

# TRANSPARENCIAS DE TELEDETECCIÓN

## 4. Sensores RADAR

### 4.3 El Radar de Apertura Sintética (SAR)

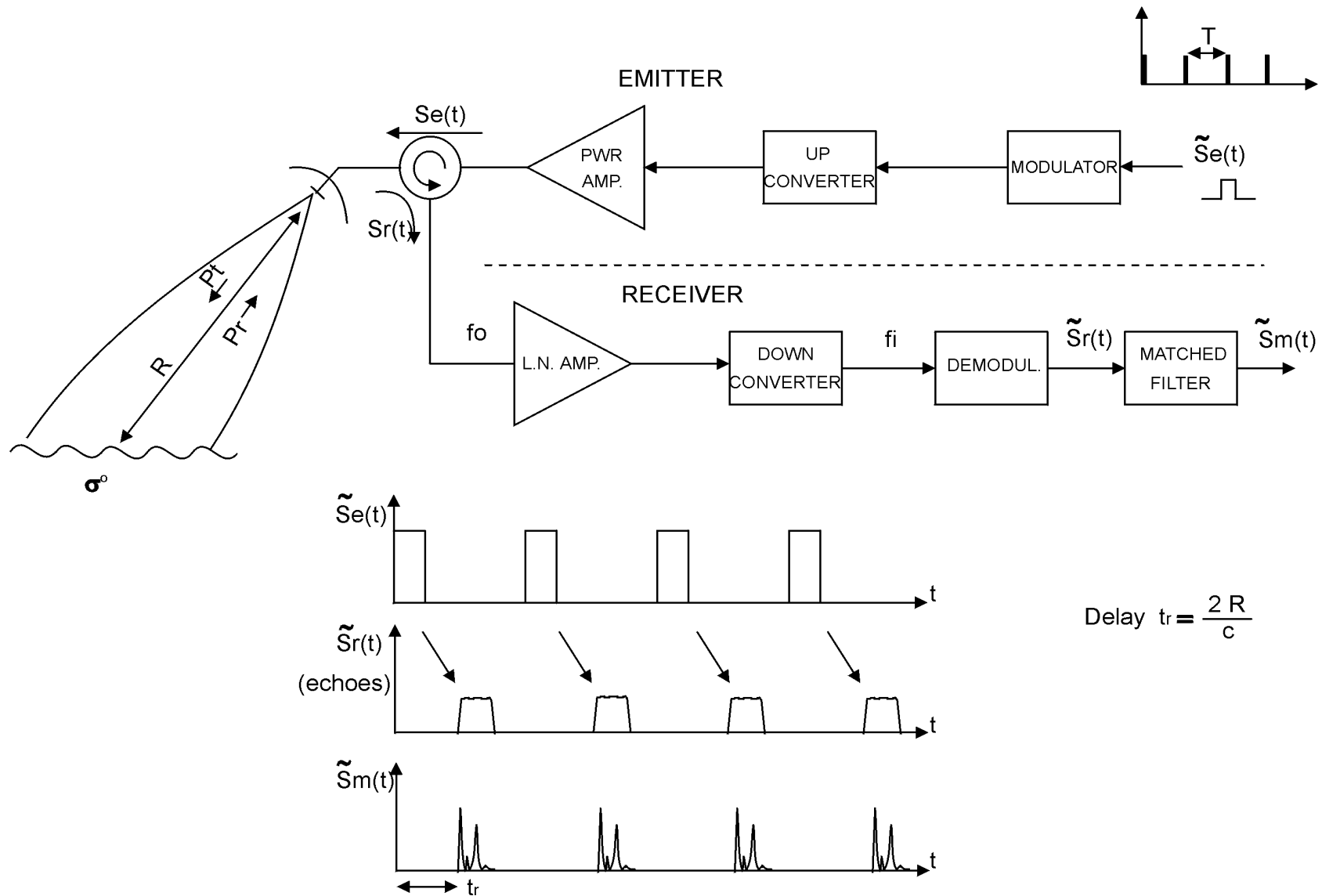
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Adriano Camps

Dpto. de TSC-UPC

Marzo de 2000

# Radar pulsado

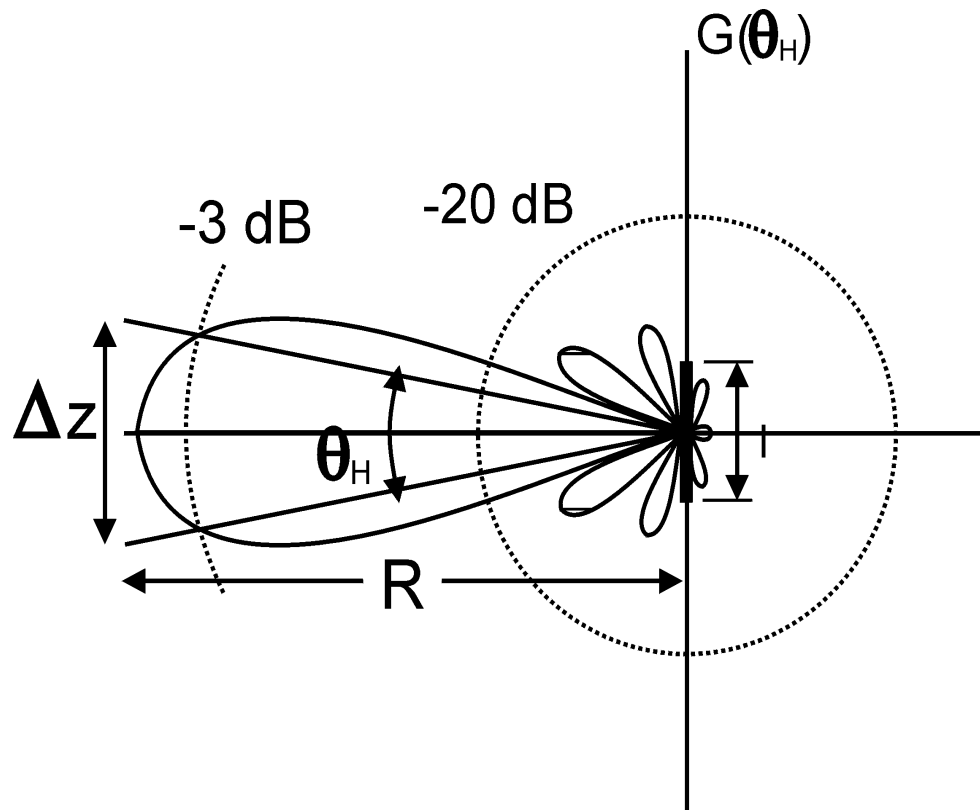


## **Radars:**

**poseen 3 recursos para discriminar (resolver) blancos cercanos**

- **Resolución angular: características antena.**
- **Resolución en distancia: pulso utilizado (Ancho de banda).**
- **Resolución en velocidad: tratamiento espectral Doppler (formación de la apertura sintética).**

**Resolución angular: capacidad para distinguir entre dos blancos que difieren únicamente en posición angular: ancho haz de la antena (apertura real).**



**$\mathbf{q}_H$  : acimut**

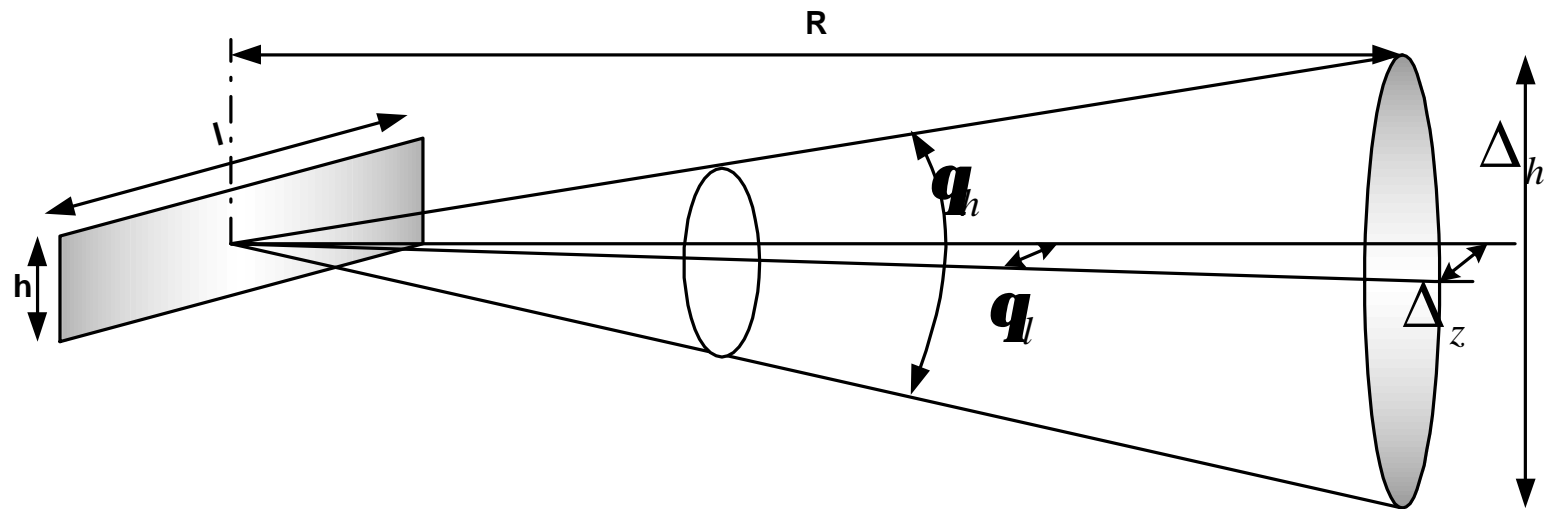
**$\mathbf{q}_V$  : elevación**

$$\mathbf{q}_H \rightarrow \frac{l}{R} \text{ rad}$$

$$\Delta z = \mathbf{q}_H \cdot R$$

**$\Delta z$  : res. transv.**

# Haz de la antena radar

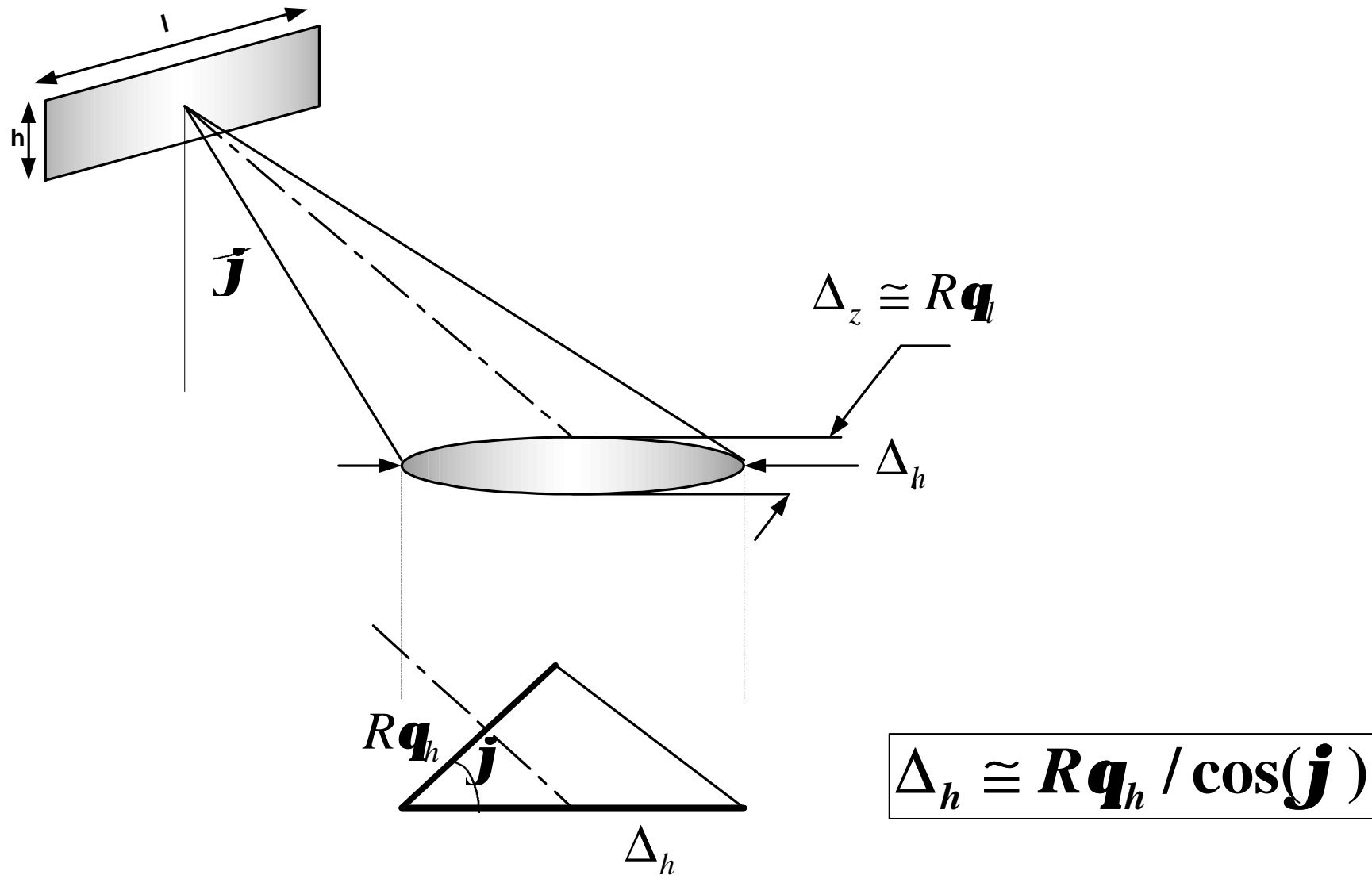


$$\mathbf{q}_h \cong \mathbf{l} / h$$
$$\mathbf{q}_l \cong \mathbf{l} / l$$

$$\Delta_h \cong R \mathbf{q}_h$$
$$\Delta_z \cong R \mathbf{q}_l$$

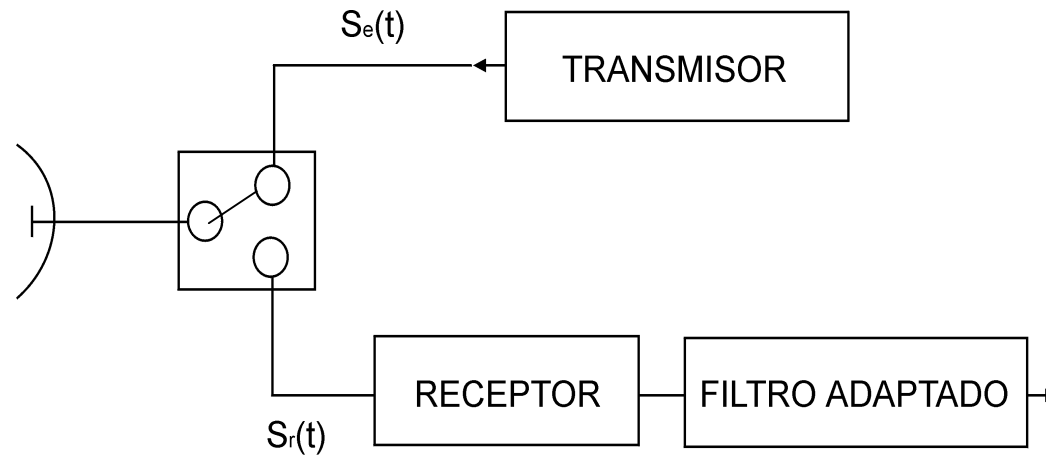
huella

# Huella sobre superficie inclinada



# Resolución en distancia

## Radar pulsado



**Supongamos que el radar envía un único pulso**

$$S_e(t) = a(t) \cos(\omega_0 t + \Phi(t))$$

*a(t),  $\Phi(t)$ : modulaciones de amplitud y fase*

$$S_e(t) = a(t) \cos(\omega_0 t + \Phi(t))$$

$a(t), \Phi(t)$  : *modulaciones de amplitud y fase*

**En notación más compacta**

$$S_e(t) = \Re \left\{ \tilde{S}_e(t) e^{j\omega_0 t} \right\}$$

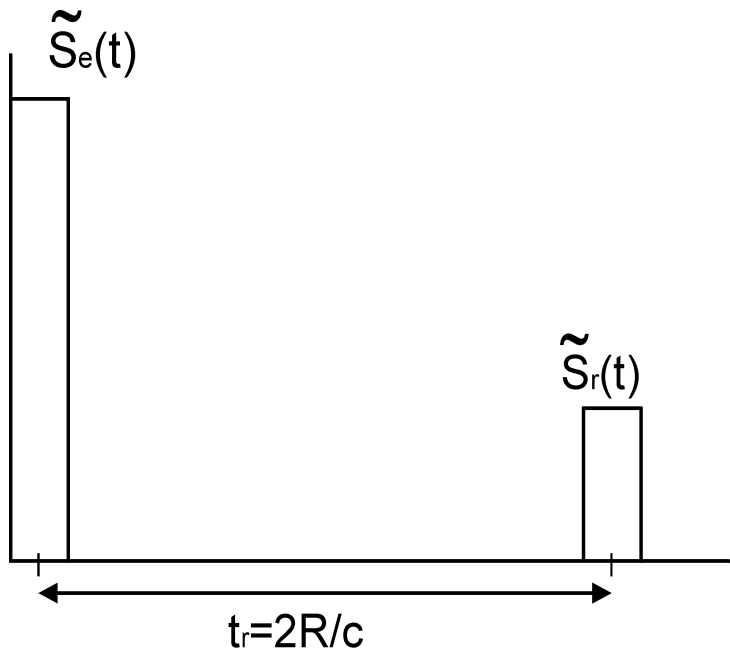
$$\tilde{S}_e(t) \stackrel{\Delta}{=} a(t) \cdot e^{j\Phi(t)} : \textit{equiv. paso bajo}$$

*o mod. compleja*

$\tilde{S}_e(t)$  : *contiene toda la información  
del pulso emitido*



## Eco de un blanco inmóvil a distancia R.



$\tilde{S}_r(t)$  : réplica atenuada  
y retardada de  $\tilde{S}_e(t)$

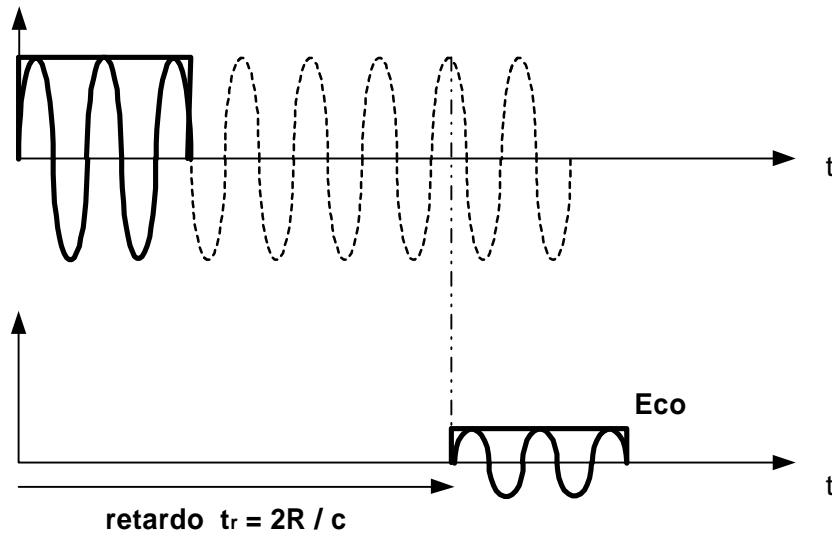
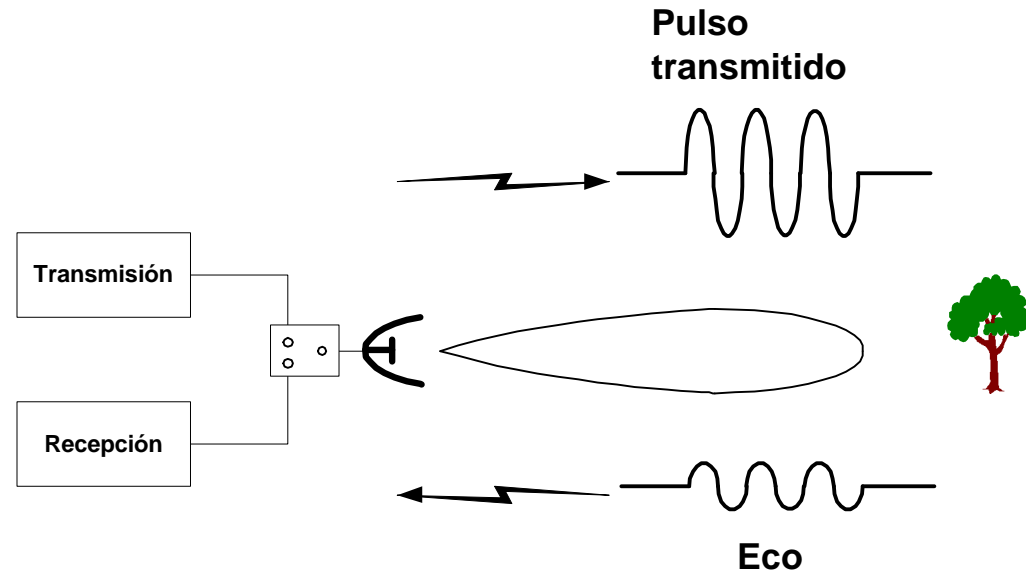
para :  $R = 150 \text{ Km}$

$t_r = 1 \text{ ms}$

$$\tilde{S}_r(t) = k\tilde{S}_e(t - t_r)e^{-j2kR} \quad (\text{fase camino recorrido})$$

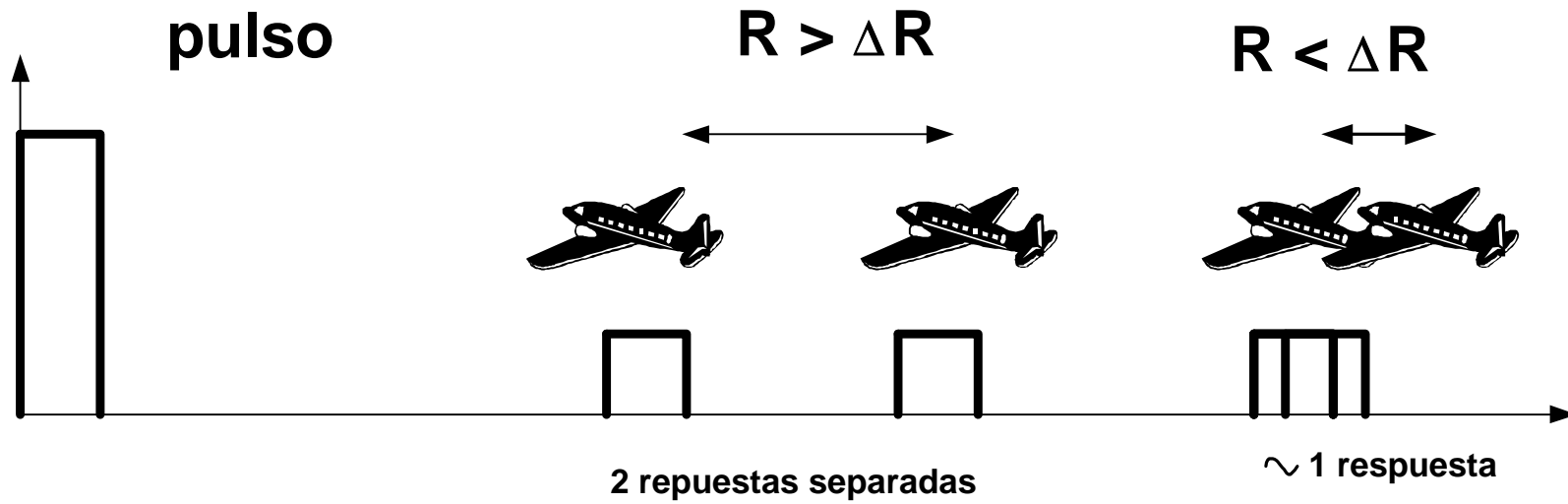
$$\tilde{S}_r(t) = k'\tilde{S}_e(t - t_r), k' = ke^{-j2kR} \quad (\text{cte. compleja})$$

# Radar: determinación de la distancia

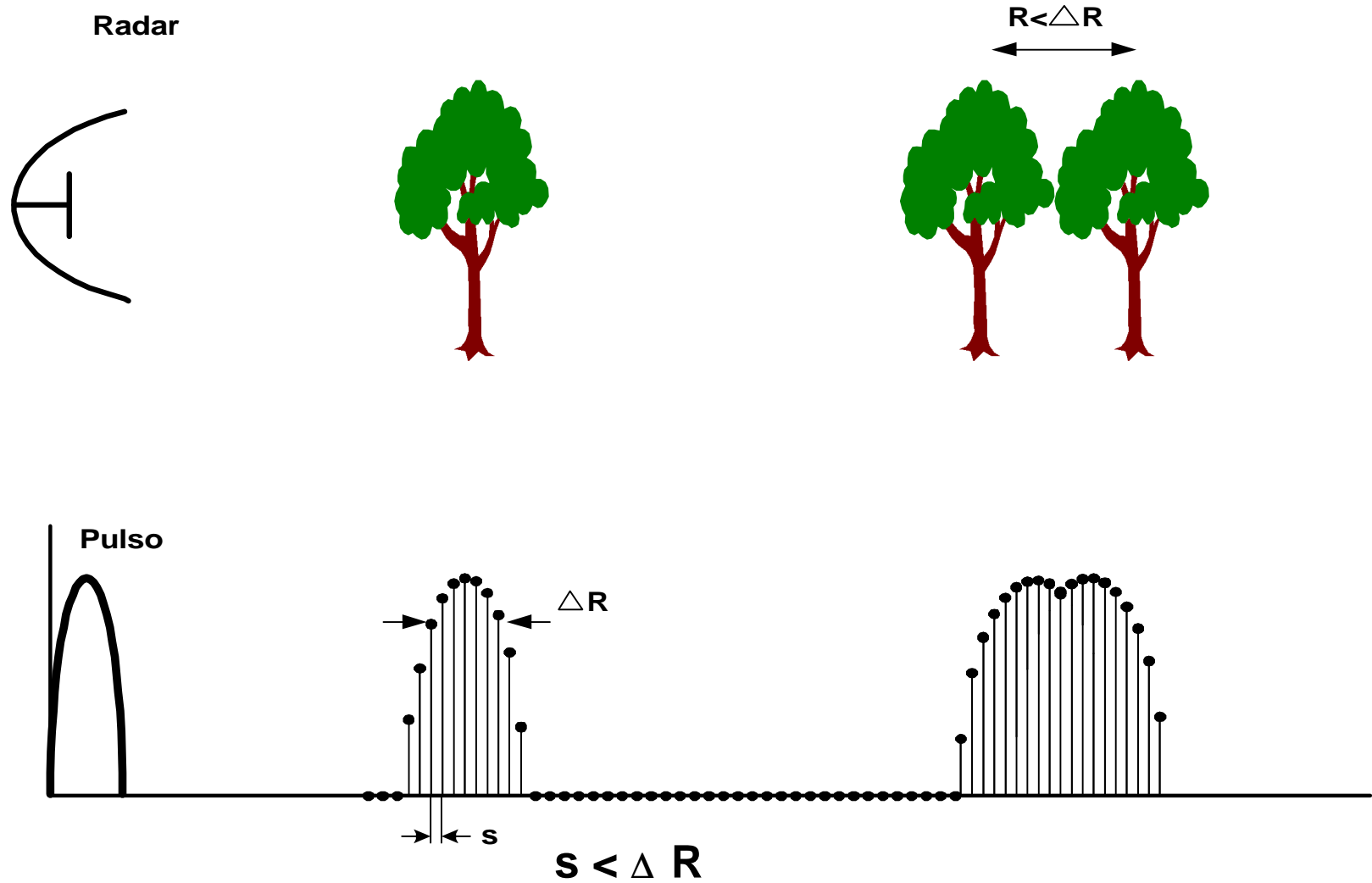


$$R = c t_r / 2$$

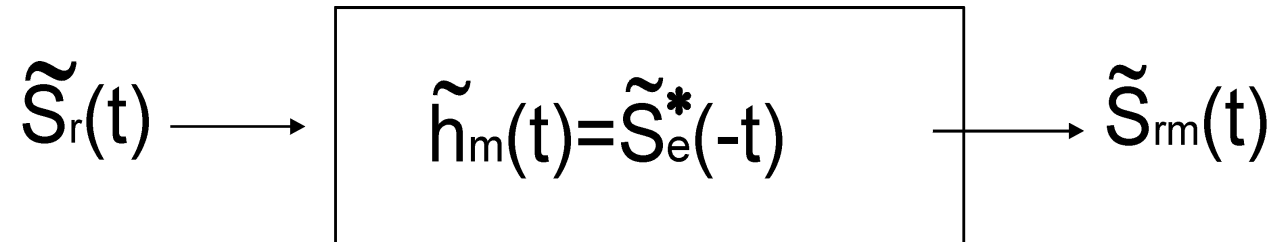
# RADAR: resolución en distancia $\Delta R$



# Resolución ( $\Delta R$ ) y muestreo ( $s$ )



## El Filtro Adaptado

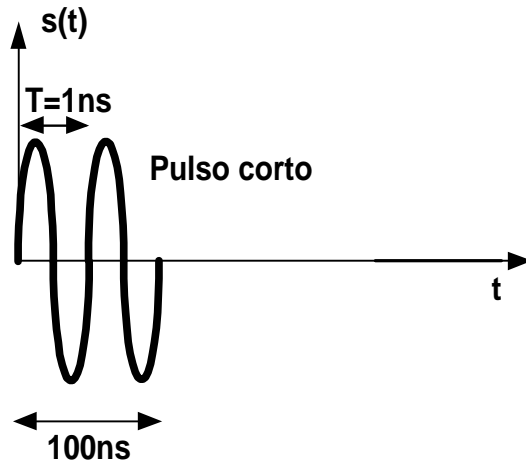


$$\tilde{S}_{rm}(t) = \frac{k'}{2} \tilde{S}_r(t) * \tilde{h}_m(t) = \frac{k'}{2} R_{ss}(t - t_r)$$

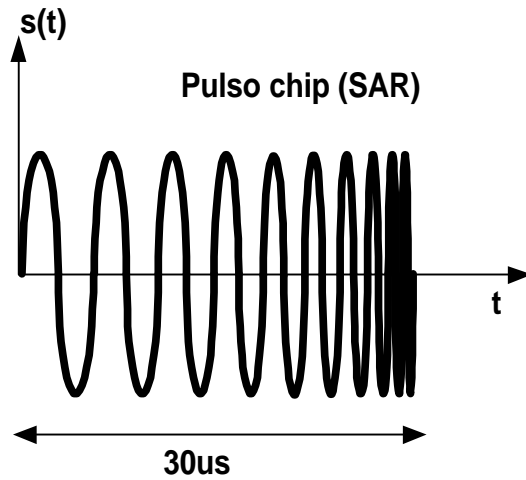
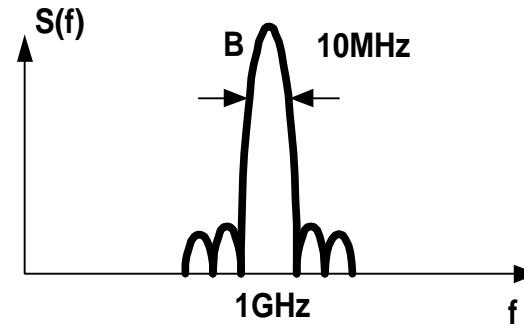
donde  $R_{ss}(t) = \int_{-\infty}^{\infty} \tilde{S}_e(\mathbf{t}) \cdot S_e^*(\mathbf{t} - t) d\mathbf{t}$   
(Autocorrelación)

$$R_{ss}(t) \leq R_{ss}(0) = 2E \text{ (energía del pulso)}$$

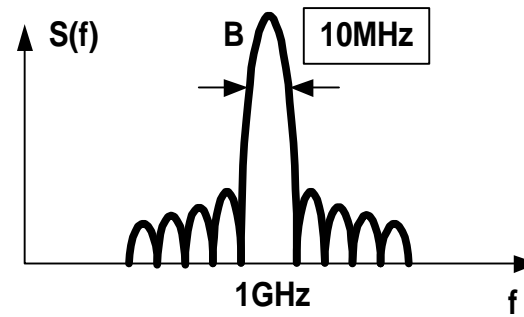
# Pulsos RADAR



TFourier  
→



TFourier  
→



**B: Ancho de banda**

$$\Delta R = c / 2B$$

## Tipos de pulso (duración $\tau_0$ )

- Rectangular:

$$\text{Ancho de banda } B \rightarrow \frac{1}{\tau_0}, \Delta t = \frac{1}{B} \rightarrow \tau_0$$

- Chirp:

$$\text{Ancho de banda } B \gg \frac{1}{\tau_0}, \Delta t = \frac{1}{B} \ll \tau_0$$

**Factor de  
compresión:**

$$\mathbf{r} = \frac{\tau_0}{\Delta t} = \tau_0 \cdot B$$

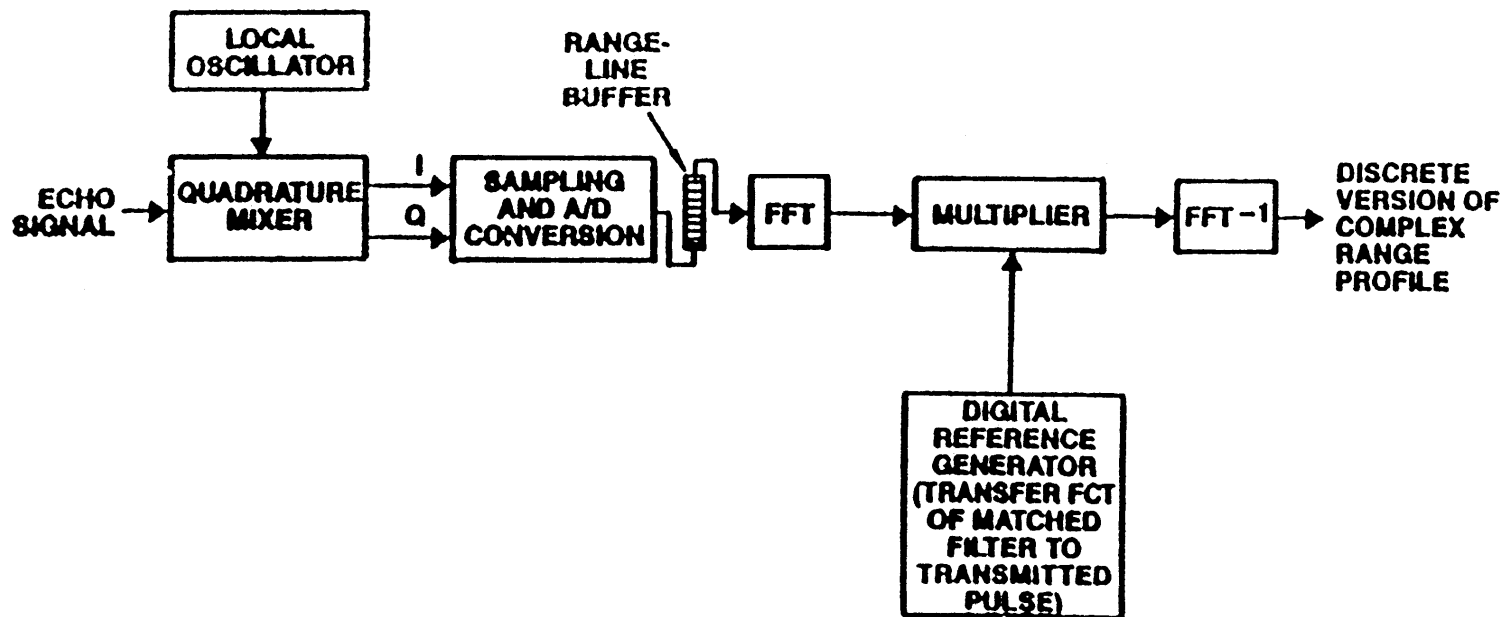
**Res.  
distancia:**

$$\Delta R = \frac{c \cdot \Delta t}{2} = \frac{c}{2 \cdot B}$$

# Resolución longitudinal

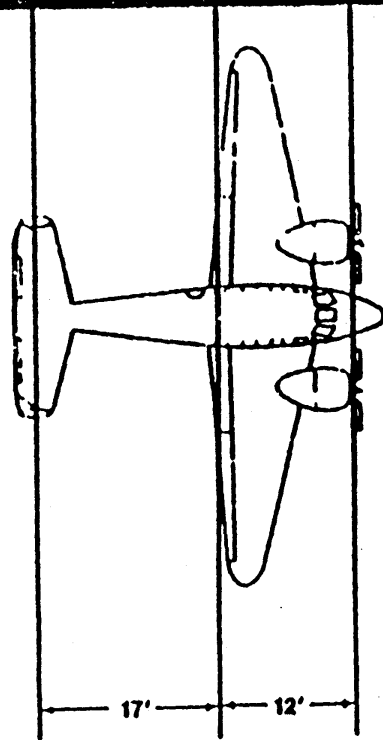
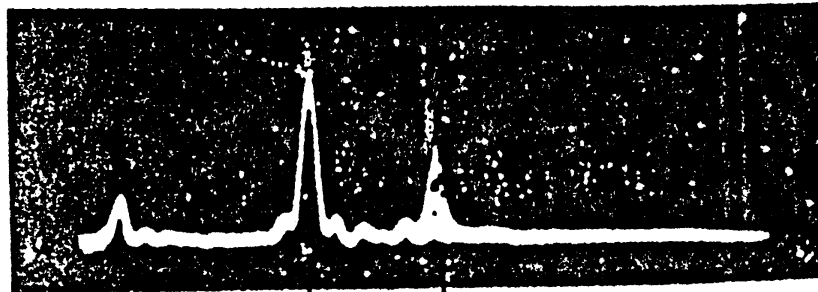
## Compresión digital de pulsos

$$s(t) \longrightarrow \boxed{h(t) = s^*(-t)} \longrightarrow s(t) * h(t) = F^{-1}\{S(f) \cdot H(f)\}$$





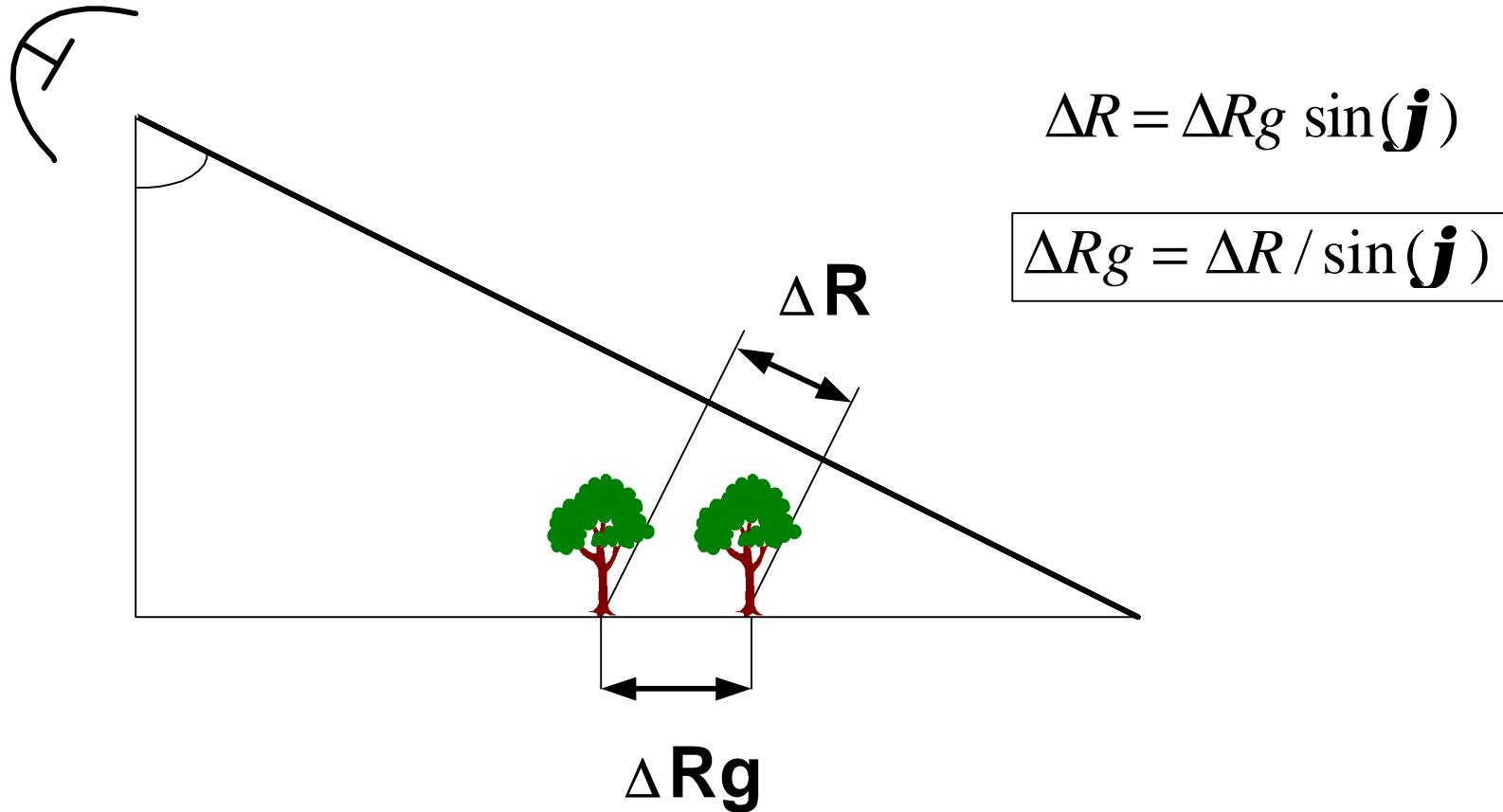
# HRR Signature of C-45 Aircraft at S Band



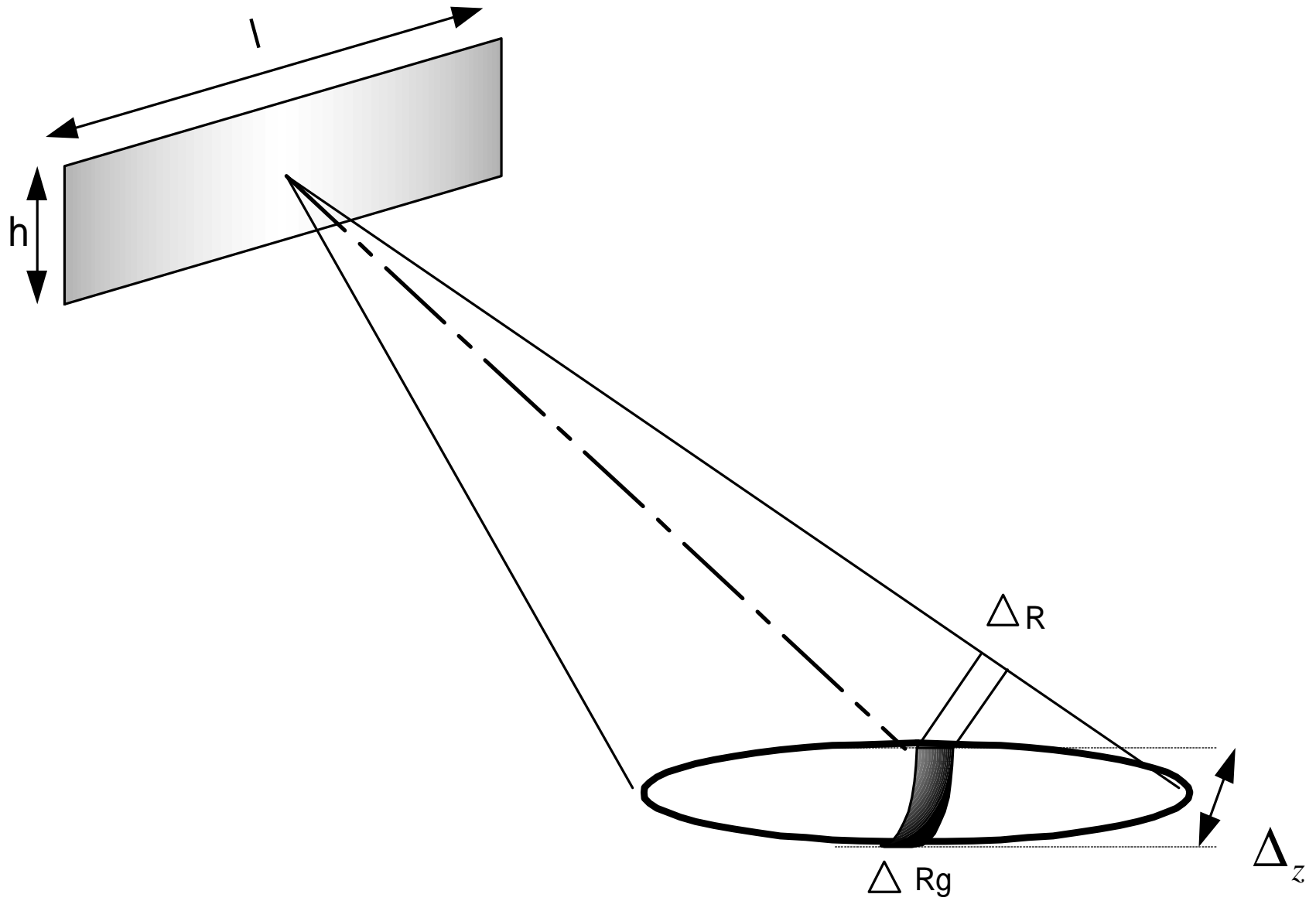
Resolución longitudinal

$$\Delta R = \frac{c\Delta t}{2} = \frac{c}{2B}$$

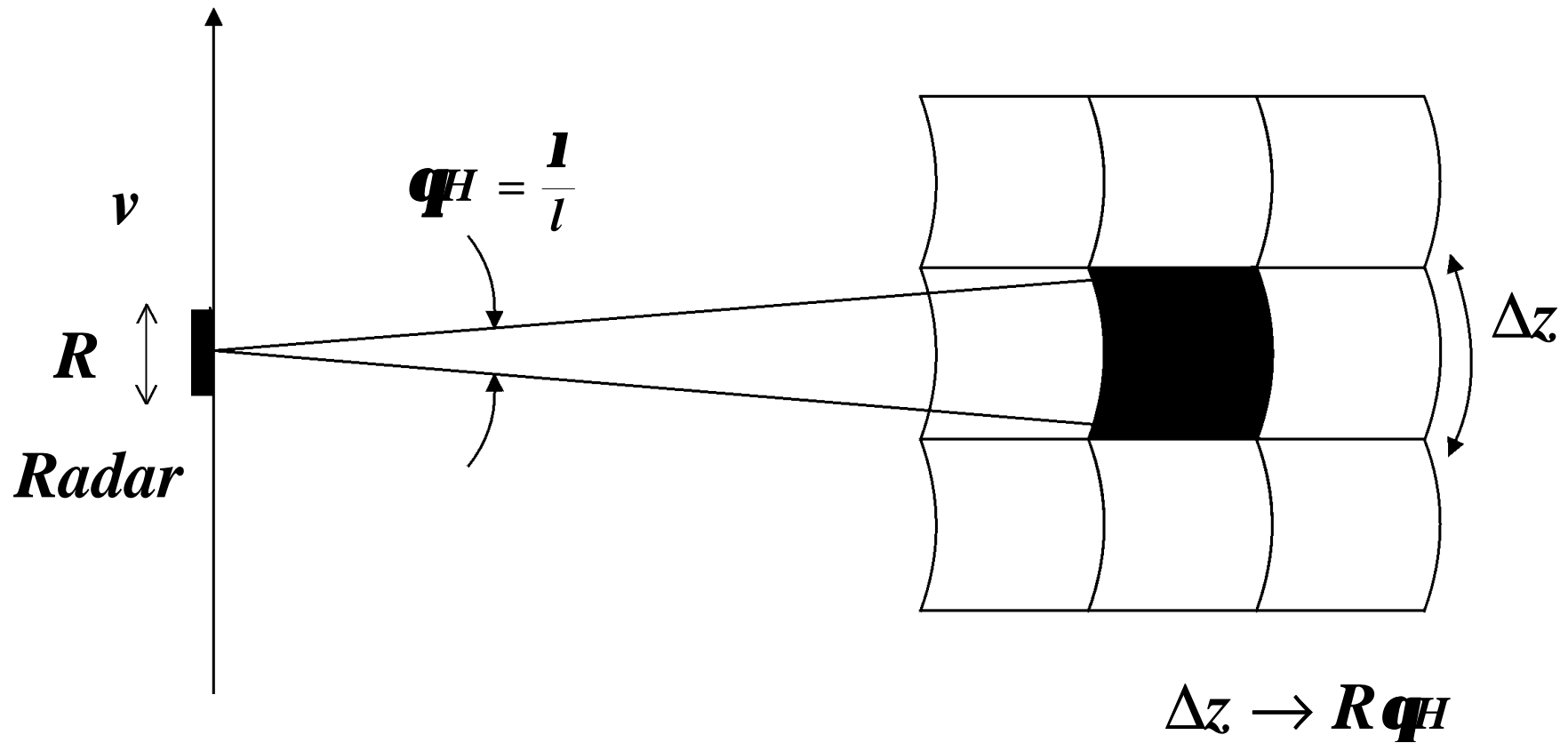
# Resolución en tierra $\Delta R_g$



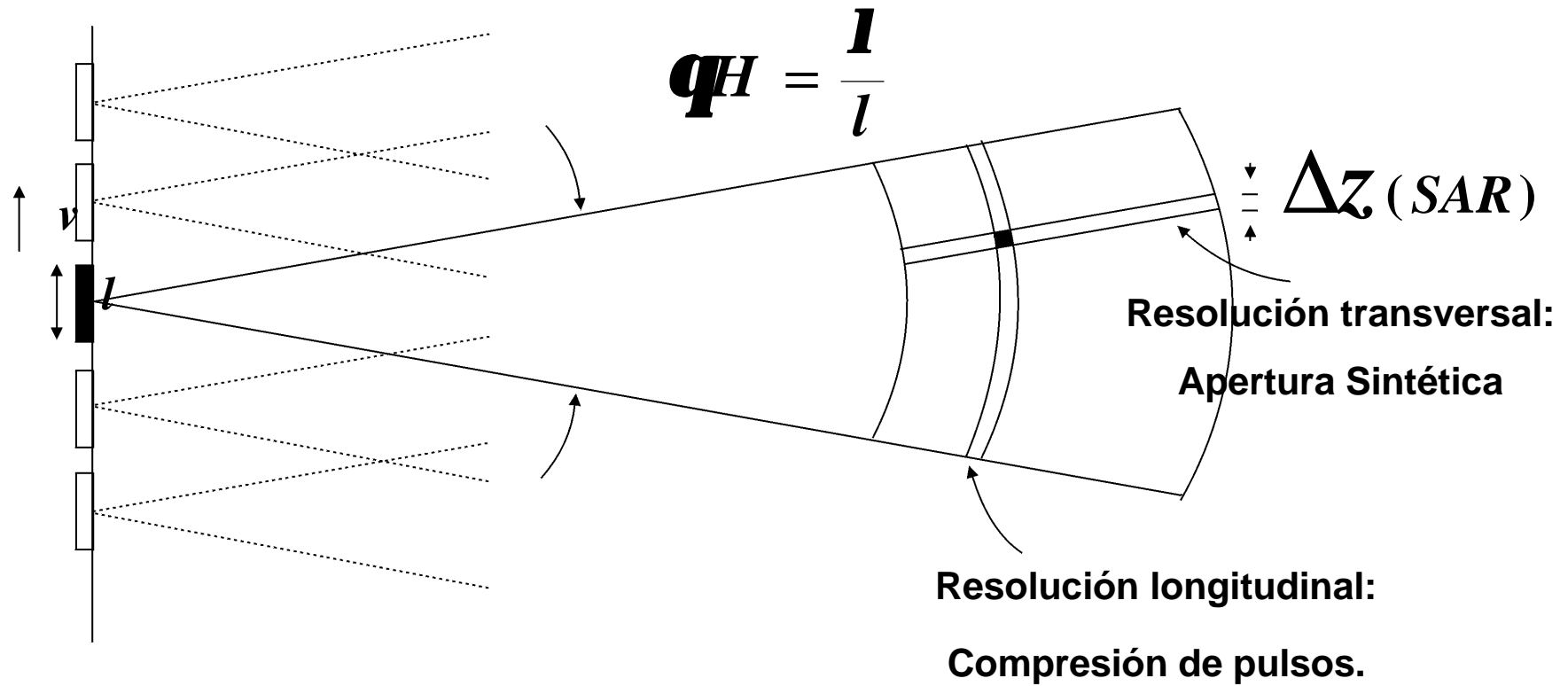
# Resolución en distancia en la huella



# Radars de imagen con apertura real (SLAR) Side Looking Aperture Radar



# Radars de apertura sintética (SAR)



$$\Delta z (SAR) \ll R q_H$$

Con una apertura sintética se obtiene mayor resolución lateral

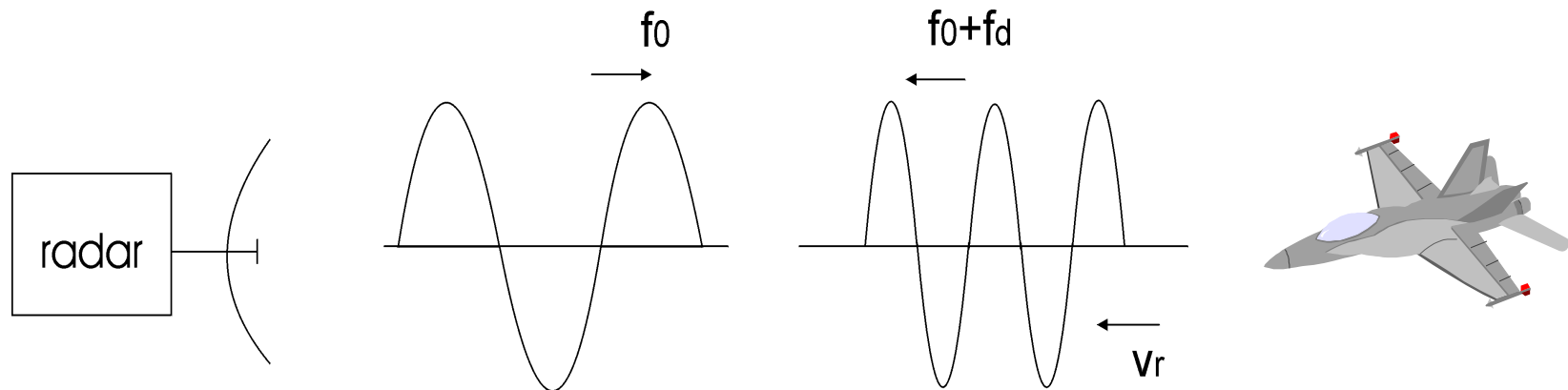
## Blanco en movimiento a distancia $R(t)$

**Eco:**  $\tilde{S}_r(t) = k \tilde{S}_e[t - tr(t)] e^{-j2kR(t)}$

*si*  $R(t) = R_o + v_r t$  ;  $v_r$  : **vel. radial**

$e^{-j2kR(t)} \rightarrow e^{-j2\pi f_d t}$  ;  $f_d$  : **frec. doppler**

$f_d = -\frac{2f_o}{c} v_r$  ;  $f_o$  : **portadora radar**

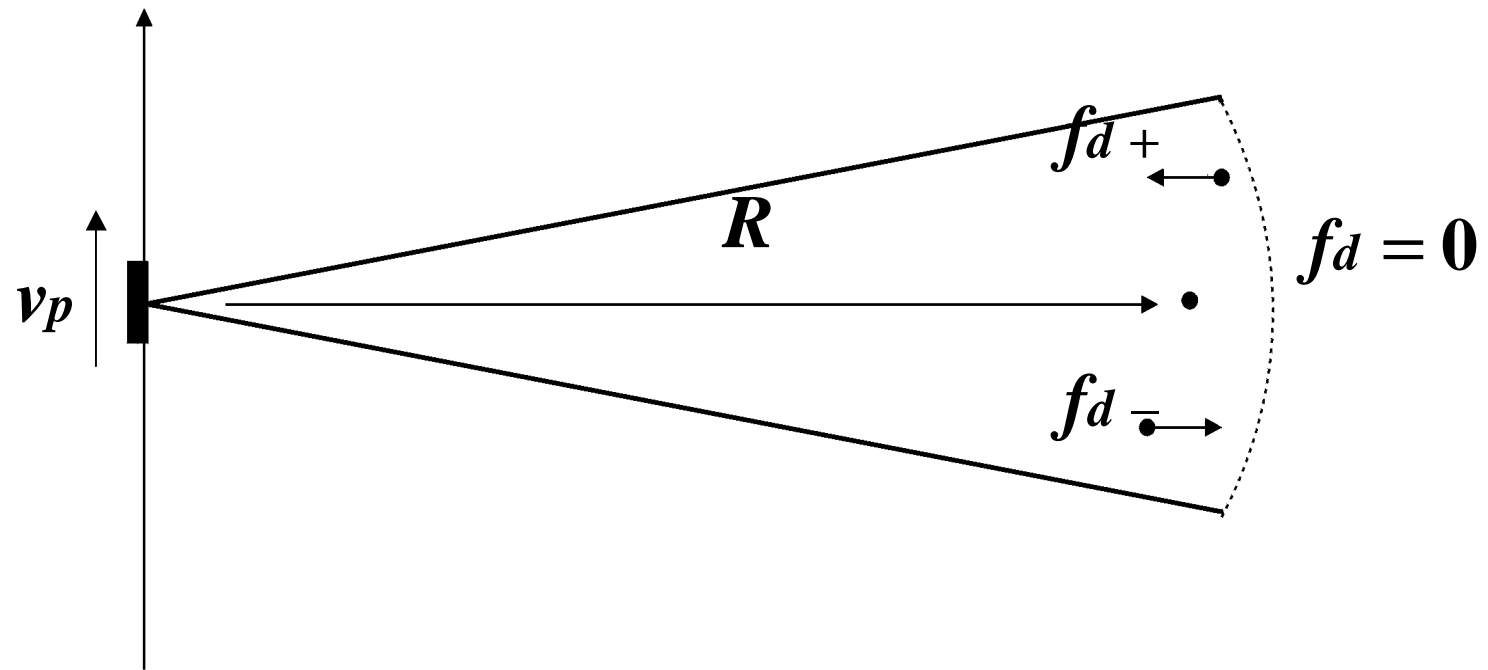


**$f_d$  se superpone a la frec. portadora del radar.**

# SAR: alta resolución transversal

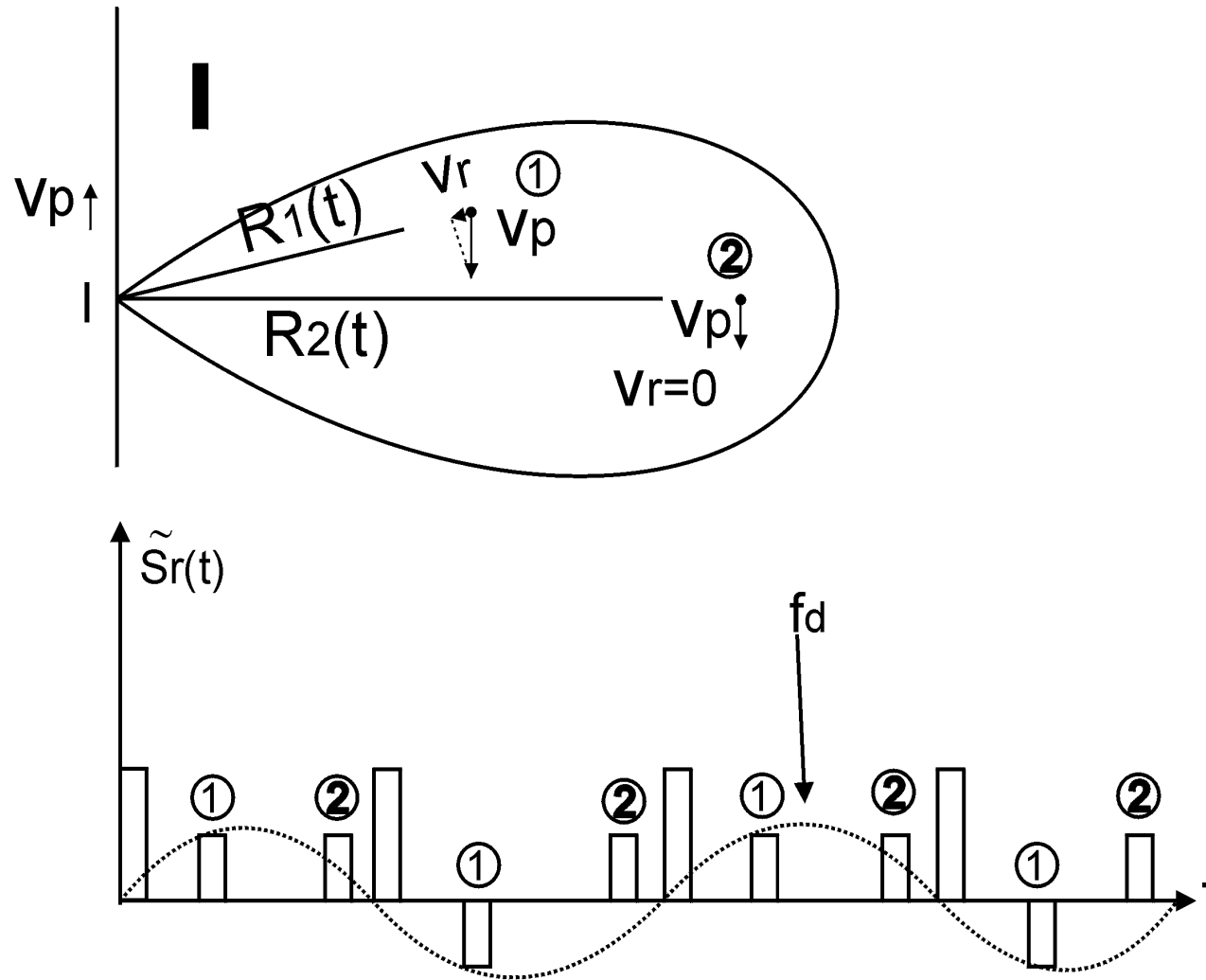
## Interpretaciones

- Tratamiento Doppler



Mediante filtrado podemos resolver los tres blancos

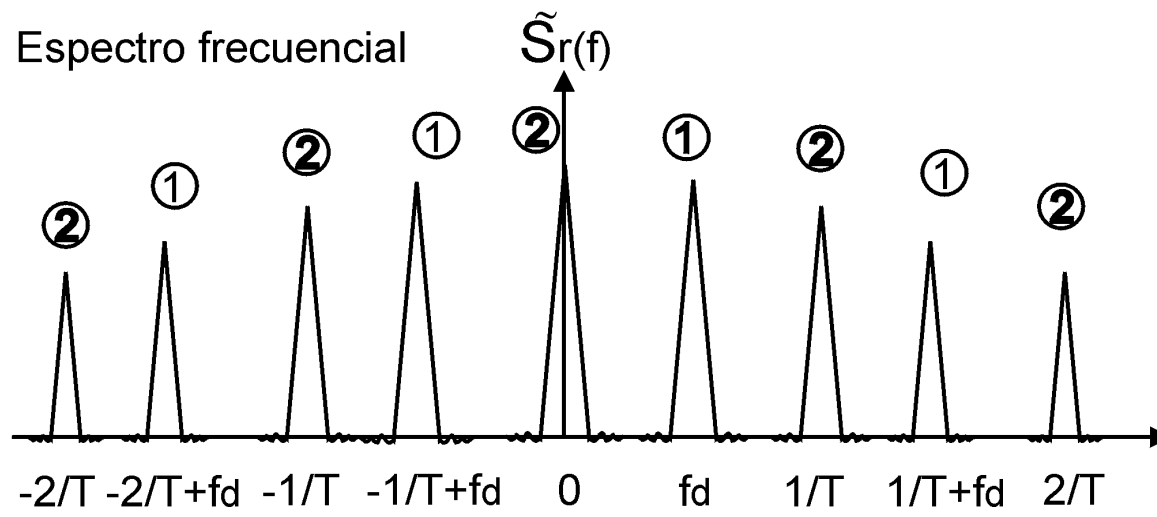
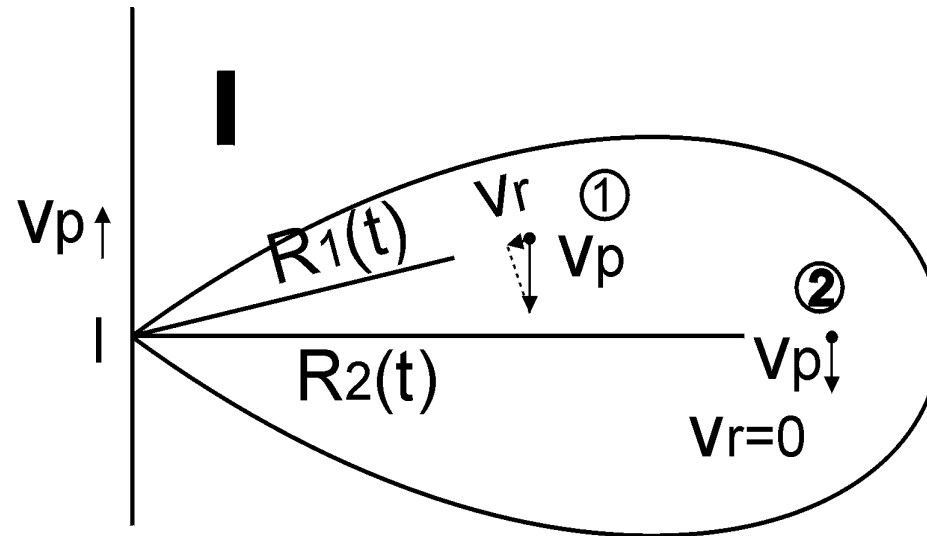
# Efecto doppler: discrimina transversalmente en un SAR



① ② pueden discriminarse por su característica doppler diferente.

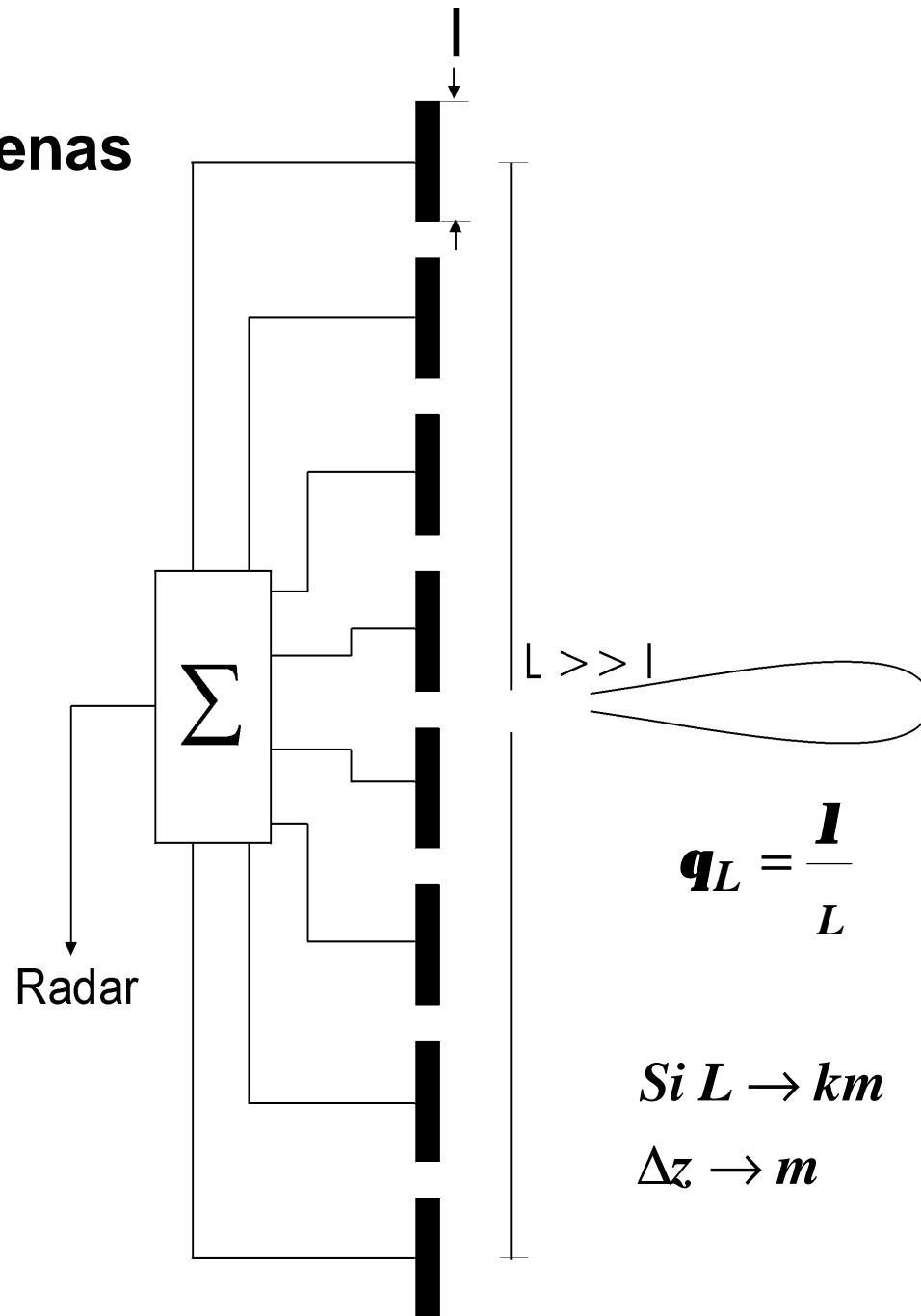


# Efecto doppler: discrimina transversalmente en un SAR



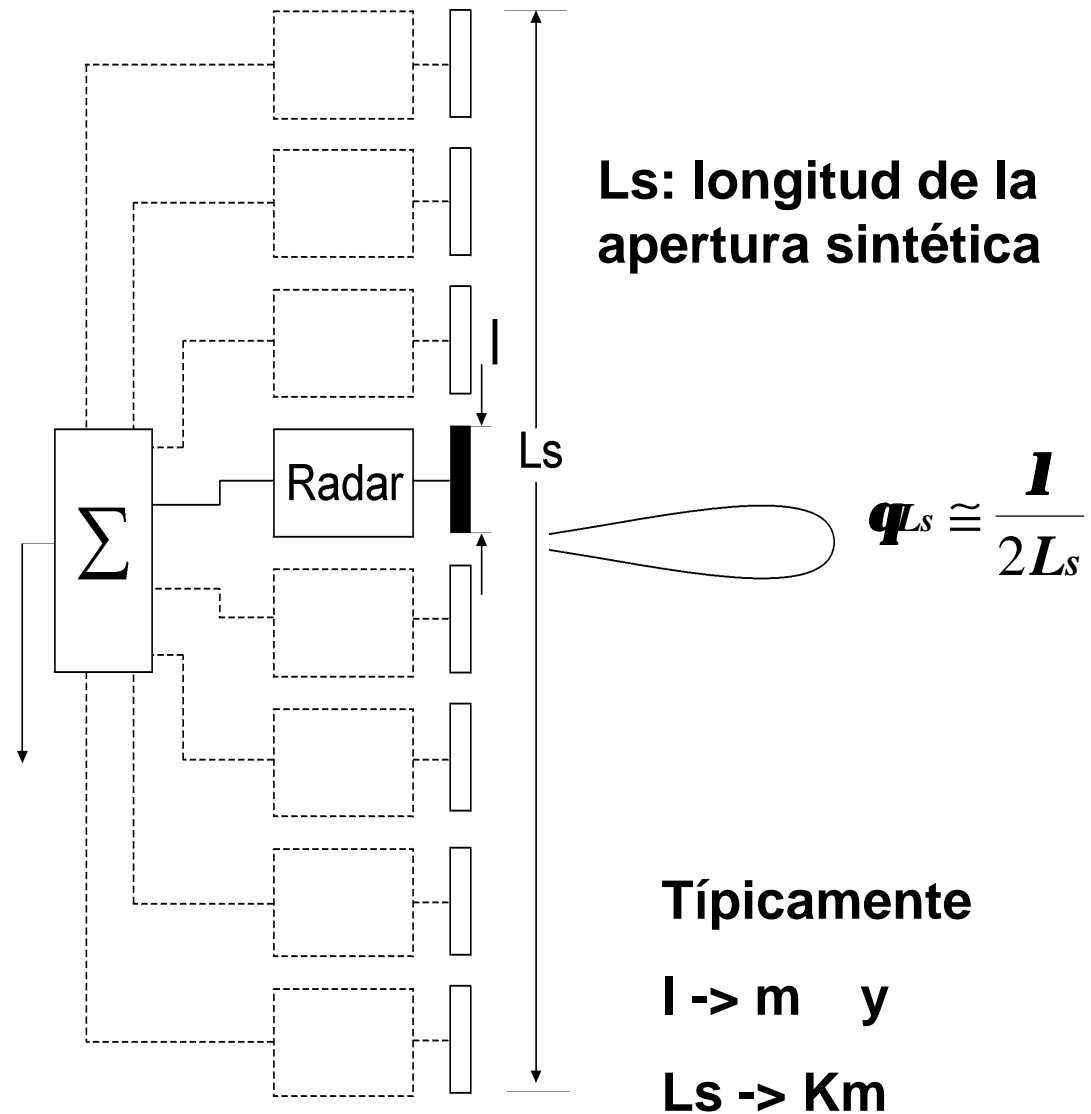
# Agrupación real de antenas

Problema: si  $L \rightarrow km$   
no podemos embarcar  
la antena en un satélite  
o avión.

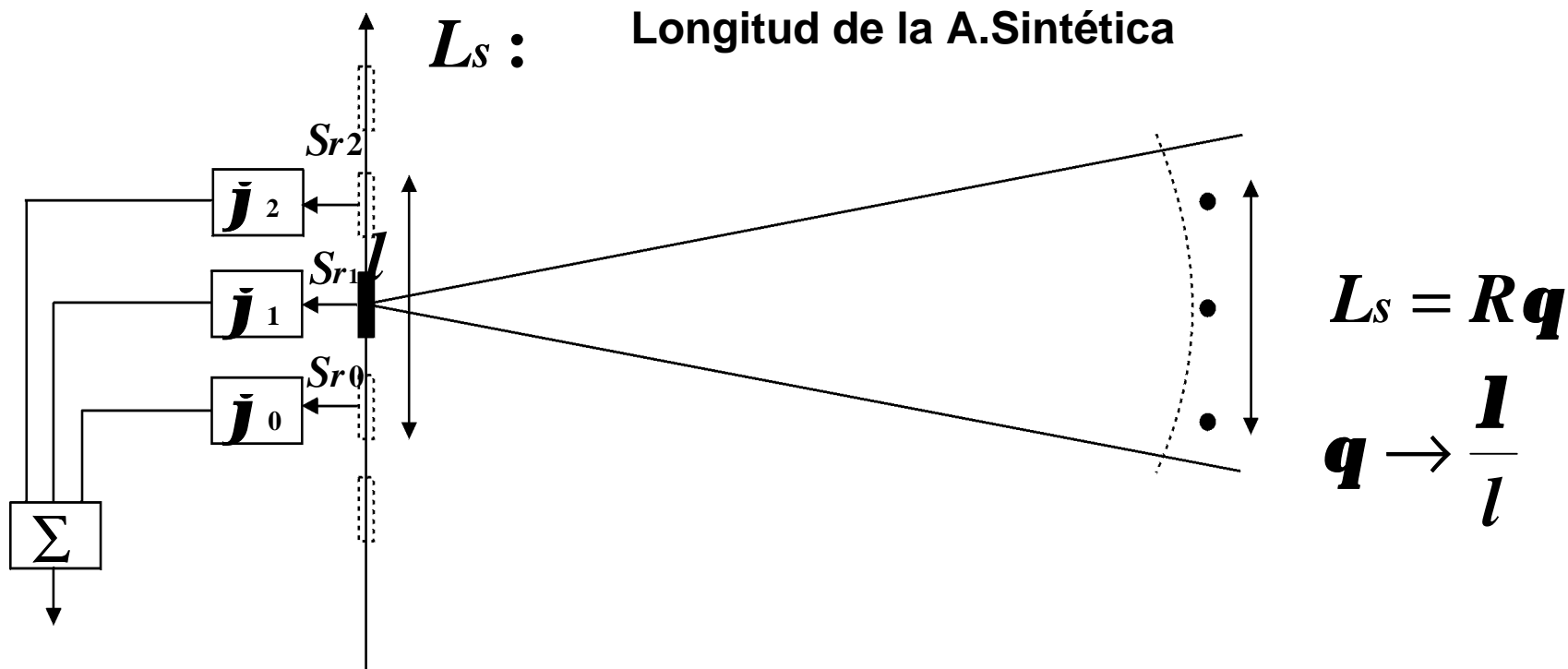


# AGRUPACIÓN (APERTURA) SINTÉTICA

- Cada elemento se utiliza como emisor/receptor de manera independiente
- El radar es un sistema coherente: oscilador muy estable que mantiene la fase en el trayecto.
- Podemos combinar coherentemente los ecos que obtiene una única antena a lo largo de la trayectoria

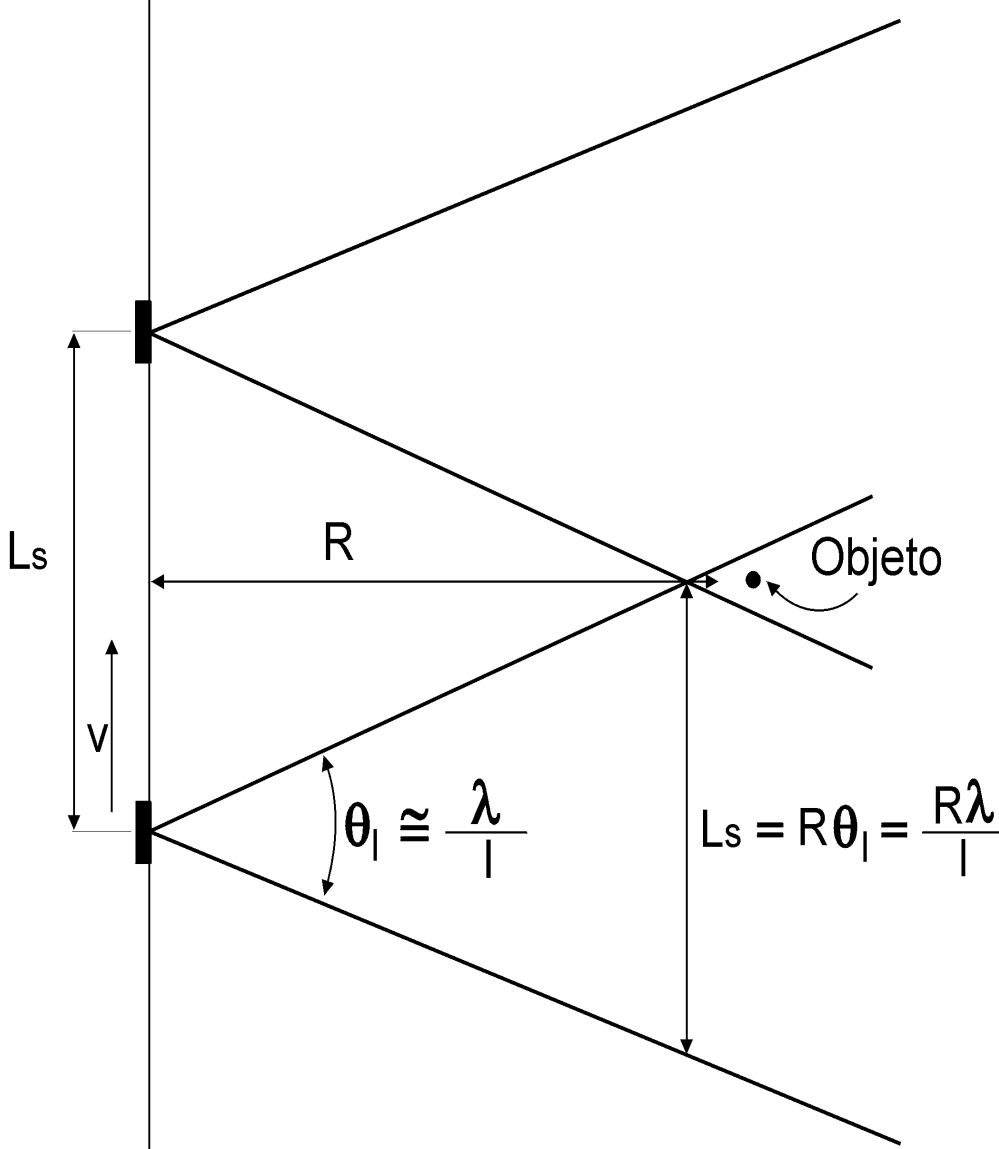


# Apertura o antena sintética



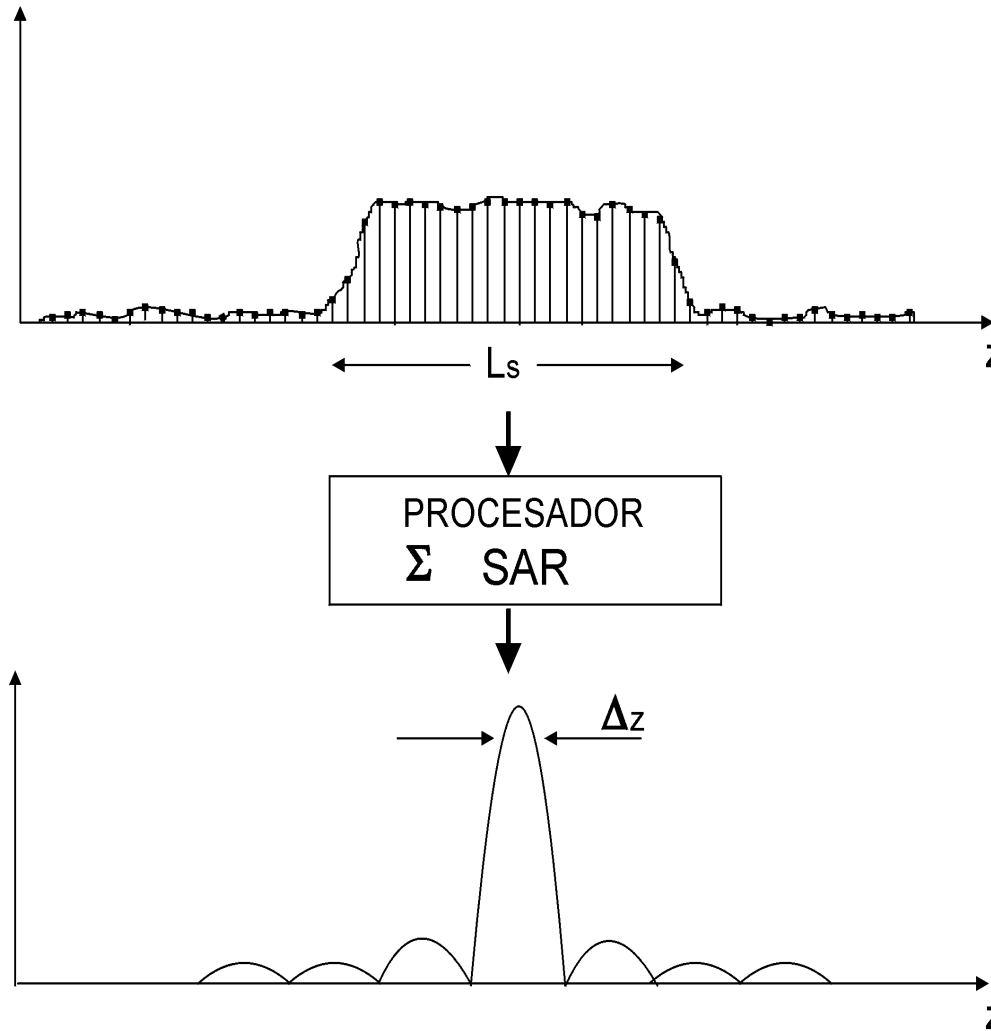
Con las fases adecuadas podemos resolver los tres blancos

# Longitud de la apertura sintética $L_s$



# Procesamiento de los ecos radar

(Raw data)

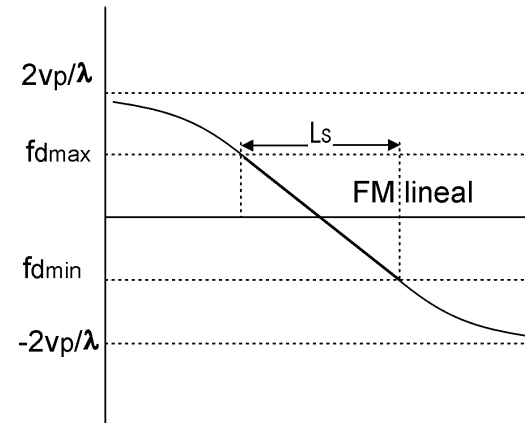
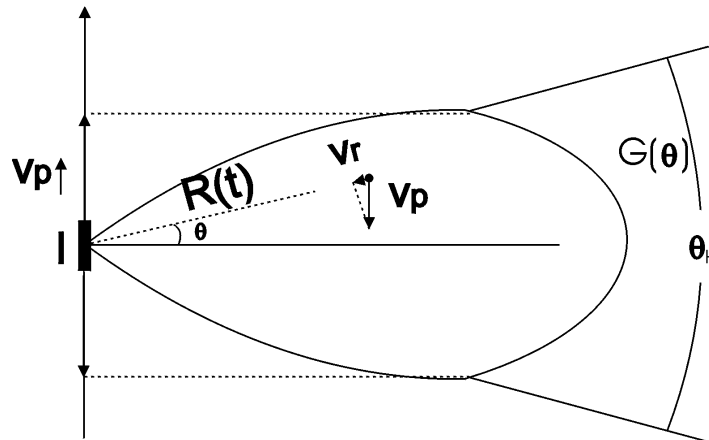


$$\Delta z = R\theta_{L_s} = R \frac{\lambda}{2L_s} = R \frac{\lambda l}{2R\lambda} = \frac{l}{2}$$

$\Delta z$ : independiente de R, f, v, etc

Si  $l = 10$  mts.  $\Rightarrow \Delta z = 5$  mts.

# Historia Doppler



$$f_d = \frac{-2v_r}{\lambda}$$

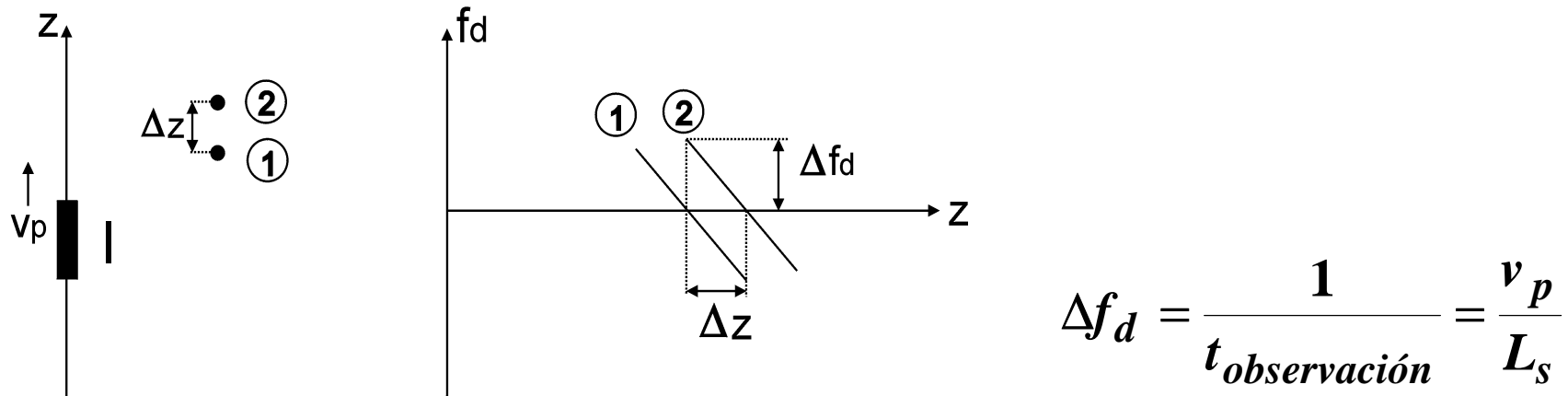
La frec. Doppler (dentro del haz  $\theta_H$ ) evoluciona casi linealmente entre  $f_{dmax}$  y  $f_{dmin}$

$$v_r = v_p \text{ sen } \mathbf{q} \rightarrow v_p \mathbf{q} \quad ; \quad \mathbf{d}f_d = f_{dmax} - f_{dmin} = \frac{2v_p \mathbf{q}_H}{\lambda} = \frac{2v_p \mathbf{l} / l}{\lambda} = \frac{2v_p}{l}$$

$$\text{Pendiente doppler} = \frac{\Delta \mathbf{d}f_d}{dt} = \frac{\mathbf{d}f_d}{dz} \frac{dz}{dt} = \frac{\mathbf{d}f_d}{L_s} v_p = \frac{2v_p^2}{lL_s} = \frac{2v_p^2}{\lambda R_0}$$

## Resolución lateral (acimutal):

capacidad de separar dos blancos próximos.



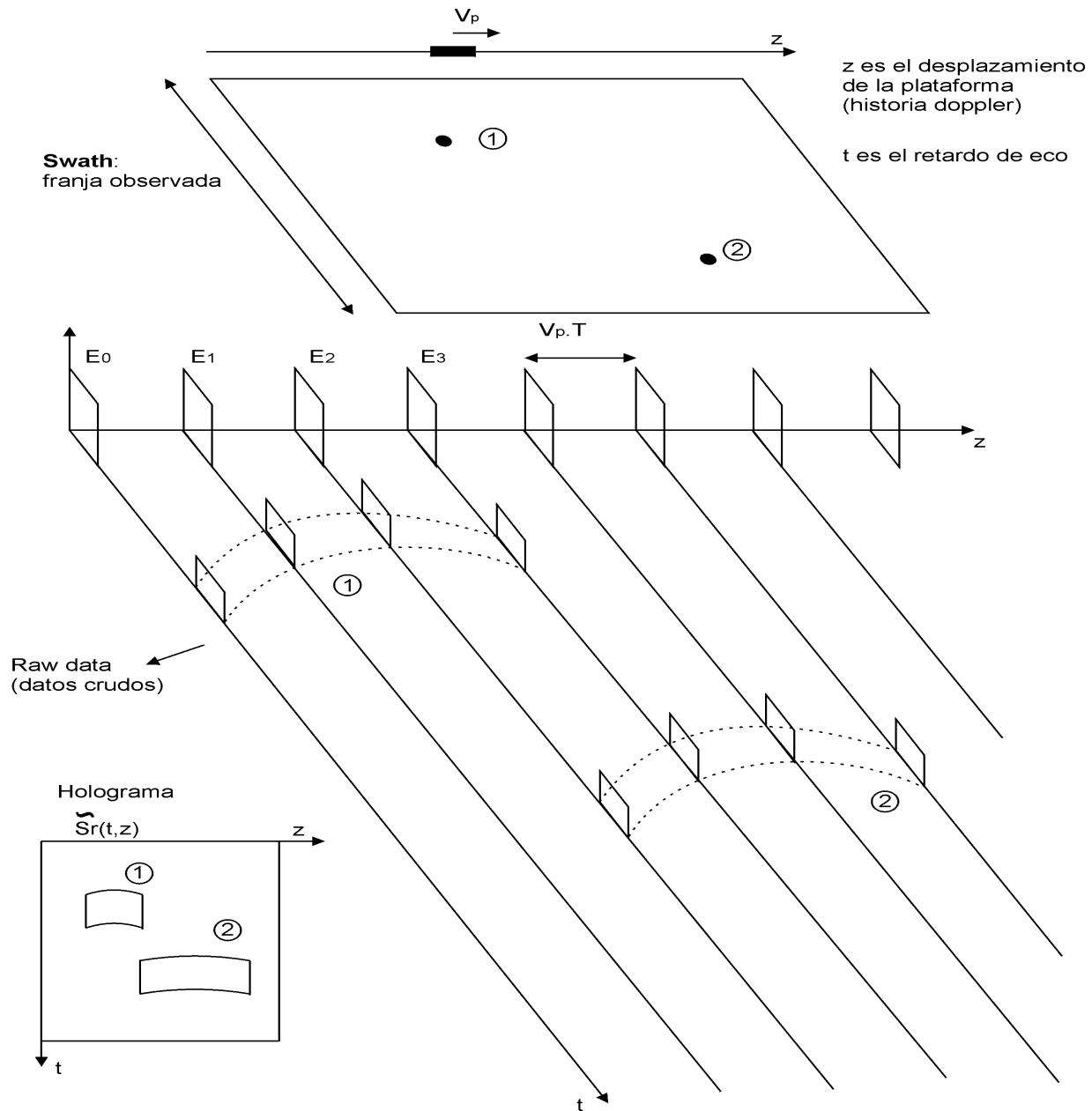
La resolución  $\Delta f_d$  se traduce en una resolución lateral según la pendiente doppler respecto a acimut ( $z$ ).

$$\Delta z = \Delta f_d \frac{1}{df_d/dz} = \frac{v_p}{L_s} \frac{L_s}{df_d} = \frac{v_p}{2v_p/l} = \frac{l}{2}$$

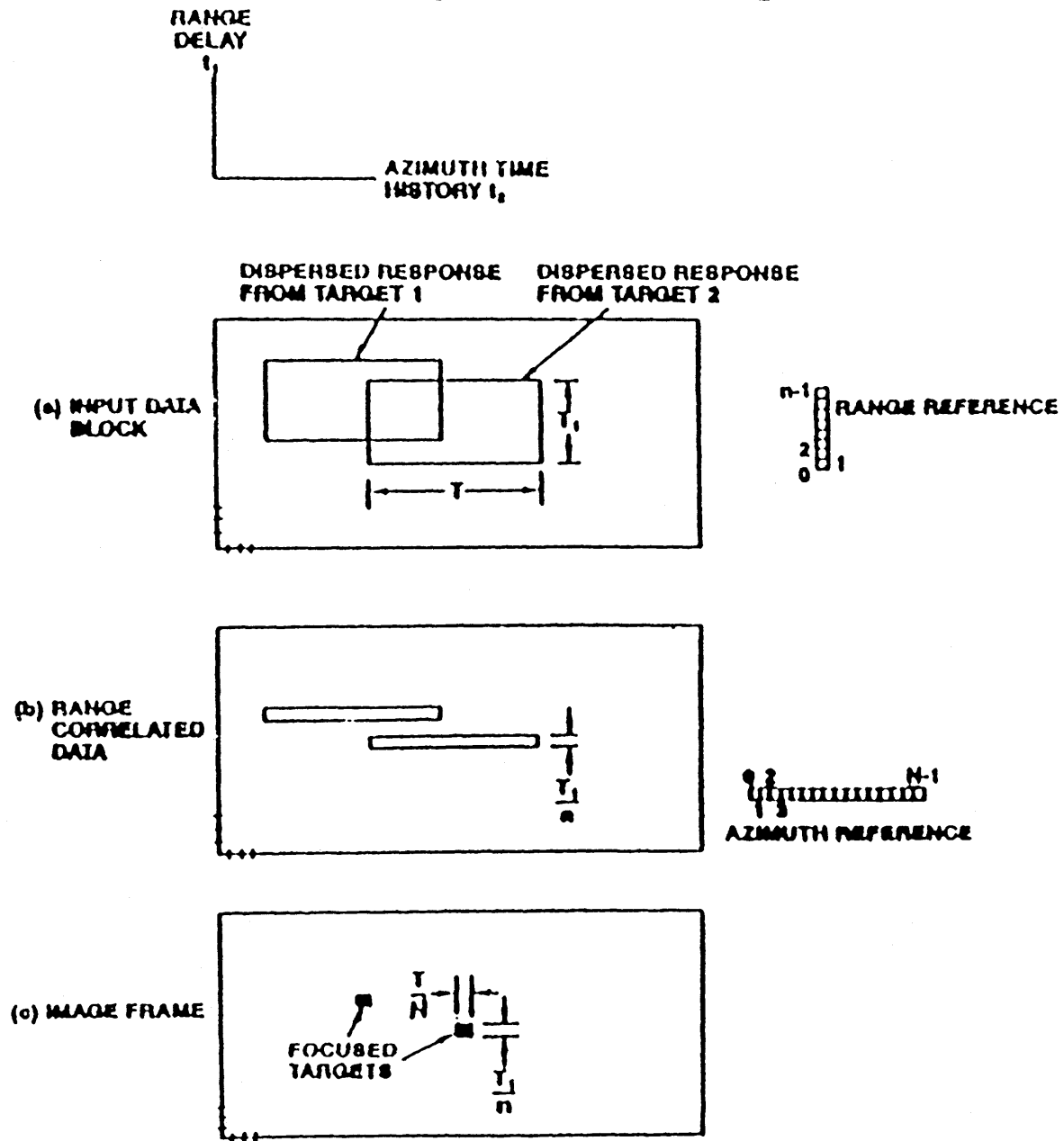
La resolución transversal máxima SAR es  $l/2$  (1/2 dimensión de la antena)



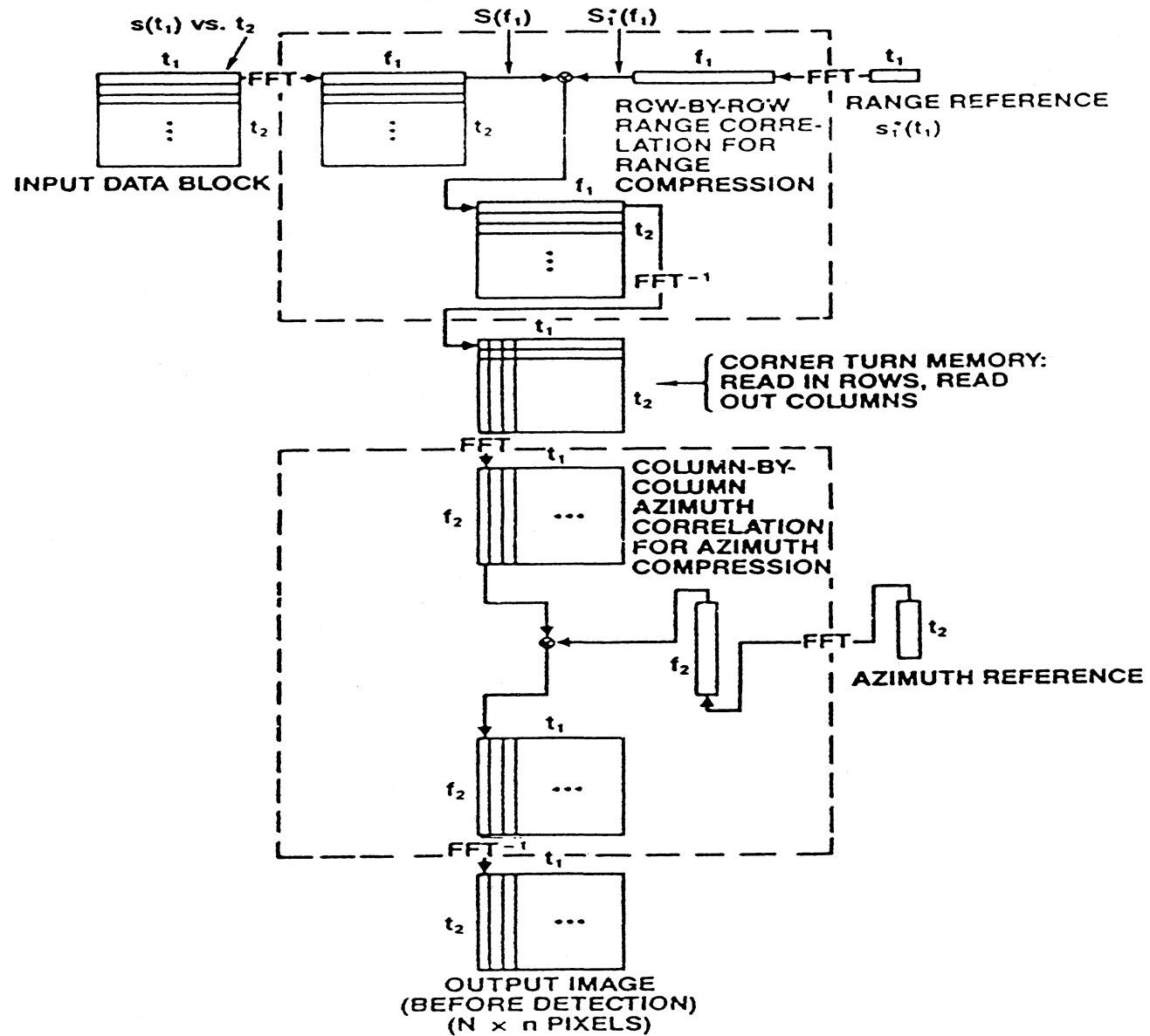
# Señal adquirida por el SAR: $\tilde{S}_r(t,z) : 2D$



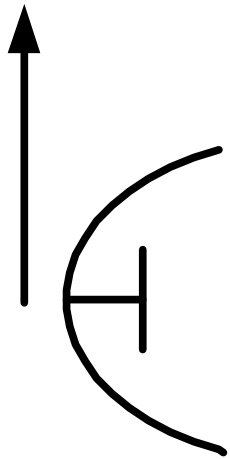
# Processing of SAR Input Data Containing Two Point Targets



# Fast correlation with One-Dimensional References



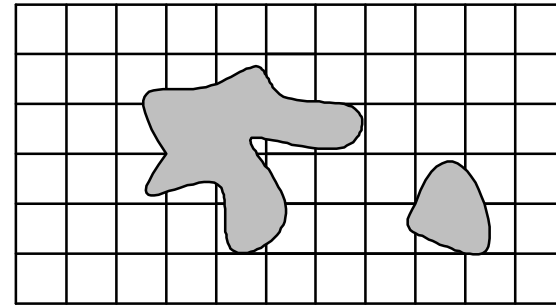
# Coordenadas de la imagen SAR




Acimut



IMAGEN



Distancia  
(retardo)



D-PAF Job Number: 345269

X-SAR/HRMGD

© DLR/DFD 1996



-28 dB -26 dB -24 dB -22 dB -20 dB -18 dB -16 dB -14 dB -12 dB -10 dB -8 dB -6 dB -4 dB -2 dB 0 dB 2 dB

Pta Laberinto / Argentina  
GMT: 07-OCT-1994/20:15:32 , Data Take ID: 120.90  
Latitude / Longitude at Image Center: S 39.40° / W 62.08°  
D-PAF Product ID: X2SAR941007201532HRMGDDP19970320234926

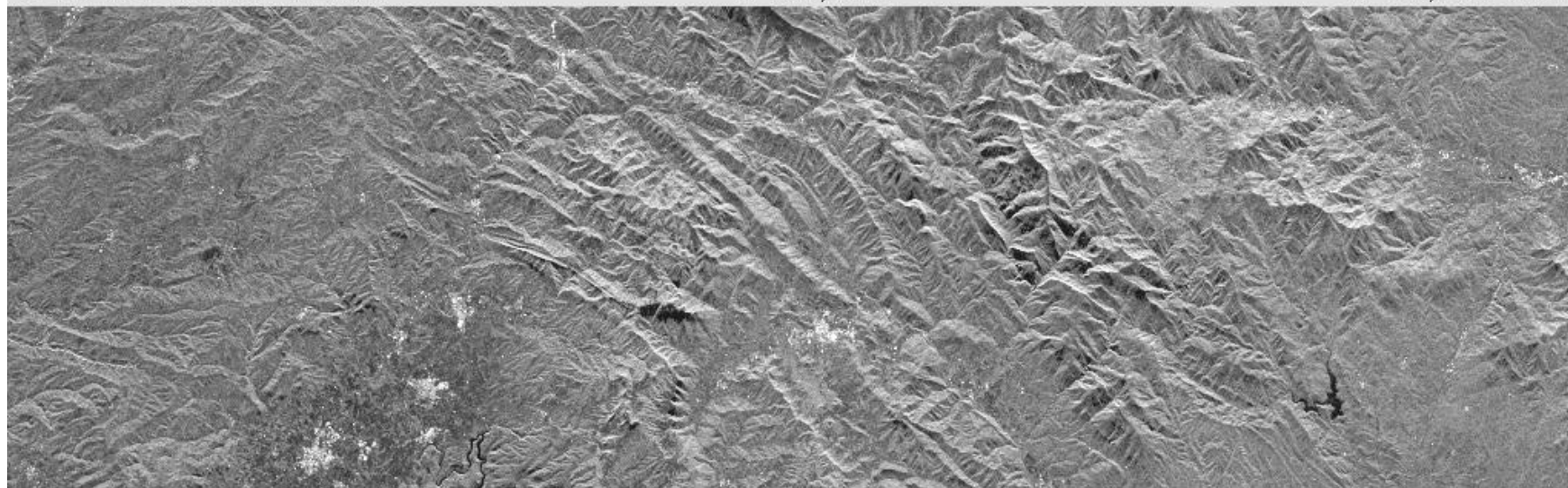
↓   ←   ↘  
Illumination   Flight Direction   North



D-PAF Job Number: 278725

X-SAR/MGD

© DLR/DFD 1996



-28 dB -26 dB -24 dB -22 dB -20 dB -18 dB -16 dB -14 dB -12 dB -10 dB -8 dB -6 dB -4 dB -2 dB 0 dB 2 dB

Vich / Spain

GMT: 12-APR-1994/05:53:26 , Data Take ID: 046.01

Latitude / Longitude at Image Center: N 42.19° / E 2.41°

D-PAF Product ID: X1SAR940412055326MGD\_\_DP19960909200251



Illumination



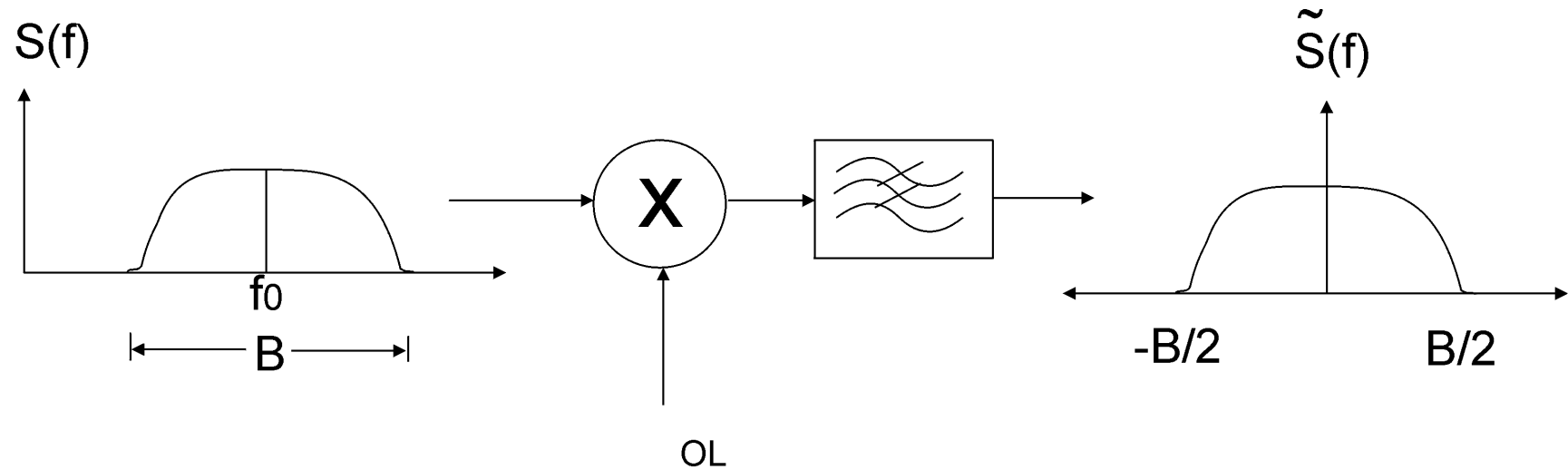
Flight Direction



North



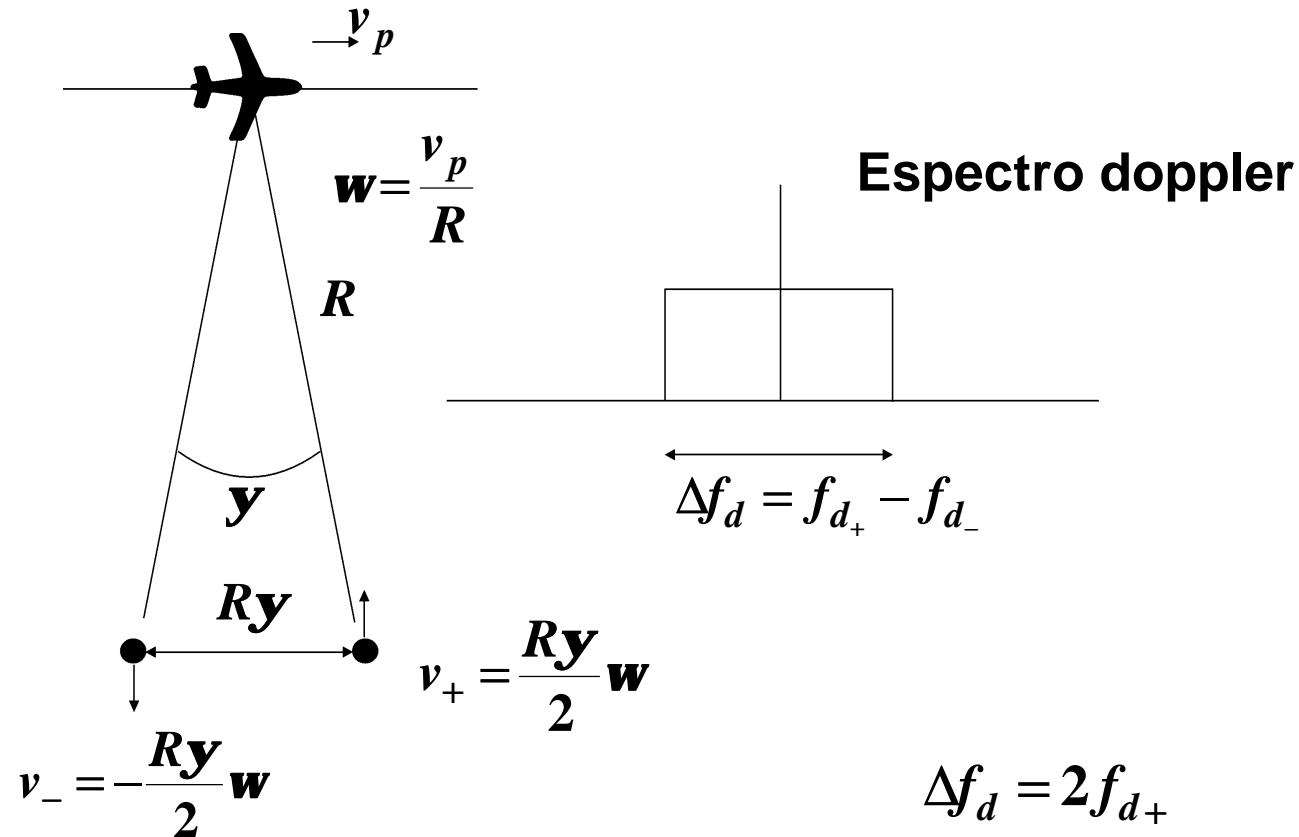
# Condiciones de muestreo de los ecos



**Nyquist**  $f_s \geq B = \frac{1}{\Delta t}$  ; siendo  $\Delta R = \frac{c\Delta t}{2}$

**1 muestra cada  $\Delta t$**   $f_s \geq B = \frac{c}{2\Delta R}$  ; si  $\Delta R = 1\text{m} \rightarrow f_s > 150\text{MHz}$

# Frecuencia de repetición de pulsos (PRF)



$$\Delta f_d = \frac{2}{l} 2v_+ = \frac{2 v_p}{l R} Ry = \frac{2v_p y}{l} \rightarrow \frac{2v_p}{l}$$

$$PRF \geq \Delta f_d \rightarrow \frac{2v_p}{l} = \frac{v_p}{\Delta r_s} ; \text{ m\u00ednimo 1 muestra cada } r_s$$



# Ecuaciones fundamentales del SAR (1)

- Resolución longitudinal (en distancia) máxima  $\Delta R$

Distancia radar (Slant range)  $\Delta R = \frac{c}{2B}$

B: ancho de banda

Distancia sobre el suelo  
(Ground range)  $\Delta R_g = \frac{\Delta R}{\text{sen } \mathbf{j}}$

$\varphi$ : ángulo de incidencia

## Ecuaciones fundamentales del SAR (2)

- Resolución transversal (en acimut) máxima  $\Delta z$

$$\Delta z_{(1\text{ look})} = \frac{l}{2} \quad l: \text{longitud antena (real)}$$

- Longitud apertura sintética  $L_s = R \alpha_H$

- Excursión de la frecuencia doppler  $\mathbf{df}_d$

$$\mathbf{df}_d = f_{dmax} - f_{dmin} = \frac{2v_p}{l} \quad ; \quad v_p : \text{velocidad del sensor}$$

# ***Ecuación del radar después del procesamiento SAR***

$$SNR^{SAR} = \frac{P_t G^2 I^2 s^0}{(4p)^3 R^4 k T_0 F B L} (R \mathbf{q}_H) \left( \frac{c t_o}{2 \sin \mathbf{j}_{in}} \right) \left( \frac{f_s}{B} \cdot \frac{PRF}{B_{Dopl}} \right)$$

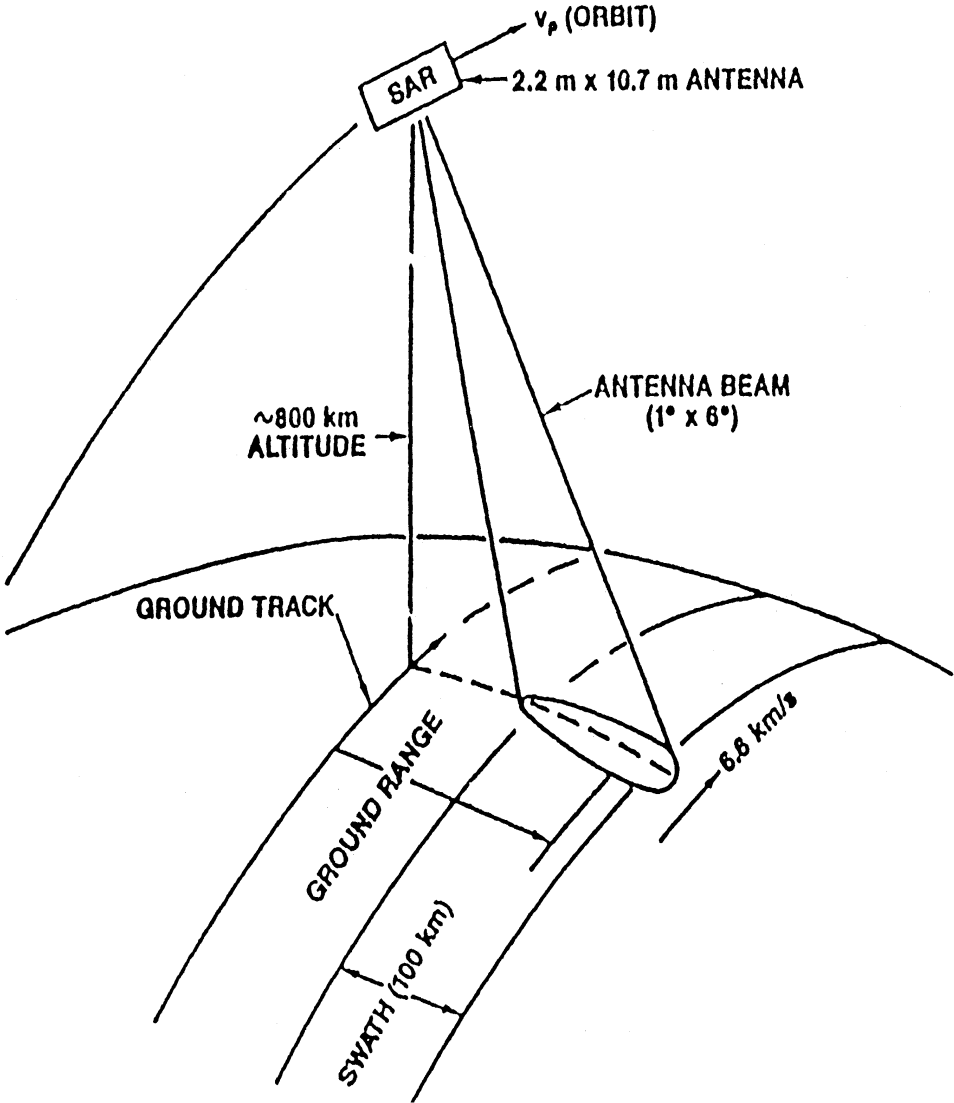
**SNR proportional to:**

- (Antena Gain)<sup>2</sup>
- (Wavelength)<sup>2</sup>
- Illuminated footprint
- Oversampling factors

**SNR inversely proportional to:**

- (Range)<sup>3</sup>
- Noise Factor
- Receiver Bandwidth
- Losses

# SEASAT SAR System



## SEASAT Design Parameters

<i>Design Parameter</i>	<i>Symbol</i>	<i>Value</i>
Center Frequency	$\bar{f}$	1275 MHz ( $\lambda = 0.235$ m)
Bandwidth	$\beta$	19 MHz
Pulse Duration	$T_1$	34 $\mu$ s
Peak Power	$P_t$	1000 W
PRF	$\frac{1}{T_2}$	1500 pps (nominal)*
Radar System Noise Temperature	$T_s$	650 K
Satellite Altitude	$h_1$	800 km
Antenna Gain	$G$	35 dB (3162)
Incident Angle	$\theta_d$	67° (at beam center)
Antenna Beamwidth in Azimuth	$\phi_3$ dB	1.0° ( $17.4 \times 10^{-3}$ rad)
Platform Velocity (Ground Track)	$v_p$	6.6 km/s
System Loss	$L$	-3 dB ( $L = 0.5$ )
Number of Looks	$n_c$	4
Single-Look Coherent Integration Angle	$\psi$	0.30° ( $5.24 \times 10^{-3}$ rad)
Range to Center of Swath	$R$	854 km
Pulses per Look	$n$	1024

\* Actual SEASAT PRF selections were 1463, 1537, and 1645. A PRF of 1500, however, will be used for illustration.

# SEASAT performance calculations

Performance Parameter	Expression	Value for SEASAT Design Parameters
Cross-Range Resolution (Four-Look) Processing	$\Delta r_c = \frac{1}{2} \frac{\lambda}{\psi}$	22.4 m*
Slant-Range Resolution	$\Delta r_s = \frac{1}{2} \frac{c}{\beta}$	7.89 m
Ground-Range Resolution	$\frac{\Delta r_s}{\sin 23^\circ}$	20.2 m*
Maximum Unambiguous Illuminated Range Extent (along the Ground Assuming a Flat Earth)	$\frac{\Delta R_I}{\sin 23^\circ} = \frac{cT_2}{2} \frac{1}{\sin 23^\circ}$	256 km
Cross-Range Ambiguity Length (at Center of Swath)	$(R\psi)_{\max} = \frac{R\lambda}{2v_p T_2}$	23 km
Single-Look Integration Length at Center of Swath	$\mathcal{L} = R\psi$	4.5 km
Single-Look Integration Time	$T = nT_2$	0.68 s
Average Pixel Signal-to-Noise Ratio (per Look)	$\frac{S}{N} \begin{cases} \text{desert} & -4.4 \text{ dB} \\ \text{woods} & +12.6 \text{ dB} \\ \text{cities} & +16.7 \text{ dB} \\ \text{sea (SS-3)} & +8.0 \text{ dB} \end{cases}$	
Range Migration during Four Looks	$M' = \frac{1}{8} \frac{R(4\psi)^2}{\Delta r_s}$	6 cells
Range Focusing Depth per Look for $\phi(\omega_s) = \frac{\pi}{2}$	$(\Delta R)_f = \frac{8(\Delta r_c)^2}{\lambda}$	17 km

\*The actual SEASAT resolution cell size after processing is reported to be 25 m x 25 m [8].

## Ku-Band Synthetic Aperture Radar Imagery

Sandia operates a Ku-Band (15 GHz) synthetic aperture radar carried by the Sandia Twin Otter aircraft. Data is collected at ranges of 2 to 15 km, and processed into images in real-time.



China Lake  
L.A.  
Airport





# Washington

