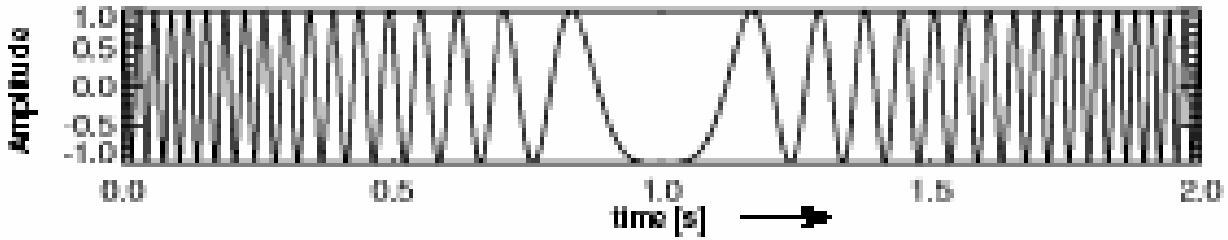
Phase/Degree



Frequency/Hz



Normalized Anplitude



$V = 70\ msec^{-1}$, $\lambda = 5{,}6\ cm$, $r_0 = 5000\ m$

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Phase Reference

Phase contents all Target Information required. Quadratic Demodulation provides Phase Information with INPHASE (I) & QUADRATURE (Q) Component.

$$I(t) = A\cos\left(2\pi\frac{v^2 t}{\lambda r_o}t\right) \quad \& \quad Q(t) = A\sin\left(2\pi\frac{v^2 t}{\lambda r_o}t\right)$$

$$S_{sig}(t) = I(t) + jQ(t) = \exp\left(j2\pi\frac{v^2 t}{\lambda r_o}t\right) \quad \text{with} \quad A = 1$$

Target Position at t=0 where $f_D = 0$

Further Information by Correlation with Reference Function for Point Target

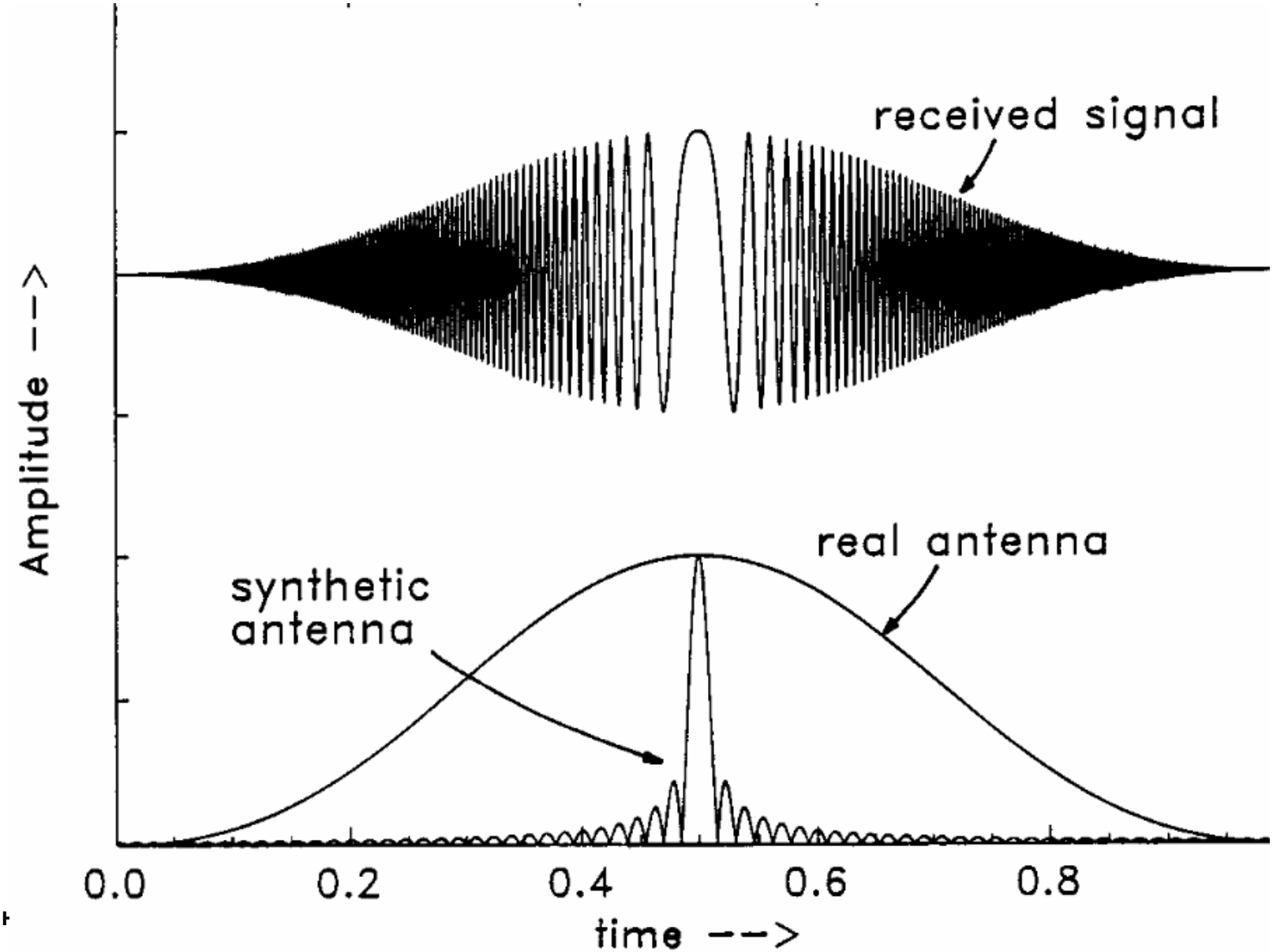
$S_{ref}(t) = S_{sig}(t)$

$S_o(t)$ at Correlator Output

$$S_{cor}(t) = \int_{-\frac{T_D}{2}}^{+\frac{T_D}{2}} S_{sig}(t) S_{ref}^*(t-\tau)dt = \exp\left(-j2\pi\frac{v^2\tau}{\lambda r_o}\right)\int_{-\frac{T_D}{2}}^{+\frac{T_D}{2}} \exp\left(-j2\pi\frac{v^2\tau}{\lambda r_o}t\right)dt$$

$$\boxed{S_{cor}(\tau) = \exp\left(-j2\pi\frac{v^2\tau^2}{\lambda r_o}\right)\mathrm{sinc}\left(\pi\frac{v^2 T_D}{\lambda r_o}\tau\right)}$$

RAR – SAR Point Target Signal Comparision



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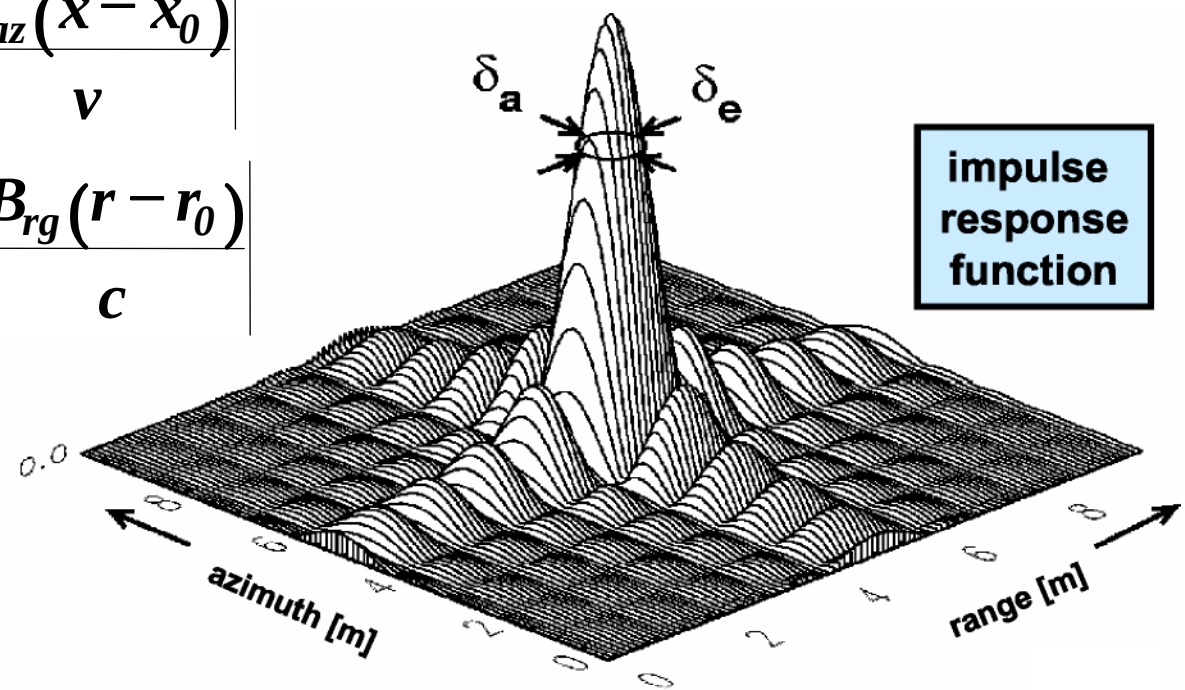
SAR Processing uses Pulse Response Function in both Azimuth and Range Impulse Response Function

$$\left|s_{az}(x)\right| = \left|\sqrt{B_{az}T_D}\right| sinc\left|\pi \frac{B_{az}(x-x_0)}{v}\right|$$

$$\left|s_{rg}(r)\right| = \left|\sqrt{B_{rg}T_{rg}}\right| sinc\left|2\pi \frac{B_{rg}(r-r_0)}{c}\right|$$



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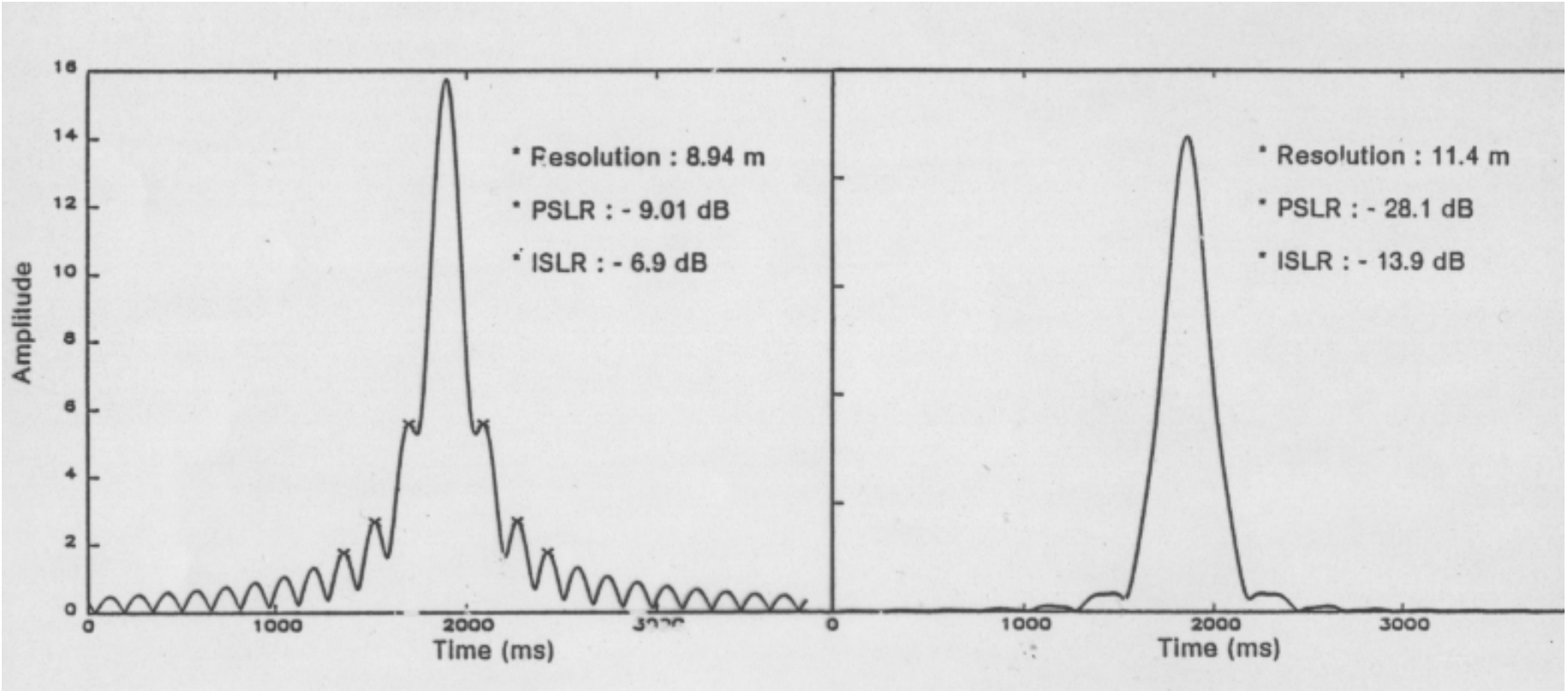
Quality Measures

Peak Sidelobe Ratio & Integrated Sidelobe Ratio

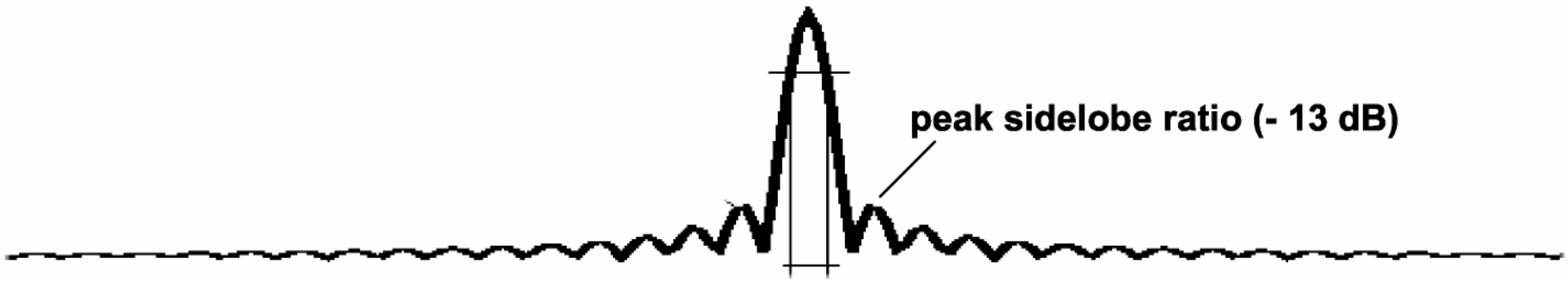
$$PSLR = \frac{\text{Power within Sidelobes}}{\text{Power within Main Beam}} \qquad ISLR = \frac{\text{Power within Sidelobes}}{\text{Power within Diagram}}$$



Quellenangabe

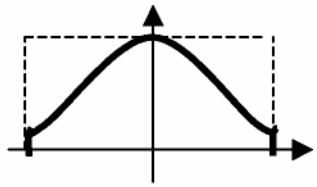
Influence of Weighting

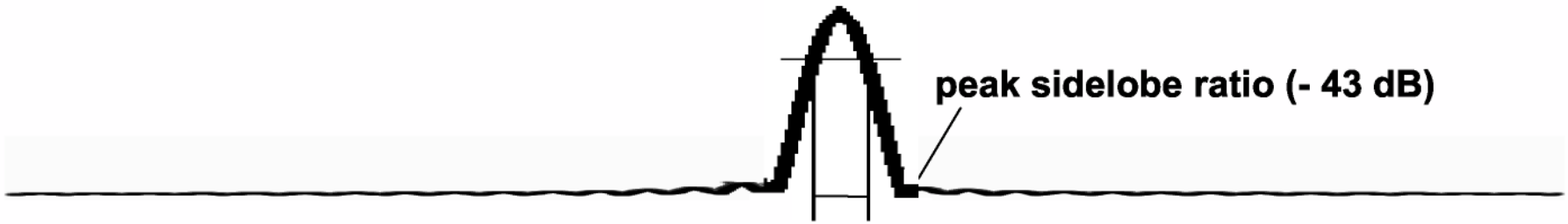
- **Impulse response function without weighting:** $\mathrm{sinc}(x) = \sin(x)/x$



3dB resolution

Impulse response function with Hamming weighting (= 0.54) ***w (t)*** **=**

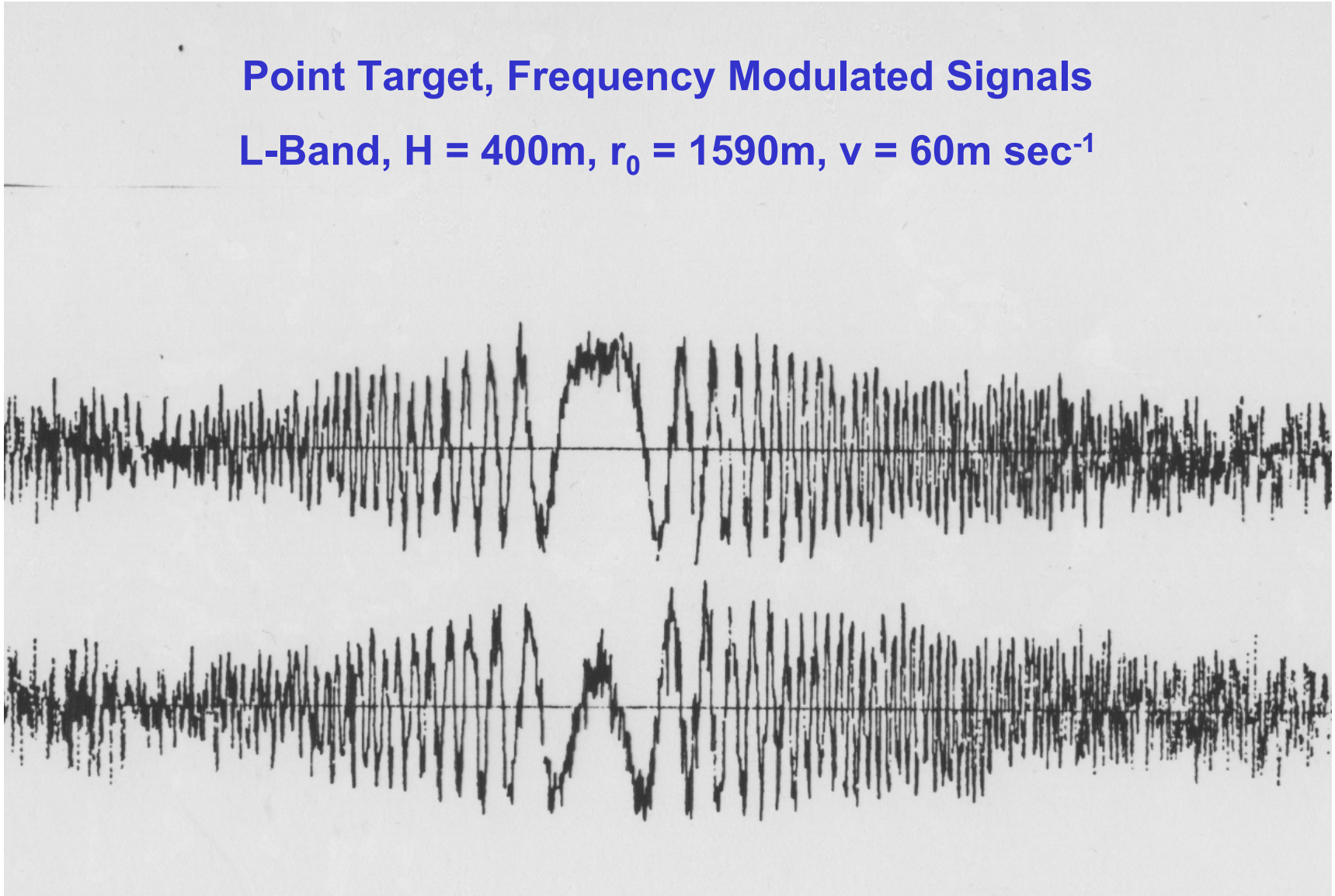




3dB resolution

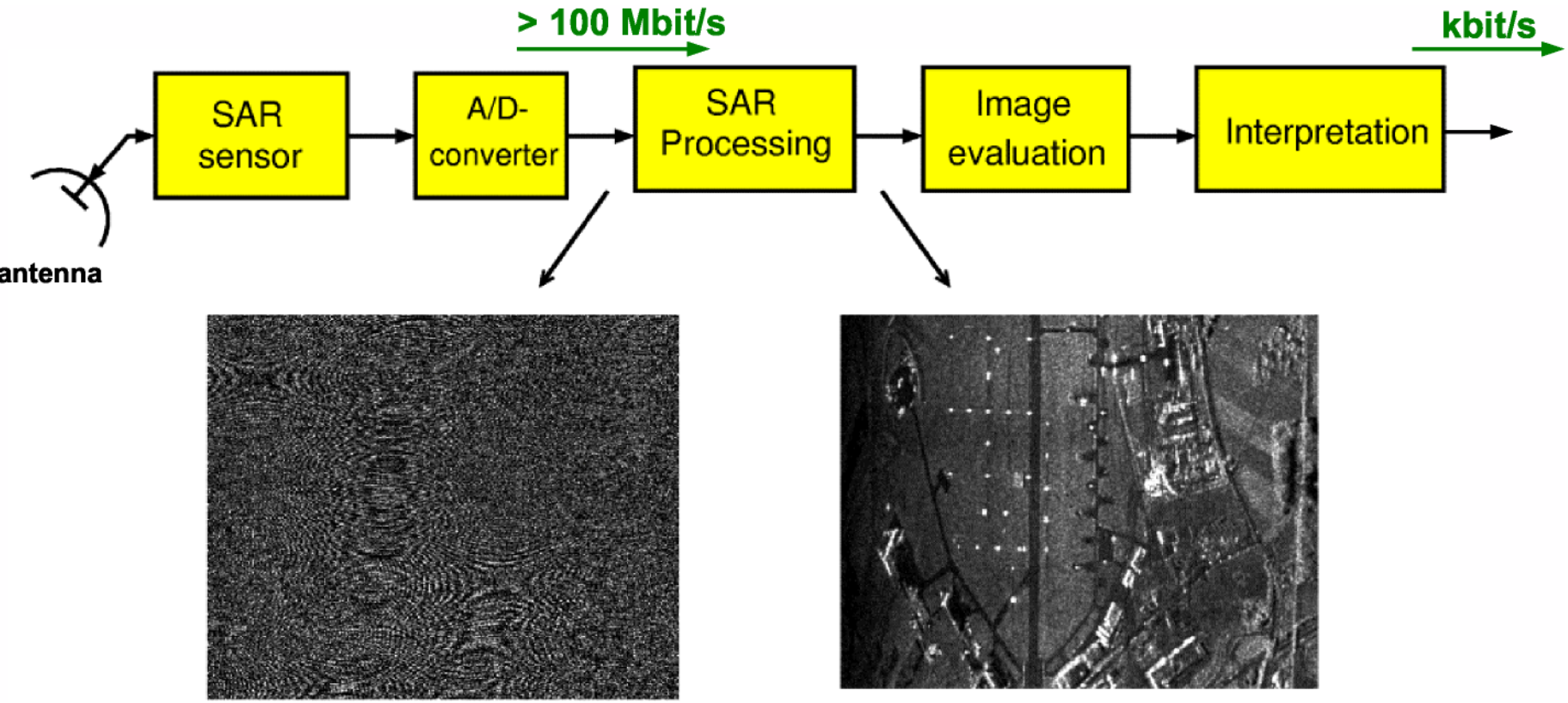
Quellenangabe

SAR, Measured I- & Q-Signals



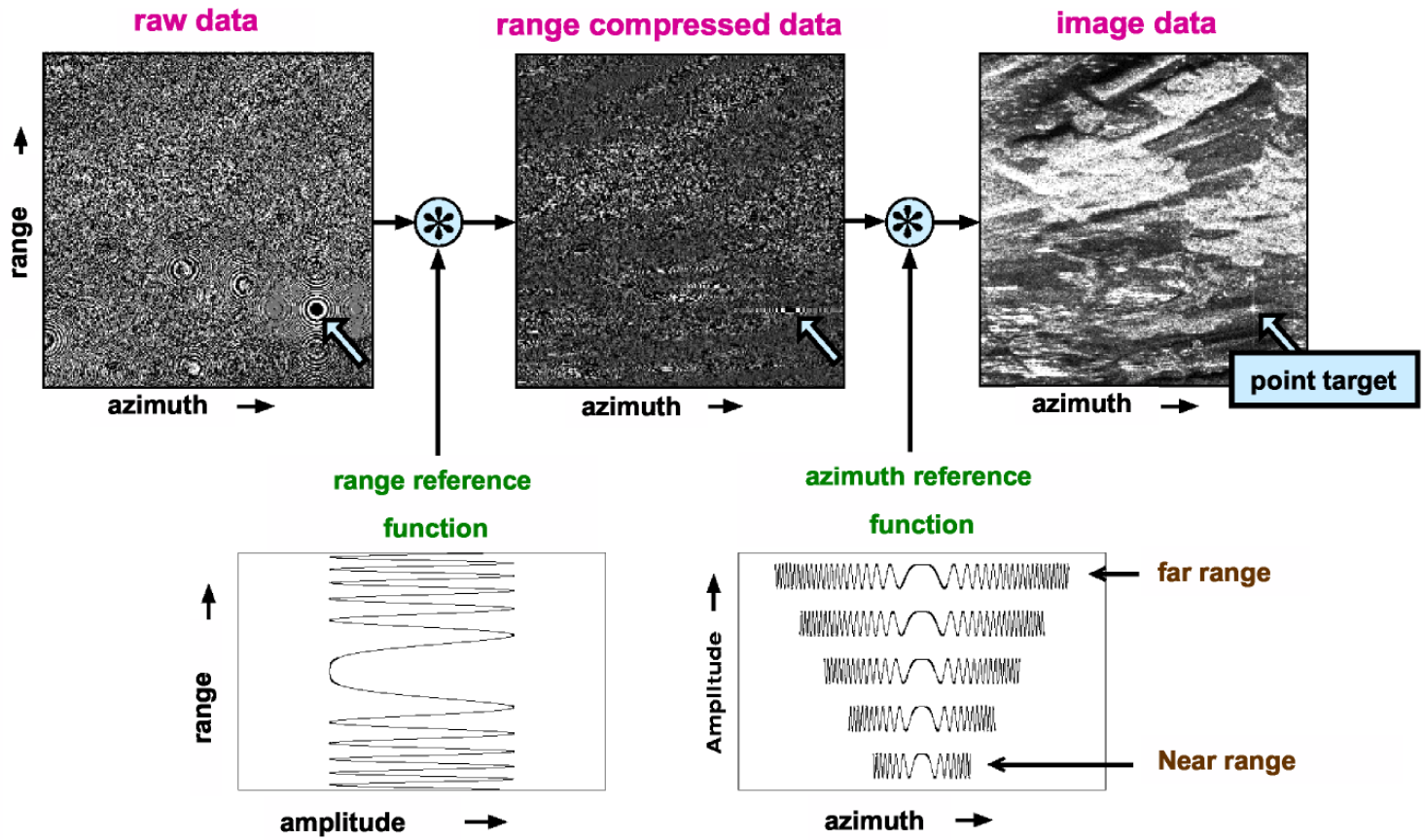
Quellenangabe

SAR Data Flow



Quellenangabe

SAR Processing Image Formation



Different Azimuth Reference Functions for different Range Gates

Characteristics of Impuls Response Function

Hamming weighting (α)	resolution deterioration factor	PSLR (Peak Sidelobe Ratio)	ISLR (integrated sidelobe ratio)
none	0.88	13.2 dB	9.8 dB
0.54	1.30	43 dB	21 dB

- azimuth resolution

$$\delta_a = k_a \cdot \frac{v}{B_a} = k_a \cdot \frac{d_a}{2}$$

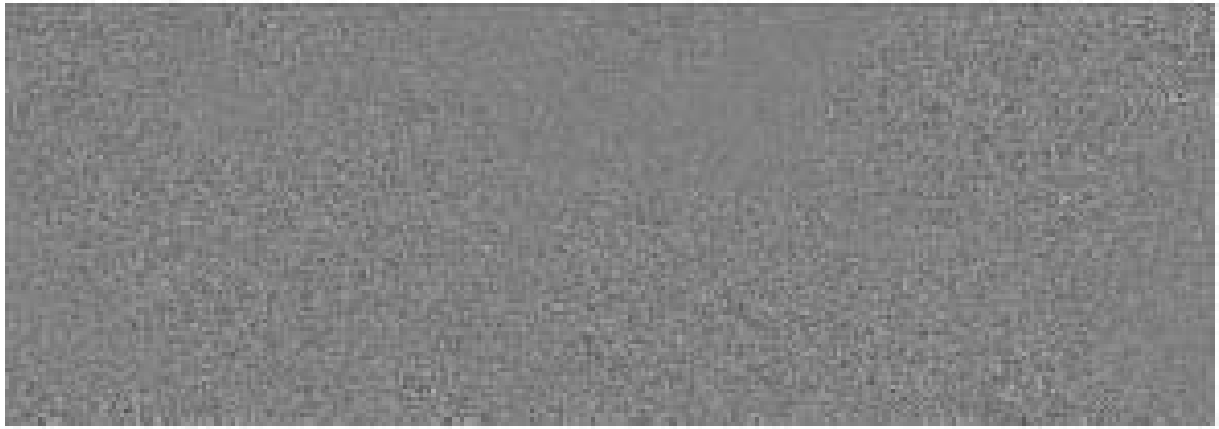
- range resolution

$$\delta_e = k_e \cdot \frac{c_0}{2 \cdot B_e}$$

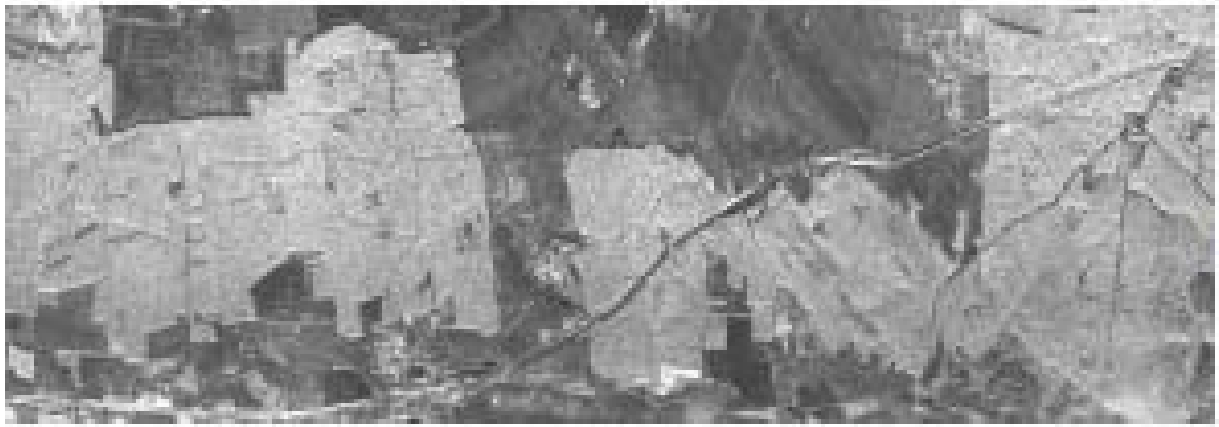
k_a = azimuth resolution deterioration factor

k_e = range resolution deterioration factor

Quellenangabe



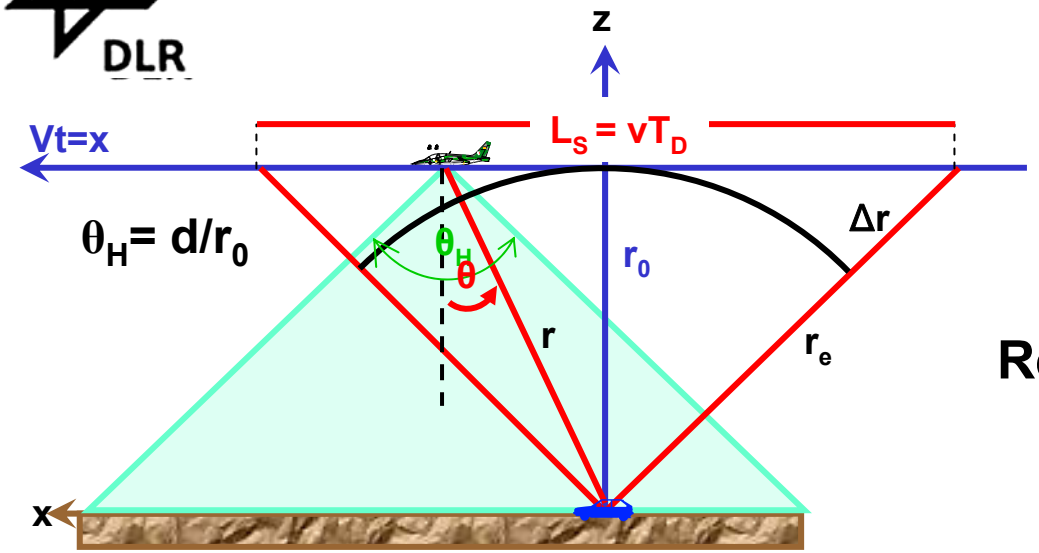
Raw Data



SAR Image

Quellenangabe

Unfocussed SAR



$(L_S/2)^2 = r_o^2 - r_o^2 \approx 2r_o(r_e - r_o)$

Focussed SAR needs Phase Compensation during Dwell Time

Unfocussed SAR ignores $\Delta r \leq \lambda/16$

Required Dwell Time for Specified δ_{az}

$$T_D = \frac{\lambda r}{v \delta_{az}}$$

$\Delta r \leq \lambda/16$ ==> Maximum Apertur Length for Unfocussed SAR

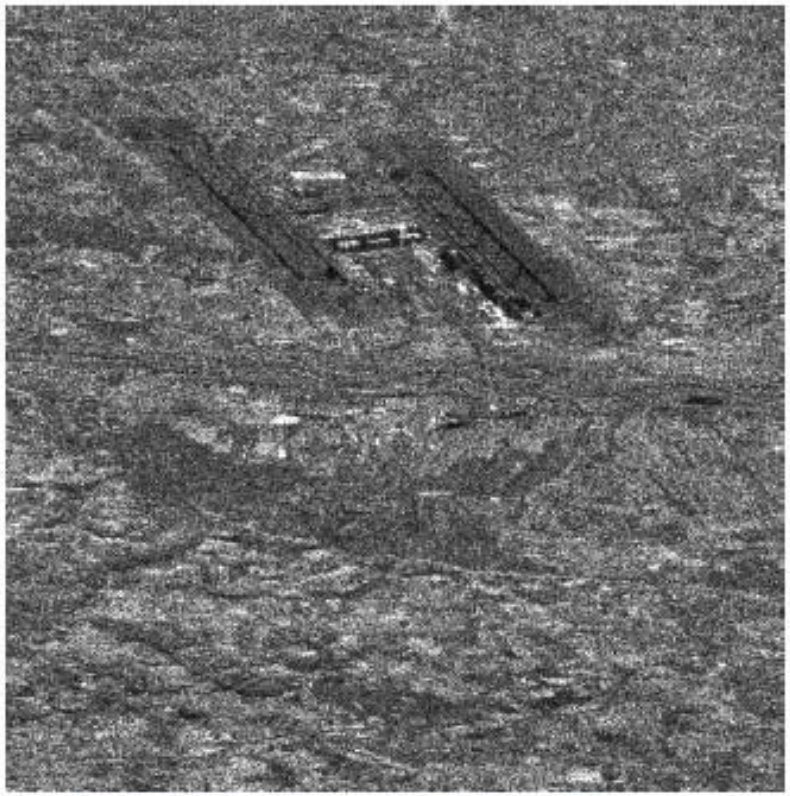
$$L_{Sun\,max} \leq \sqrt{\frac{r_0 d}{2}}$$

Resolution obtainable for Unfocussed SAR

$$\delta_{azunfoc} = \frac{1}{2}\sqrt{r\,\lambda}$$

Quellenangabe

Focussed vs. Unfocussed Processing, Munich Airport ERS-1



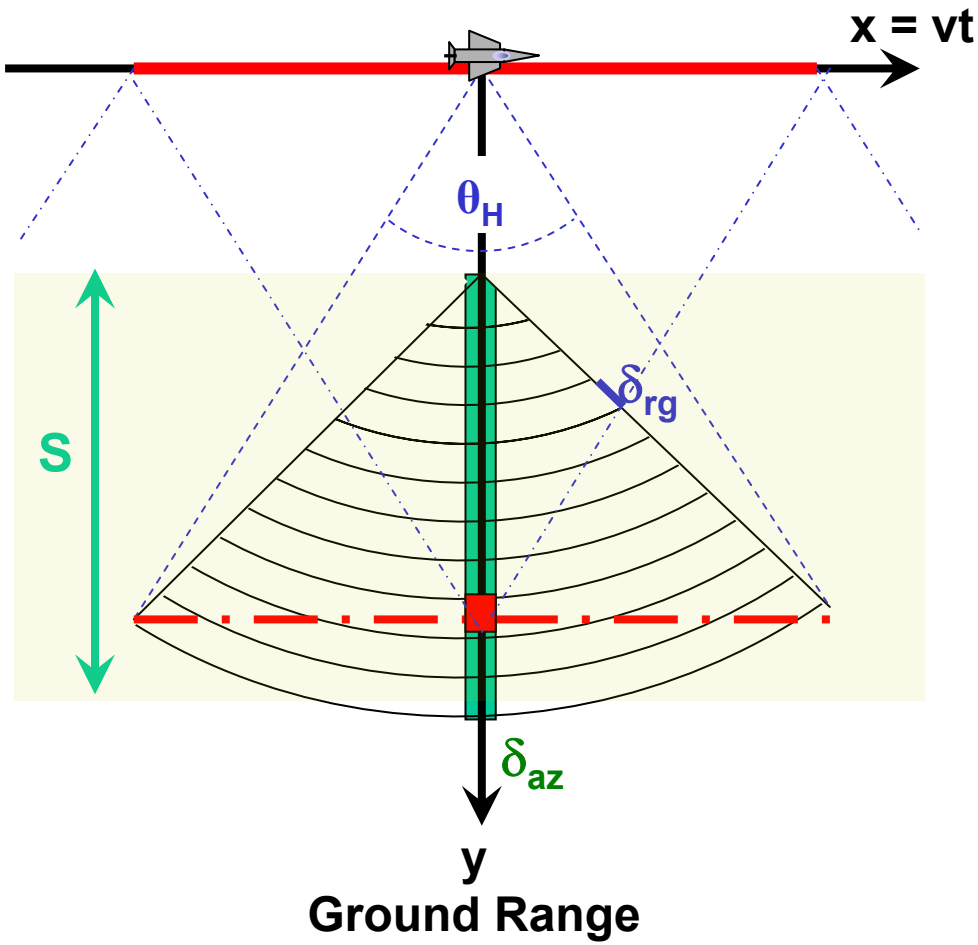
Focused Processing
- one azimuth look,
- one range look
- 7 m Azimuth resolution,
- 9 m range resolution

Unfocused Processing
- unfocussed azimuth processing
- 4 range looks
- 110 m azimuth
- 36 m range resolution

Quellenangabe

Depth of Focus (DOF)

Defines Nr. of Reference Functions required over the Whole Swath



Definition

$DoF = 2\Delta r_0$

Required Accuracy to match a given quadratic Phase Reference Function to the considered Range Maximum allowed Phase Error

$|\Delta r - \Delta r_0| = \lambda/8$

Depth of Focus (DOF)

Defines Nr. of Reference Functions required over the Whole Swath

Definition: DoF = $2\Delta r_0$

Required Accuracy to match a given quadratic Phase Reference Function to the considered Range for Maximum allowed Phase Error $|\Delta r - \Delta r_0| = \lambda/8$

$$r^2 = r_0^2 + \left(\frac{L_s}{2}\right)^2 \rightarrow \frac{dr}{dr_o} = 2r\frac{dr}{dr_0} = 2r_0 \rightarrow \frac{\Delta r}{\Delta r_0} = \frac{r_0}{\sqrt{r_0^2 + \left(\frac{L_s}{2}\right)^2}} \approx 1 - \frac{1}{8}\frac{L^2}{r_0^2}$$

$$|\Delta r - \Delta r_0| = \Delta r_0 \frac{L^2}{2(2r_0)^2} = \frac{\lambda}{8}$$

$$\boxed{DOF = 2\Delta r_0 = 2\lambda\frac{r_0^2}{L^2} = 8\frac{\delta_{az}^2}{\lambda}}$$

Quellenangabe

Depth of Focus (2):

$$DOF = 8\frac{\delta_{az}^2}{\lambda}$$

The depth of focus becomes smaller as δ_{az} is made smaller.

Example:

X = 5 cm, δ_{az} = 3 m DOF ≈ 1.44 km

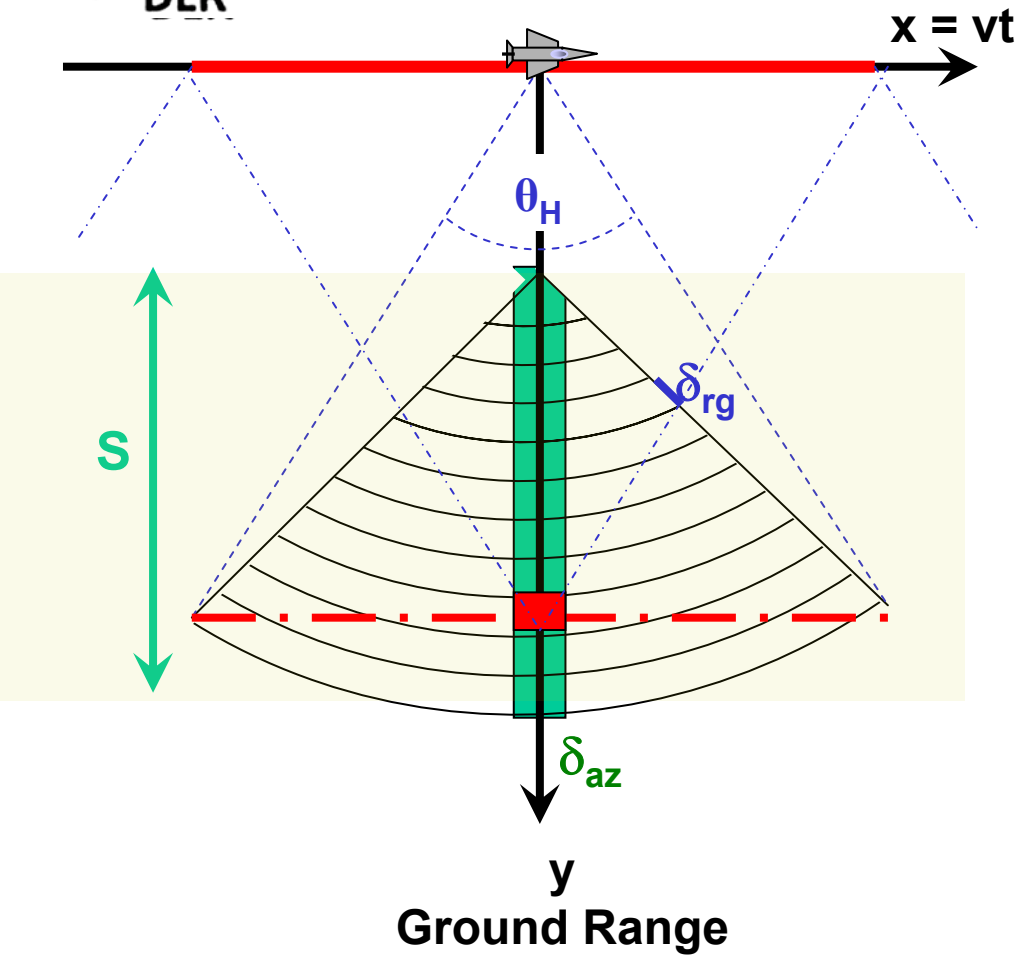
Processing of a 4.3 km swath requires 3 different reference functions.

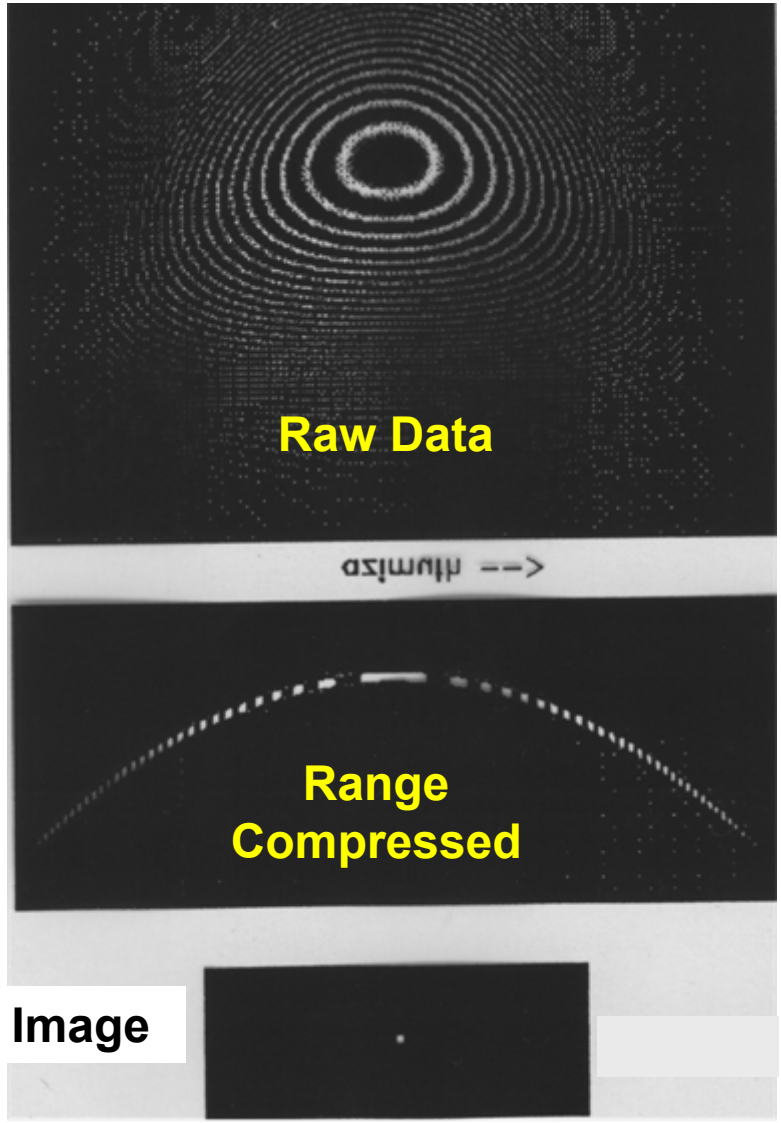
If δ_{az} = 50 cm under the same conditions: DOF ≈ 40 m

10 references are required increasing the processing complexity.

Quellenangabe

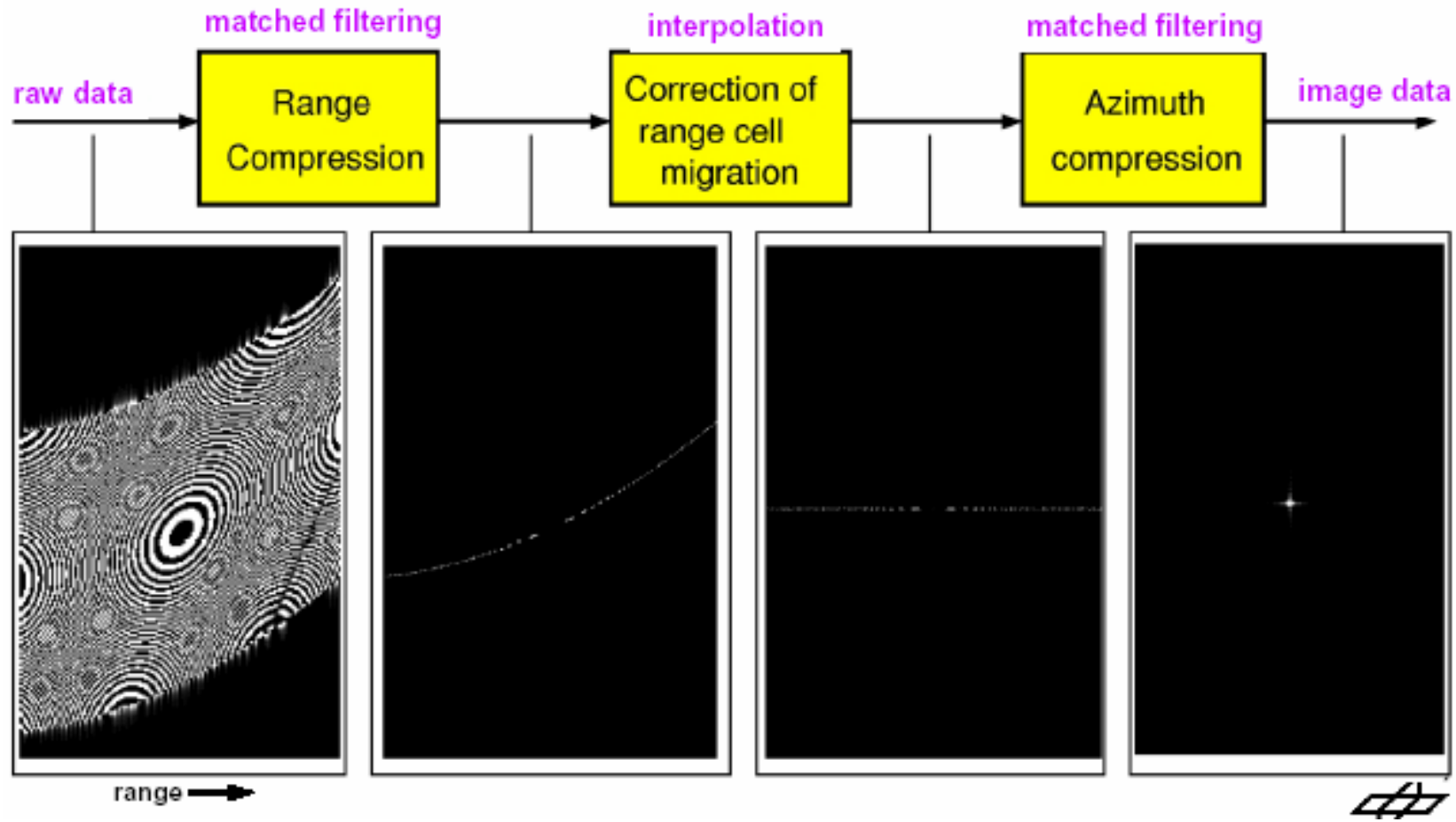
Range Curvature due to Range Cell Migration (2)





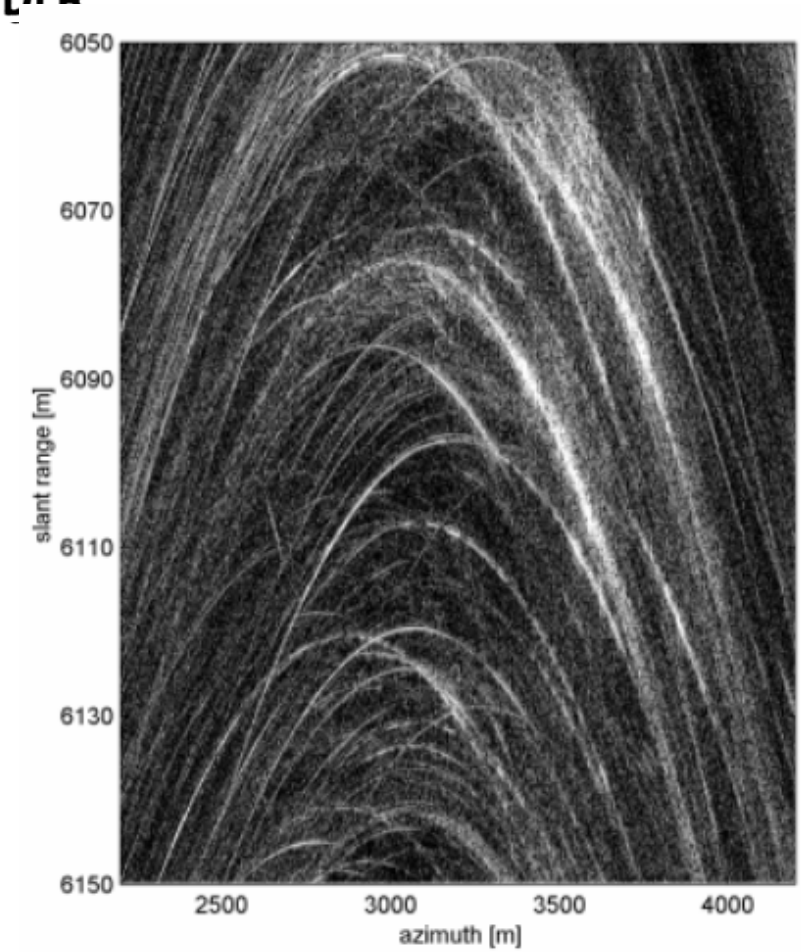
Processed Image

SAR Image Formation



Quellenangabe

Range Curvature Example



Cut out of PAMIR data after range compression, urban area, sliding mode. The processing algorithm has to deal with a distinct range curvature stretching across hundreds of range cells.

[Courtesy FGAN, Ender, Brenner, PAMIR Artikle, IEE Special Issue EUSAR 2002]

[Ender, Brenner, PAMIR Artikel IEE Special Issue EUSAR 2002, Courtesy FGAN]

Quellenangabe

Phase Errors

The Targets Phase History must be Known Precisely

Thump Rule: Phase Jitter may not exceed $\pi/8$ rad of RF-Cyle

Phase Error Reasons

- Radar Platform Instabilities
- Flight Path Deviations
- Target Motion and Acceleration
- Instabilities of SAR-Electronic
- Propagation Path Anomalies
- Orbit Excentricities
- Earth Rotation Effects

Phase Error Effects

- Decrease in Image Quality
- Range and Azimuth Defocussing
- Loss in Mainlobe Response
- Image Side Lobe Level Increase
- Target Position Shift
- Image Shift
- Decorrelation

Quellenang

SAR-Verarbeitung

- Eingangsdatenrate: 30 - 100 Mbit/Sekunde
- Geringe Datenreduktion für Rohdaten möglich
- Berechnungsaufwand: > 5 x 10^9 Operationen/Sekunde
- Vorteile der Echtzeit-SAR-Verarbeitung

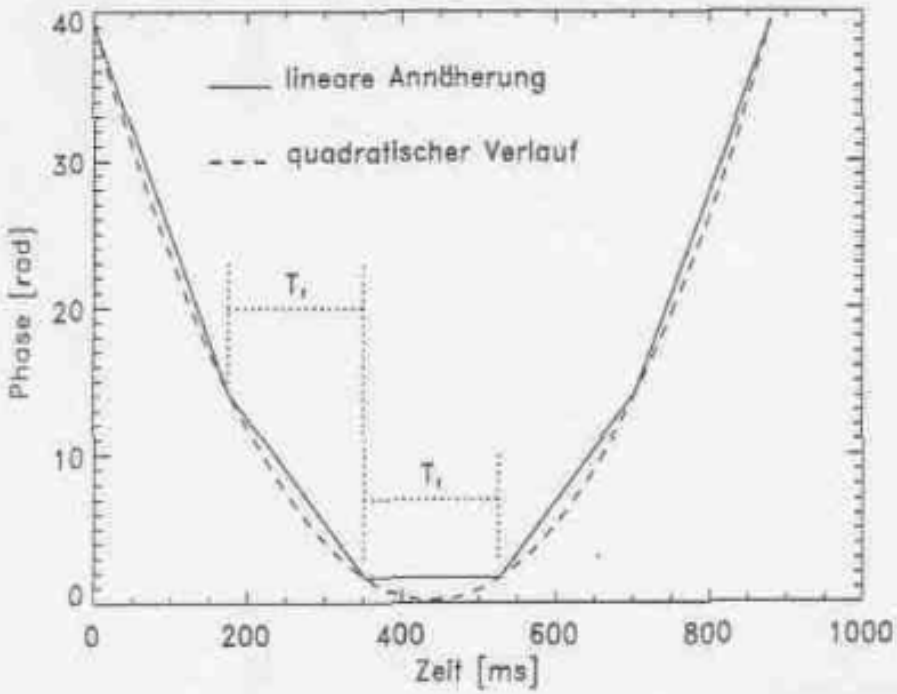
  - Gesamte SAR-Hardware kann in Echtzeit überprüft werden
  - Echtzeit-Auswertung wird ermöglicht
  - Datenrate kann stark reduziert werden
  - Datenaufzeichnung und Datenübertragung zur Empfangsstation werden vereinfacht
  - Bildprodukte können als Referenz für die Bodenprozessierung benutzt werden

- Welches Verfahren eignet sich für die Echtzeit-SAR-Verarbeitung ?

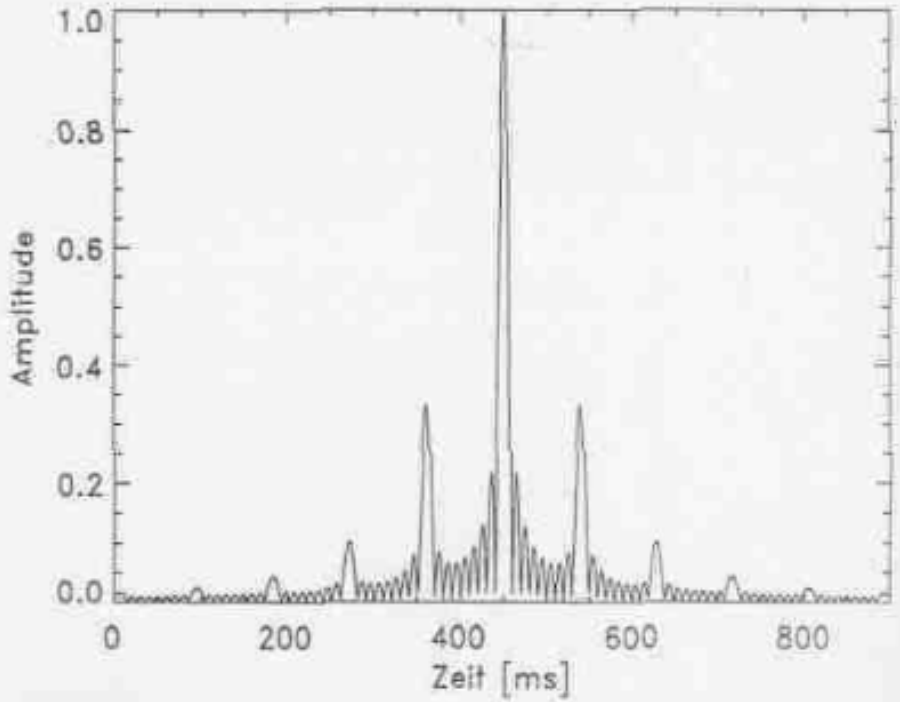
Quellenangabe

Näherung für den Phasenverlauf

Phasenverlauf für die Referenzfunktion



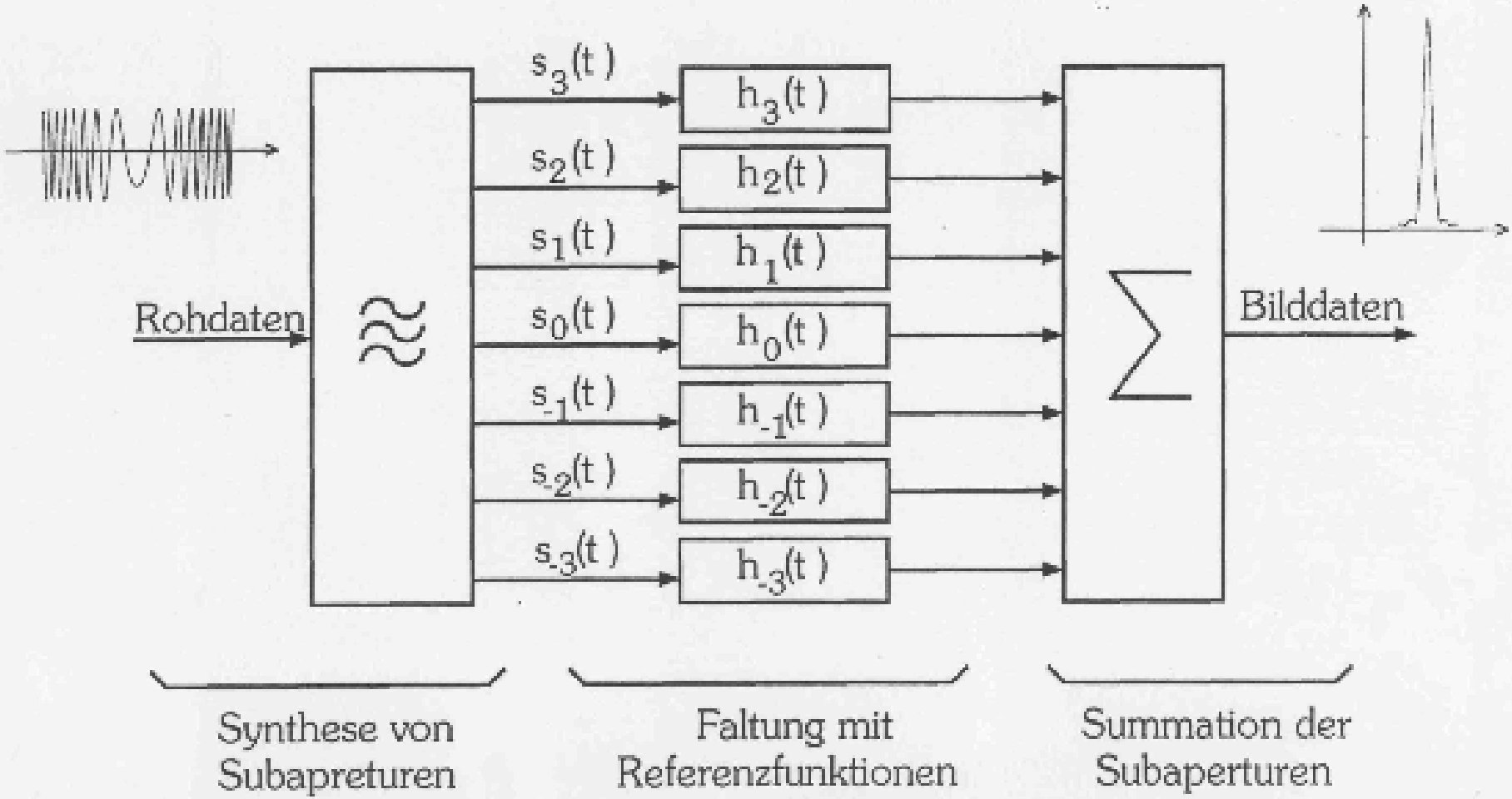
Impulsantwort



Subaperturverarbeitung

Quellenangabe

Subaperturprinzip

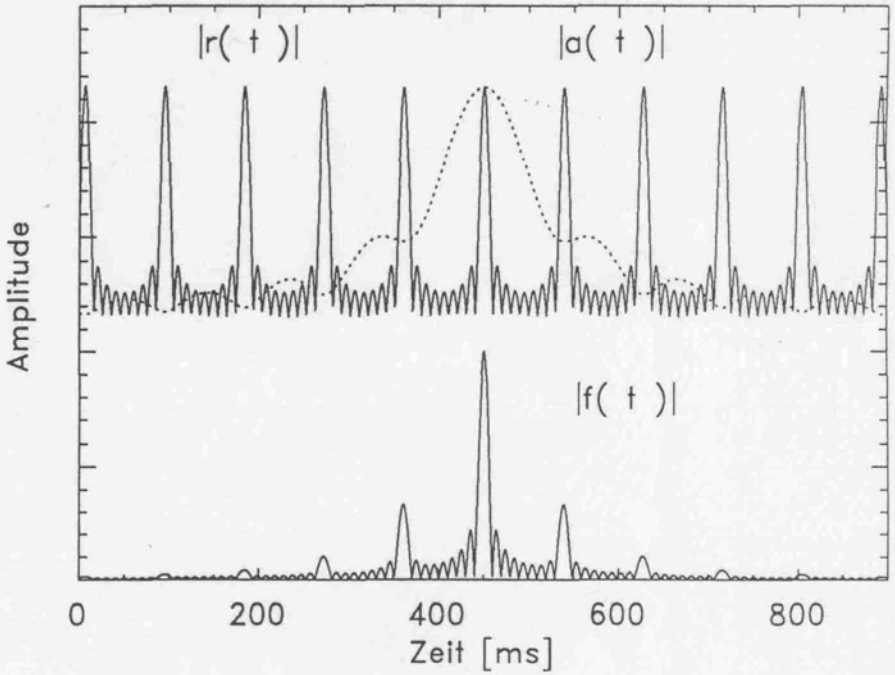


Quellenangabe

Analyse der Impulsantwort

- $$|f(t)| = \left| \sum_{-N/2}^{N/2} s_n \otimes h_n \right|$$

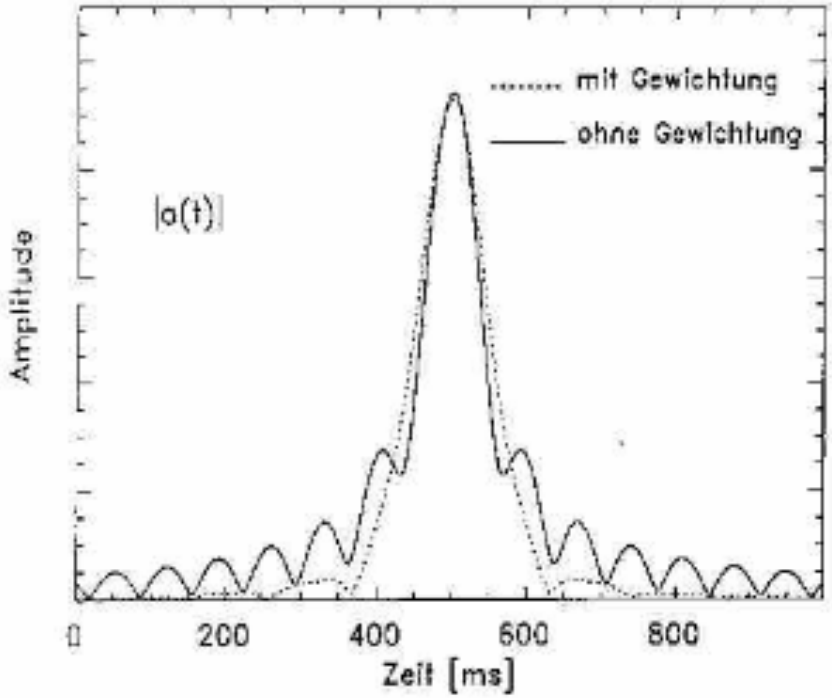
- $$|f(t)| = |a(t)| \cdot |r(t)|$$



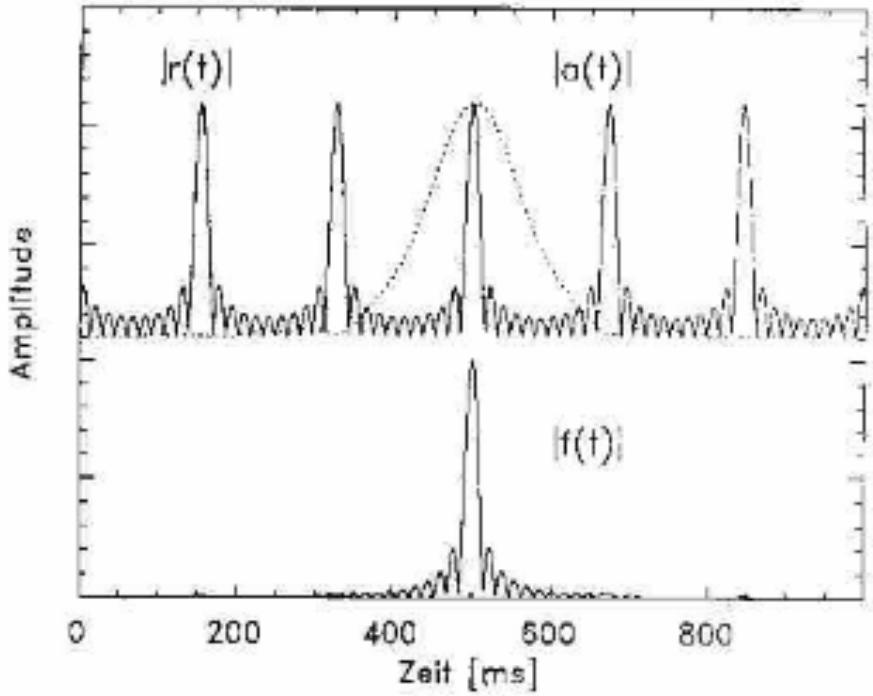
- Impulsantwort a (t) jeder Subapertur entspricht dem Ergebnis der unfokussierten Verarbeitung
- Anforderung an die Bildqualität: Nebenzipfelabstand > 30 dB

Optimierung der Impulsantwort

- Einfügung einer Gewichtung

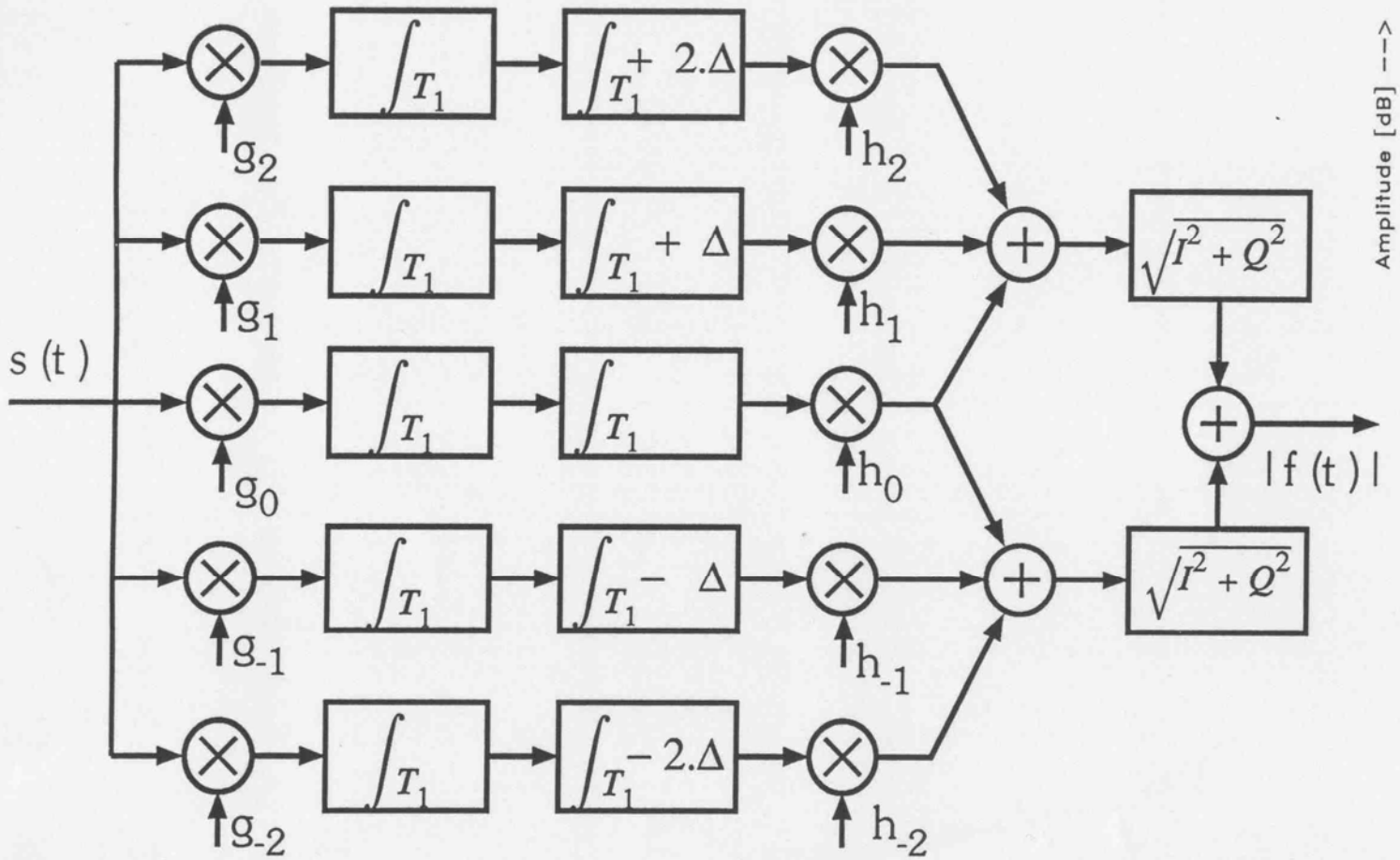


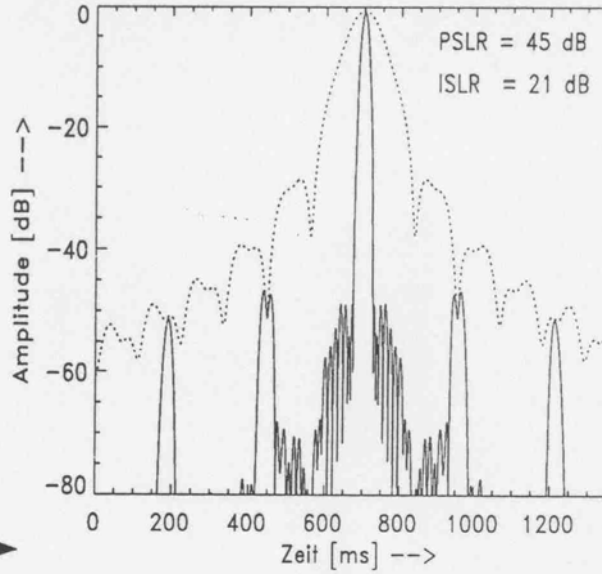
- Einfügung einer Überlappung



Quellenangabe

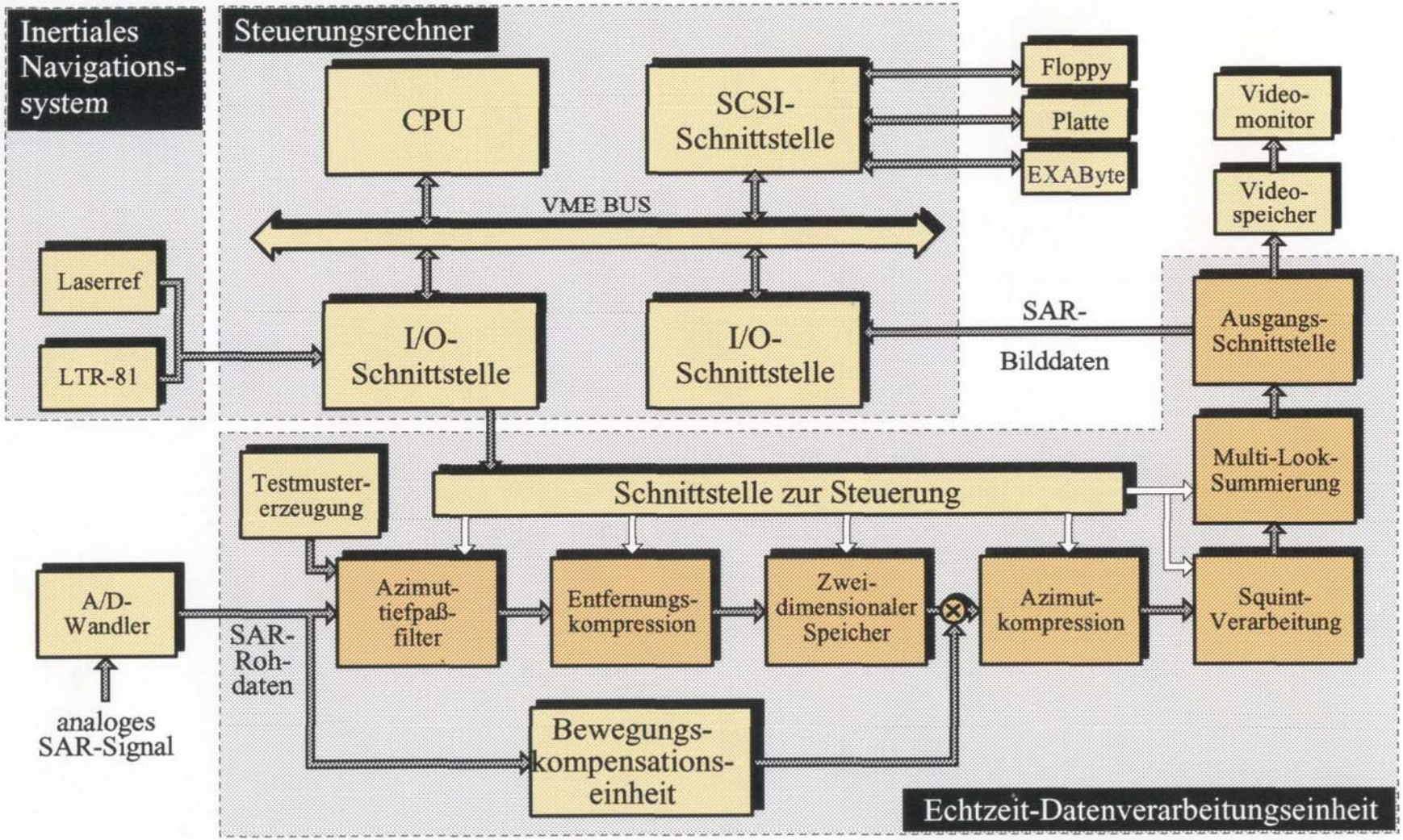
Blockdiagramm





- Verarbeitung besteht aus einer kohärenten Summierung von unfokussierten Subaperturen

DLR



Blockdiagramm des Echtzeit-SAR-Prozessors

DLR

Quellenangabe

Spezifikationen des Echtzeitprozessors

Frequenzband	P	L	C	X
Azimutauflösung [m]	16	3	3	3
Entfernungsauflösung [m]	18	3	2.7	2.7
Anzahl von "Looks"	6	2.7	6.6	8.2
Azimutbandbreite [Hz]	31	62	125	150
Entfernungsbandbreite [MHz]	18	100	100	100

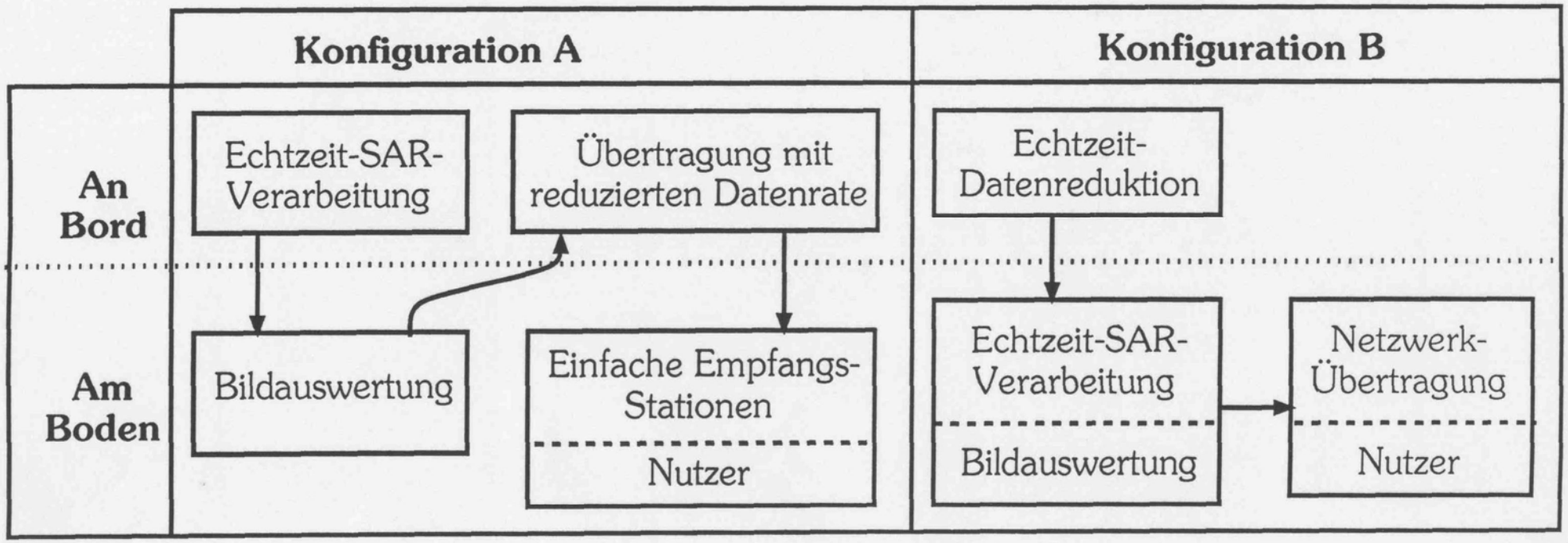
Verarbeitungsparameter

Parameter	Minimum	Typisch	Maximum
Geschwindigkeit [m/s]	50	70	300
Kleinste Entfernung [m]	1500	3000	9000
Größte Entfernung [m]	-	-	40000
PRF [Hz]	660	1000	1240

DLR

Ausblick

- Hochauflösende Echtzeit-SAR-Verarbeitung :
  - für Flugzeug-SAR-Systeme ist möglich
  - für satellitengestütztes SAR-Systeme ist zur Zeit nicht möglich
- Datenkompression an Bord ist für SAR-Rohdaten möglich
- Konfigurationen für ein zukünftiges SAR-System mit Echtzeit-Verarbeitung :

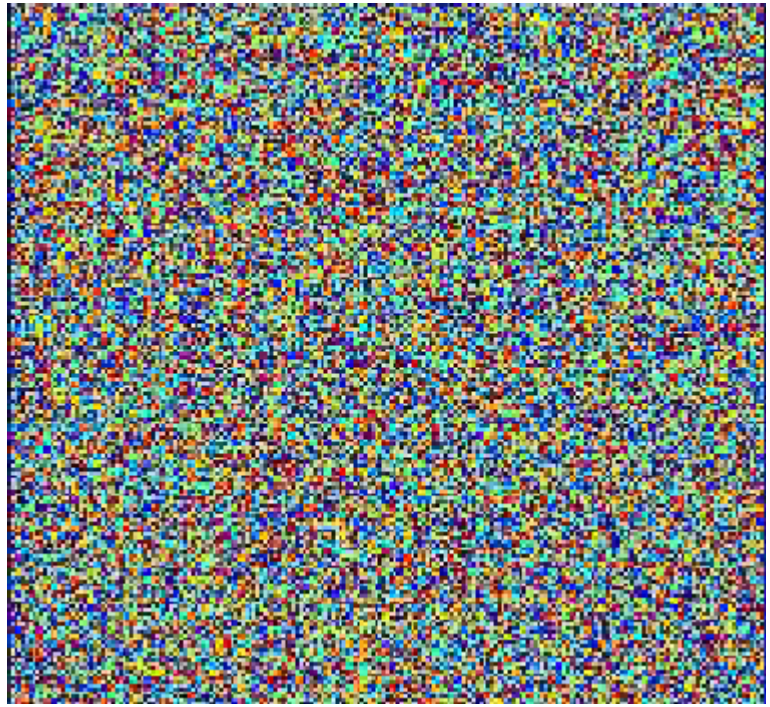


DLR

SAR Image

Amplitude

Phase



X-SAR/SIR-C, Mount Etna,

Quellenangabe

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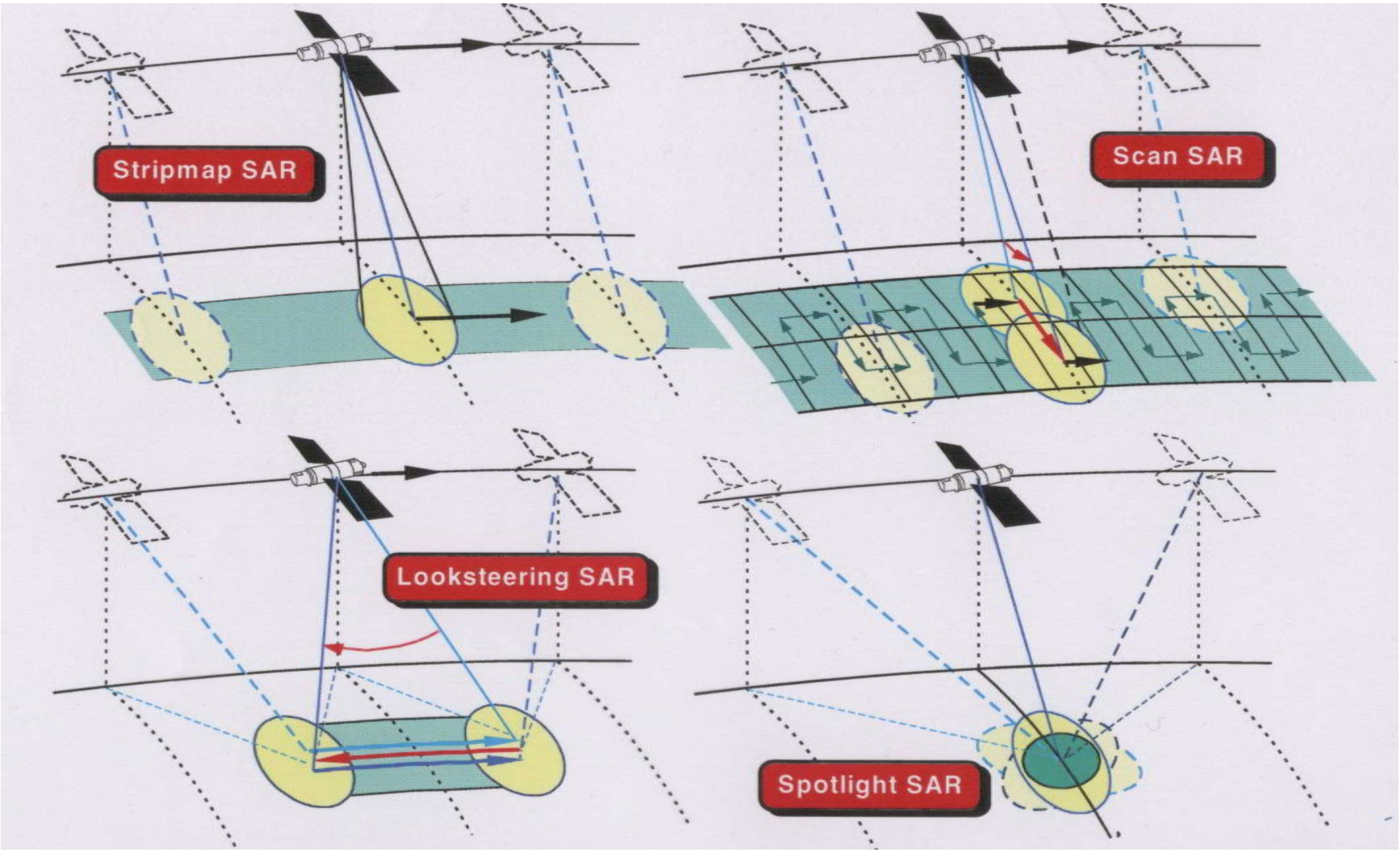
$$\left|\Delta r - \Delta r_0\right| = \Delta r_0 \frac{L^2}{2(2r_0)^2} = \frac{\lambda}{8}$$

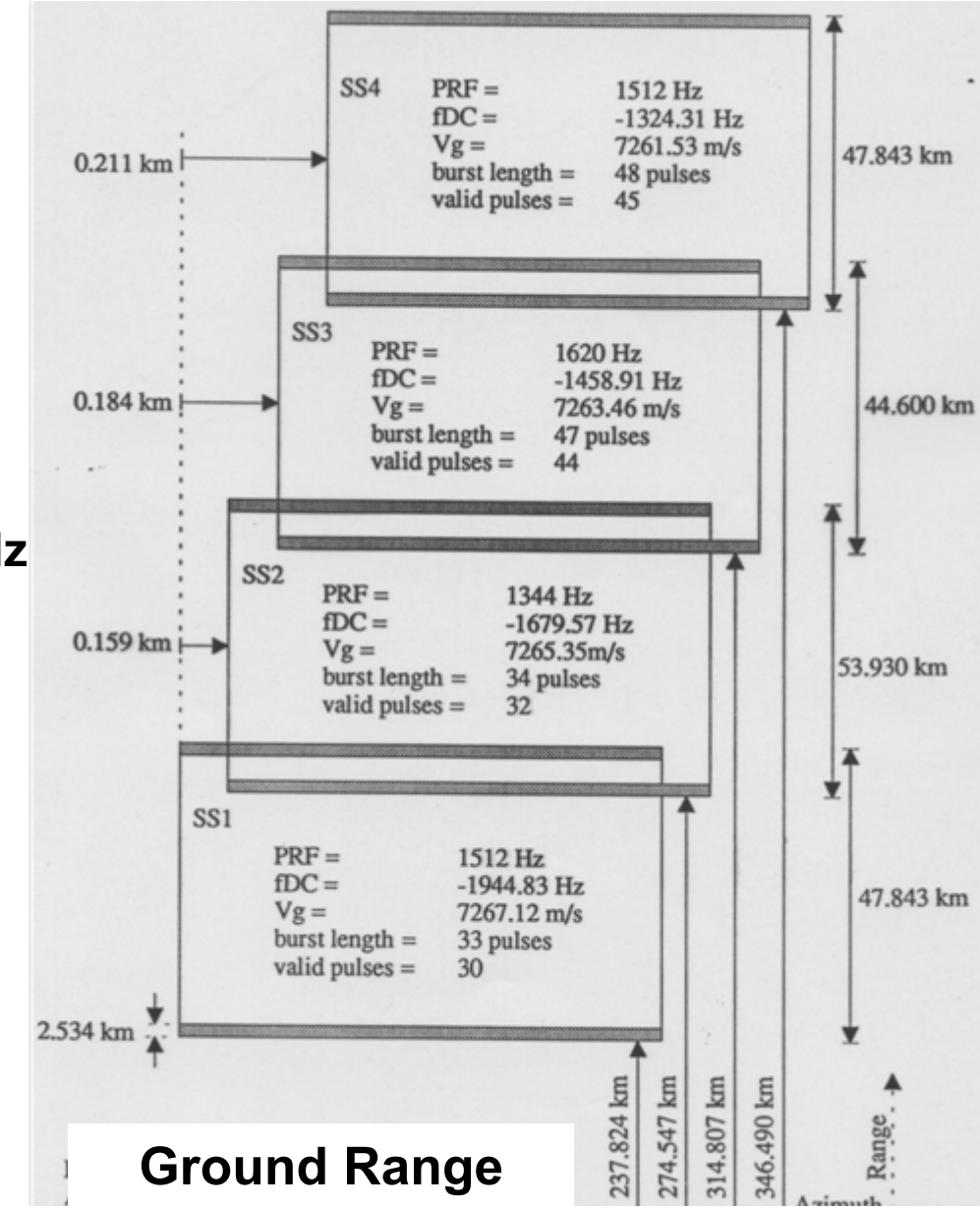
Special SAR Modes



Quellenangabe

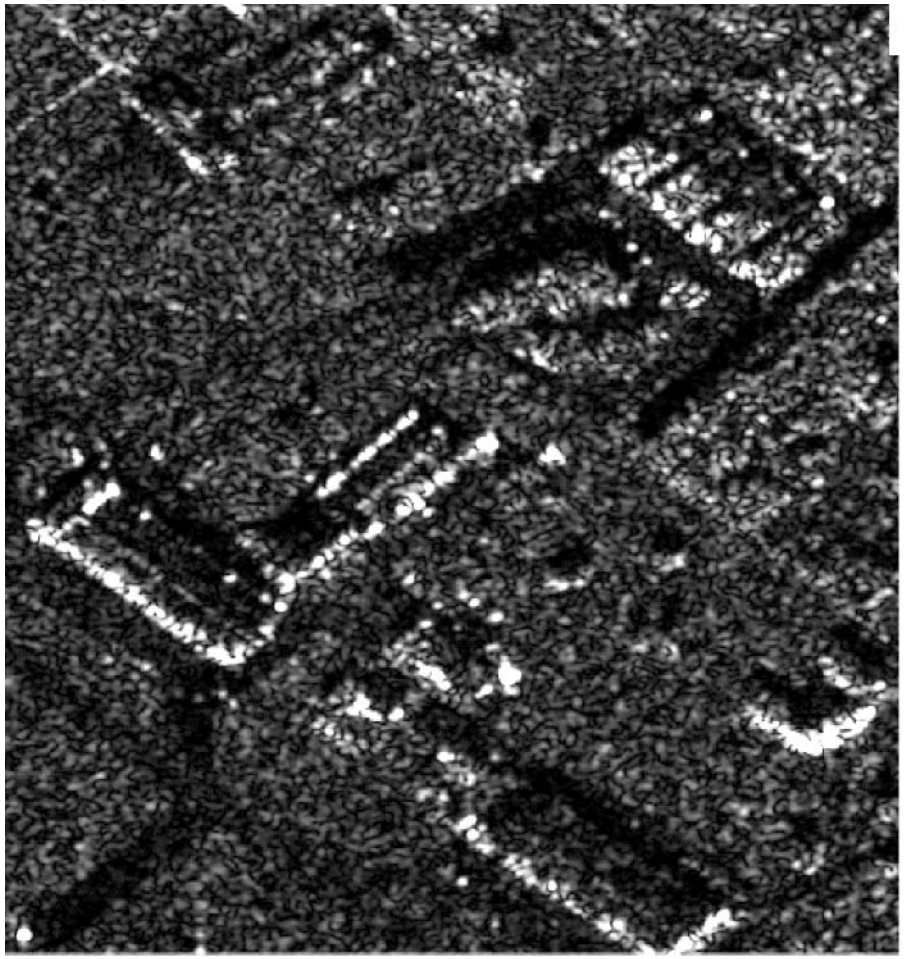
SIR-C ScanSAR, Basic Geometry & Parameter, L-Band

Range Chirp Length	**380 Samples**
Altitude	**2221,009 km**
Wavelngth	**23,9 cm**
Sampling Rate	**11,24928 MHz**

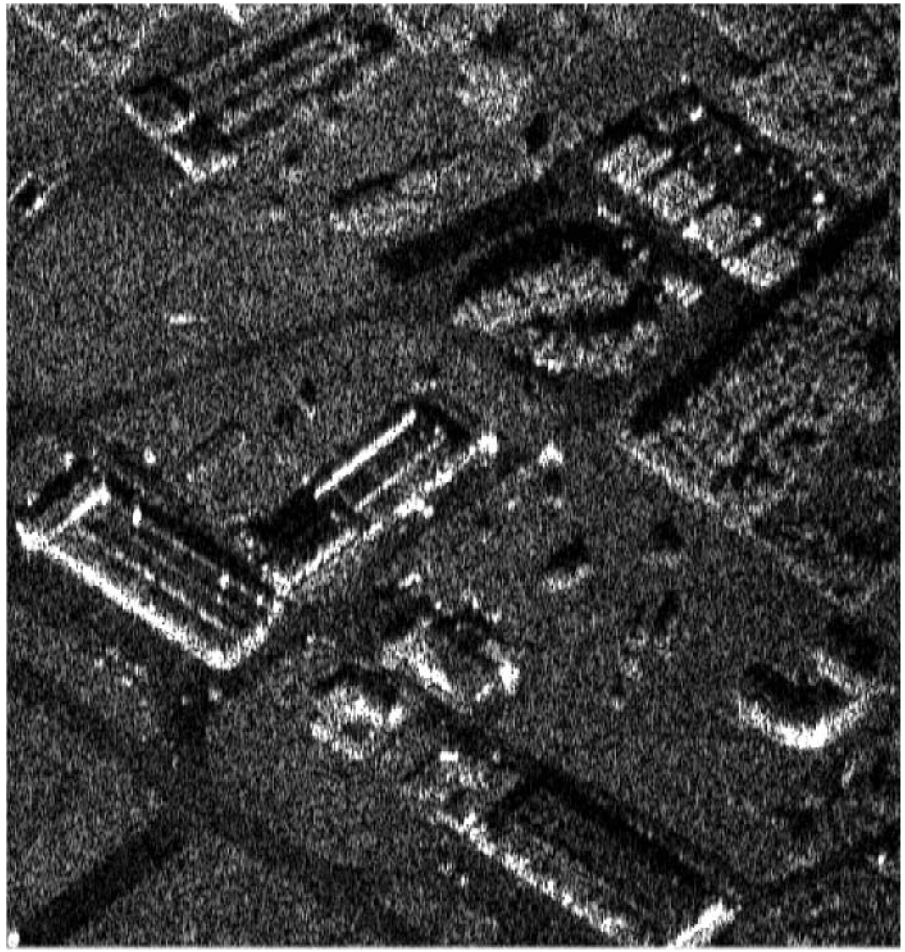


Quellenangabe

Spotlight versus Stripmap



Stripmap image
3 m azimuth resolution



Spotlight image
0.46 m azimuth resolution

Quellenangabe

SAR: Future Developments

- Higher resolution SAR systems (polarimetric, multi-frequency etc)
- Cheaper and more effective T/R-modules
- Geo-stationary transmitter with large deployable antennas and bi-static SAR receivers
- Parasitic SAR Systems (use of signals of opportunity like DTV, GPS)
- New imaging modes (polarimetric interferometry, forward looking, tomography)
- MiniSAR concepts (e.g. Cartwheel)
- Reliable retrieval of geo-physical parameters (development of inverse modeling)
- Alternative platforms (e.g. Zeppelin)
- Commercialization of SAR data (e.g. TerraSAR)
- Symbiotic use of earth observation with communication and navigation (EO/NAV/COM)

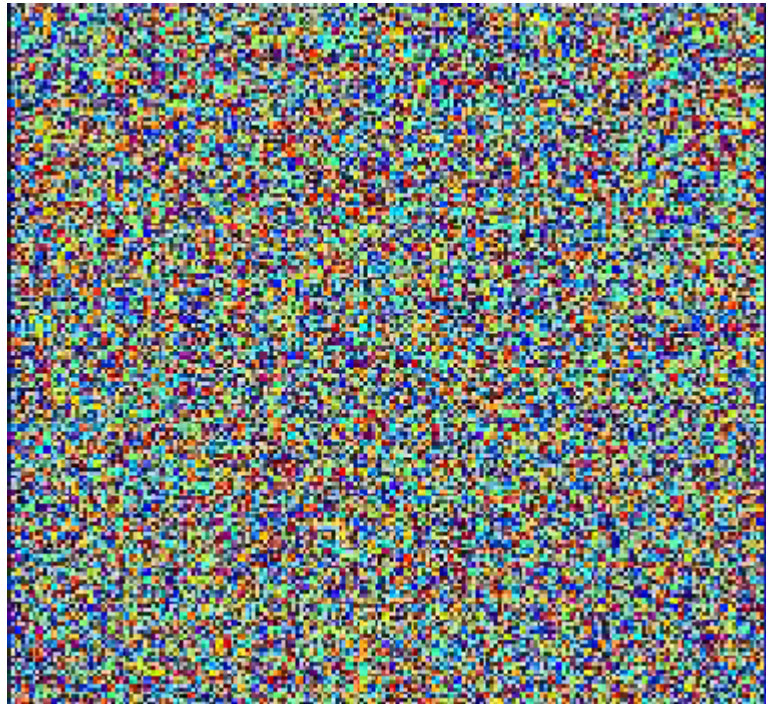
Quellenangabe

X-Band Image of Munich, E-SAR System

SAR Image

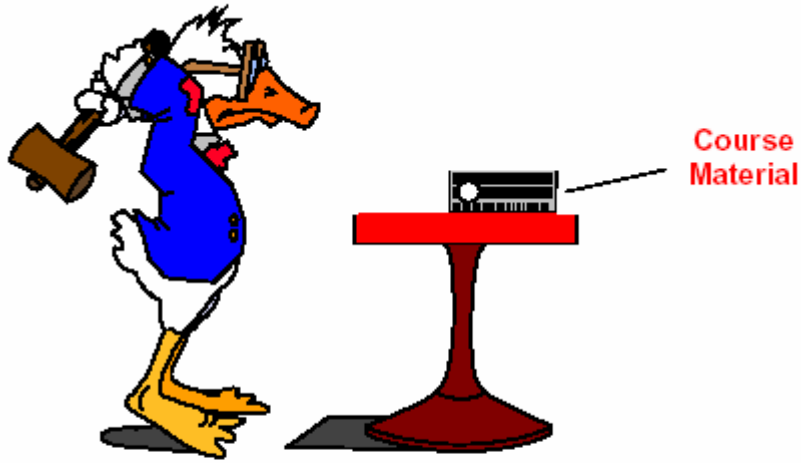
Amplitude

Phase



X-SAR/SIR-C, Mount Etna,

Quellenangabe



Don’t do it !

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Keydel, W.: Basic Principles of SAR, in AGARD Lecture Series 182; Fundamentals and special problems of Synthetic Aperture Radar,. (SAR), August 1992, published by AGARD, ISBN 92-835-0683-9, p.p. 1-1 to 1-13

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