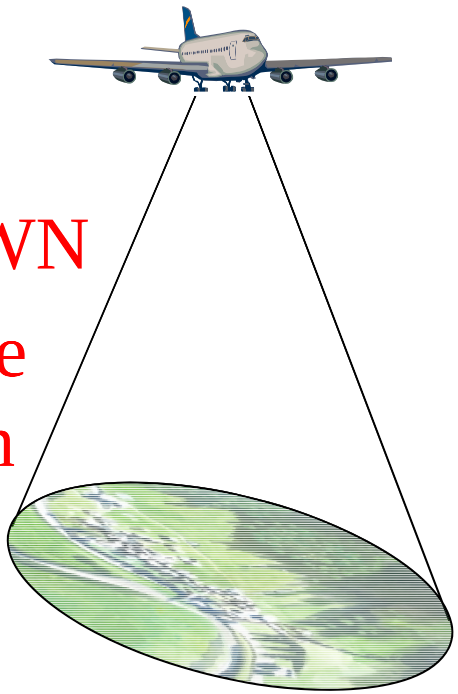
Introduction to ISAR imaging systems

Radar imaging systems

- More in general radar images are obtained by exploiting the relative motion between the radar antenna and the scene to be imaged.

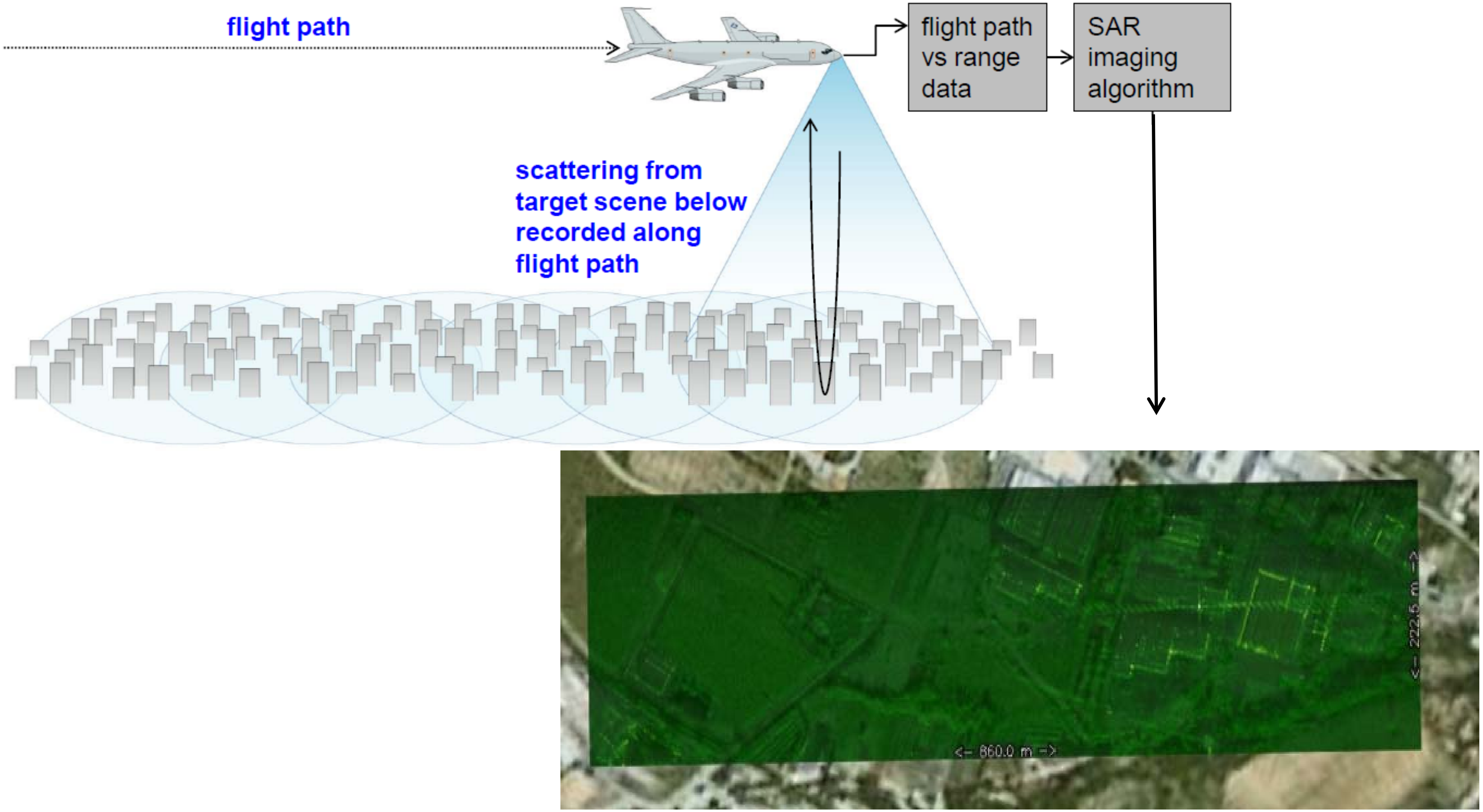
SAR:
KNOWN
relative
motion



ISAR:
UNKNOWN
relative
motion

- SAR used to image extended scenes & ISAR used to image man-made moving targets.

Airborne SAR (Synthetic Aperture Radar)

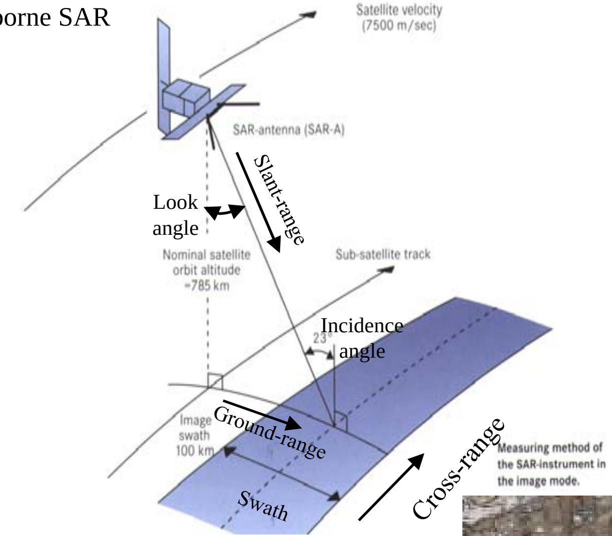


Courtesy of Selex Galileo S.p.A. (Milan, Italy)

Airborne SAR (Synthetic Aperture Radar)

Spaceborne SAR

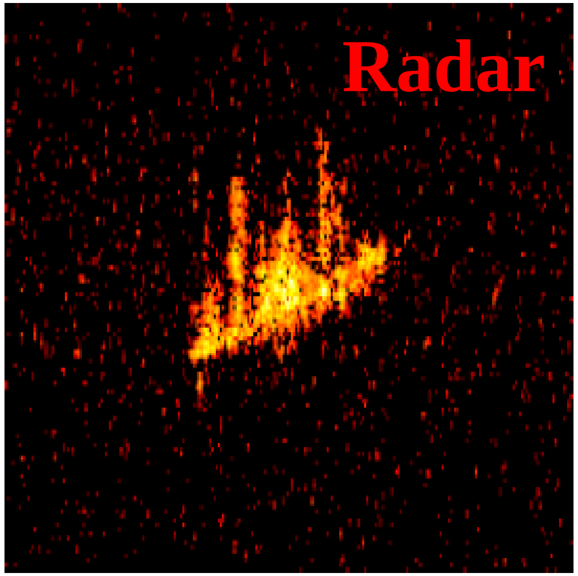
Example:
spaceborne SAR

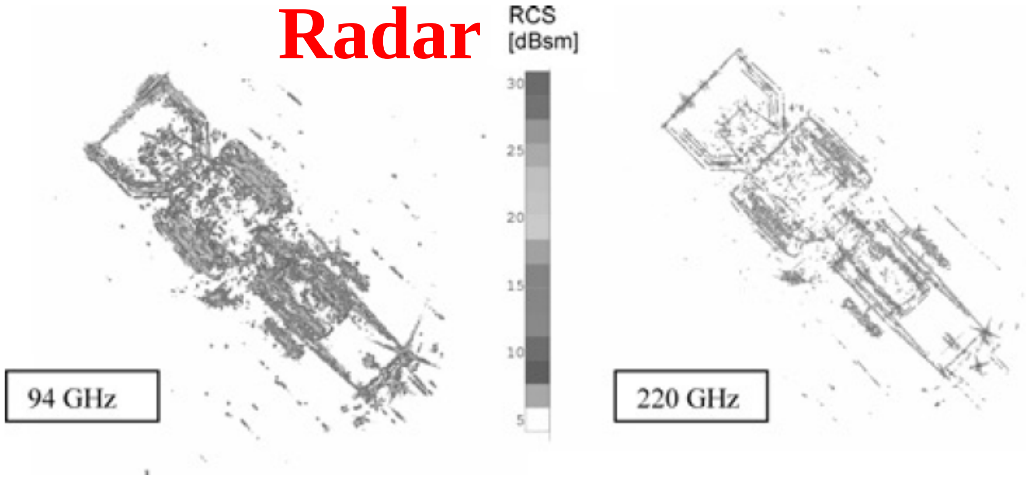


Data provided by the Italian Space Agency (ASI).

Spaceborne SAR

ISAR (Inverse SAR)

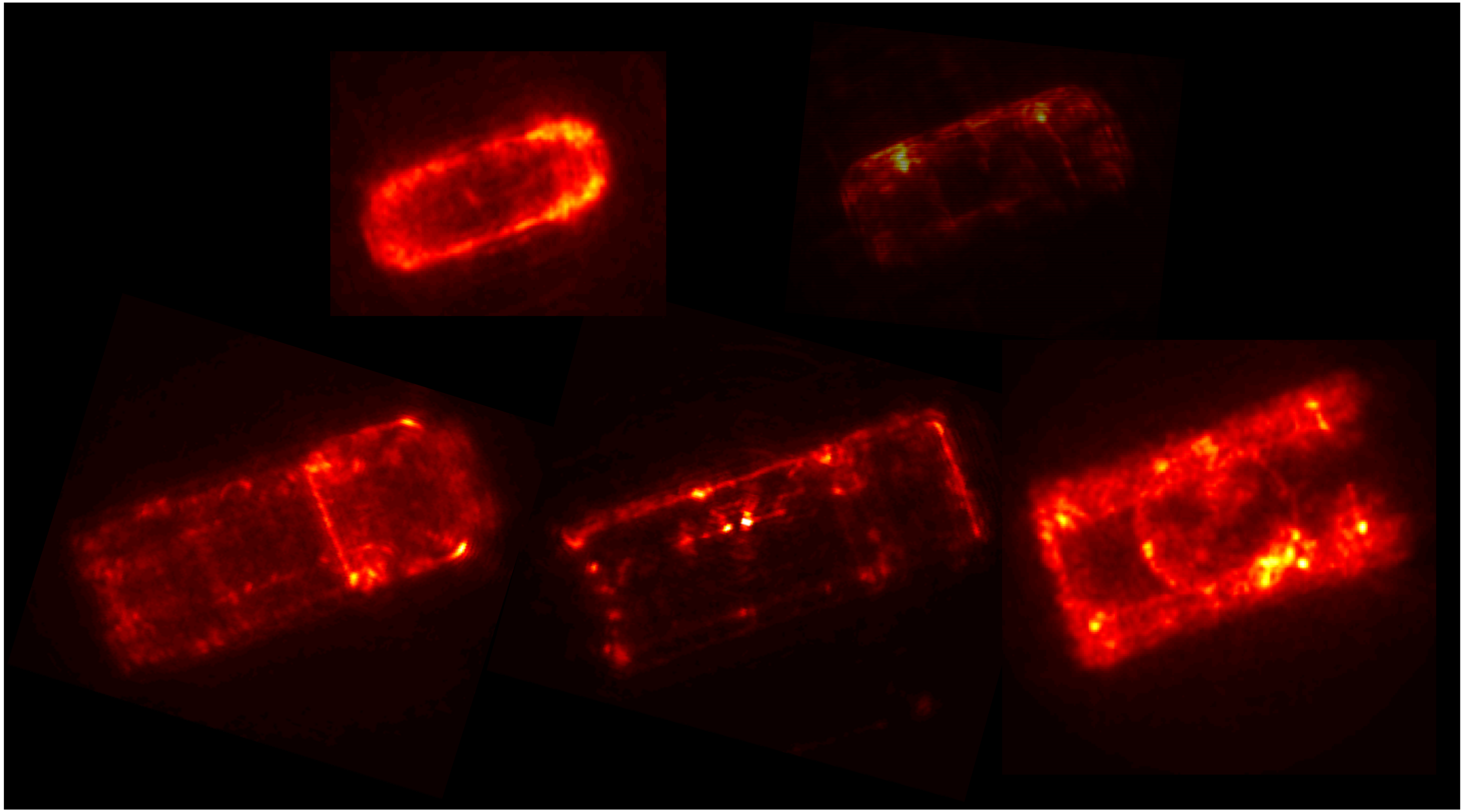




Naval Research Laboratory

From “High-bandwidth 220 GHz experimental radar”, Electronics Letters, Vol. 43, No. 20, Sept 2007

ISAR (Inverse SAR)



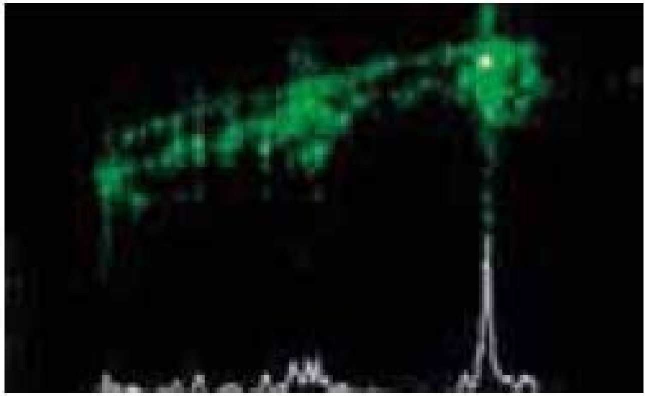
SAR & ISAR modes

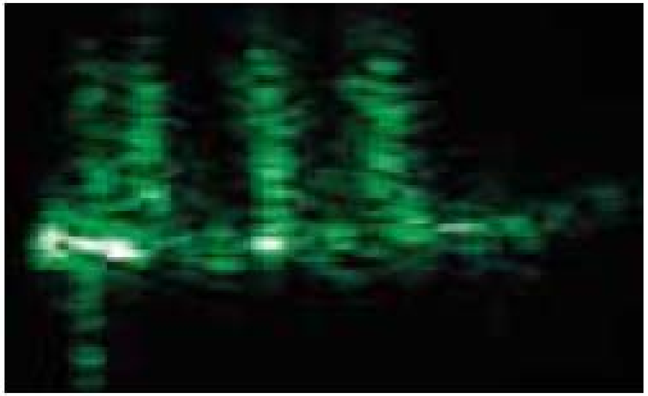
- High resolution imaging modes (both SAR & ISAR) can be embedded in surveillance radar systems;
- An example: GABBIANO radar family (SELEX ES)

✓ a cost effective, lightweight X-Band radar solution for advanced surveillance.
✓ effective in several surveillance missions over sea, land, in the air and along coastlines in all-weather conditions;
✓ Capabilities for targets detection, localization, tracking and identification, ground high resolution imaging and navigation aid.

From http://www.selex-es.com/-/gabbiano-1, Gabbiano fact sheet

SAR & ISAR modes



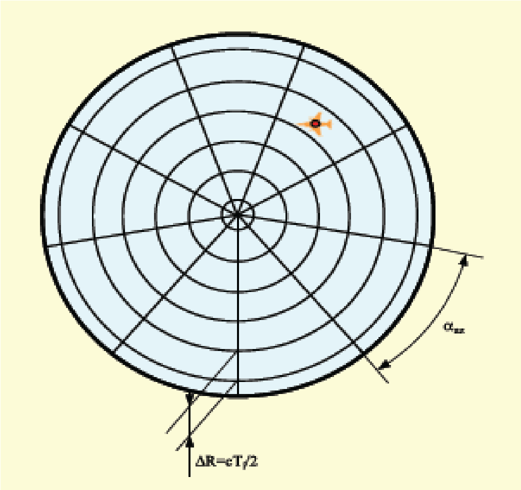


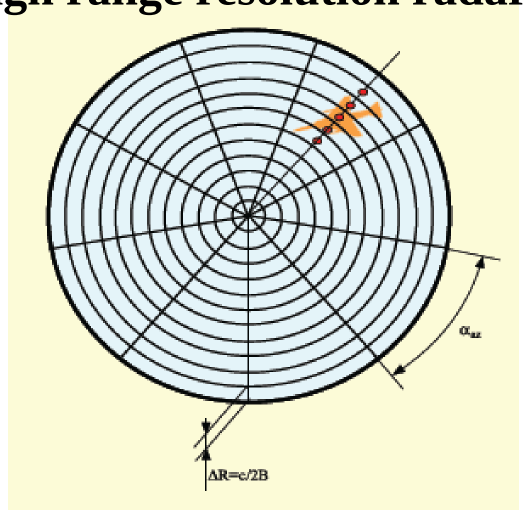
From http://www.selex-es.com/-/gabbiano-1, Gabbiano fact sheet

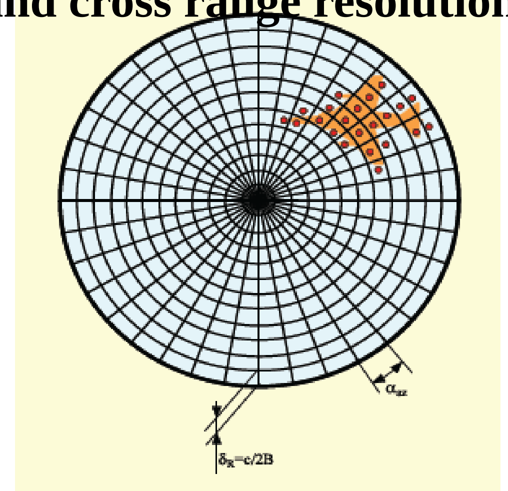
More examples available at http://infocom.uniroma1.it/rrsn/wiki/Main/ElaborazioneDelleImmaginiRadar
Slides from the talk «***Selex-ES Airborne Radar High Resolution Imaging***»

High resolution radar

Low resolution radar | **High range resolution radar** | **Imaging radar: high range and cross range resolution**







- ❑ High range resolution is achievable by transmitting wideband signals:

$$\delta_R = \frac{c}{2}\tau_c = \frac{c}{2B}$$

- ❑ High cross-range resolution is achievable by means of antennas with wide apertures: the cross-range resolution on the scene/target depends on its distance from the radar

$$\psi_a \cong \frac{\lambda}{d_a} \qquad \delta_{CR} = \psi_a R = \frac{\lambda}{d_a} R$$

- ❑ Images of scenes/targets at long distances are formed with poor resolution unless very large antennnas are employed

Doppler frequency

• Transmitted signal: pulse with length τ_p and carrier frequency f_c

$$s_{tx}(t) = rect_{\tau_p}(t) \cdot \cos(2\pi f_c t)$$

• Echo back-scattered from a target in case of relative motion between the radar antenna and the target (not considering the scale factor taking into account the attenuation between tx and rx)

$$s_{rx}(t) = s_{rx}\left(t - \frac{2R}{c}\right) = rect_{\tau_p}\left(t - \frac{2R}{c}\right) \cdot \cos\left[2\pi f_c\left(t - \frac{2R}{c}\right)\right] =$$

$$= rect_{\tau_p}\left(t - \frac{2R_0}{c}\right) \cdot \cos\left[2\pi f_c\left(t - \frac{2(R_0 + \dot{R}t)}{c}\right)\right] = rect_{\tau_p}\left(t - \frac{2R_0}{c}\right) \cdot \cos\left[2\pi\left(f_c - \frac{2\dot{R}}{\lambda}\right)t - \frac{4\pi}{\lambda}R_0\right]$$

R_0: radar-target distance at time t=0;

$\dot{R}$: target radial velocity.

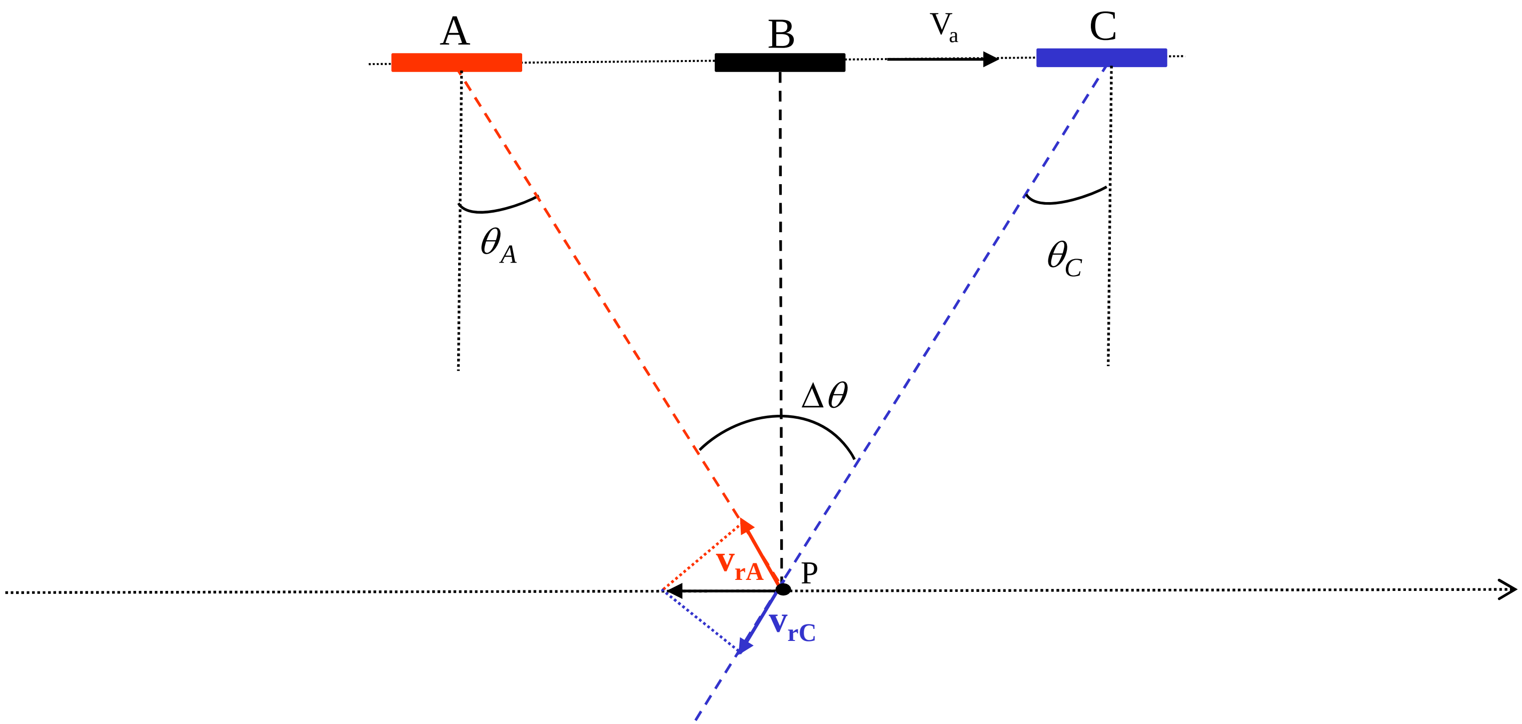
• The echo back-scattered from the target is shift in frequency with respect to the transmitted frequency of a quantity

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

DOPPLER Frequency

SAR- Synthetic Aperture Radar: azimuth resolution is obtained by exploiting the Doppler frequency induced by the relative motion.

Frequency approach to SAR (1/3)



$v_{rA} = V_a \sin(\theta_A) = v_{rMAX}$

$v_{rB} = 0$

$v_{rC} = -V_a \sin(\theta_C) = v_{rMIN}$

Position A

antenna is approaching ⇒ maximum radial velocity

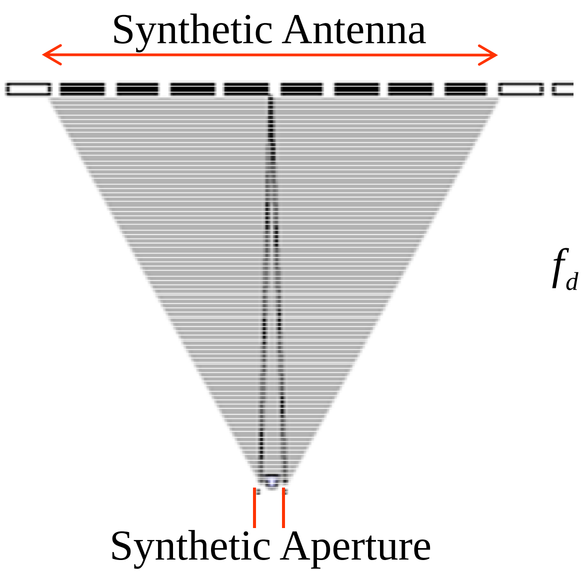
Position B

antenna at the closest approach ⇒ null radial velocity

Position C

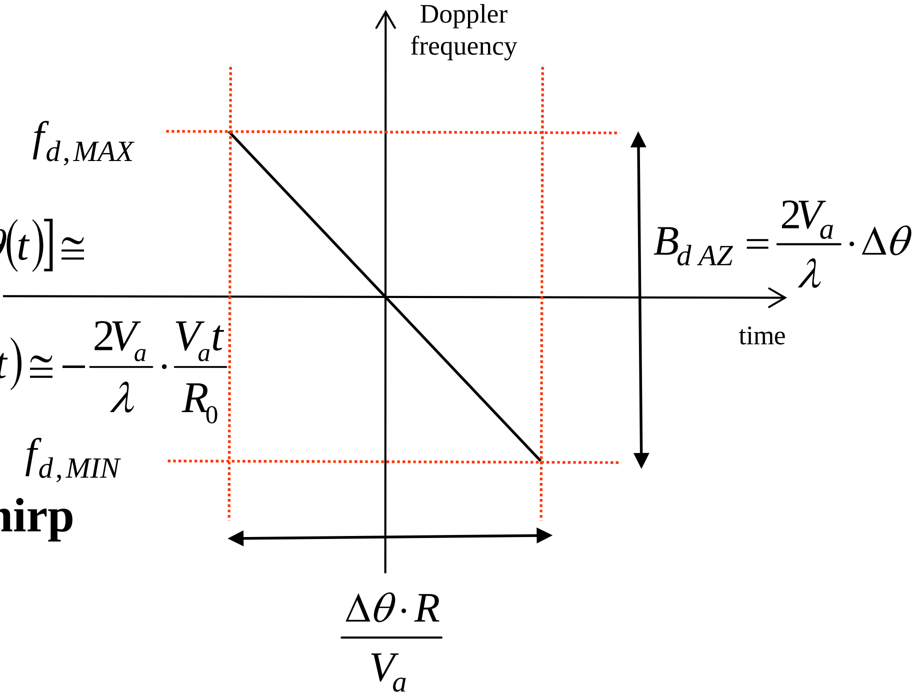
antenna is leaving ⇒ minimum radial velocity

Frequency approach to SAR (2/3)



$$f_d(t) = -\frac{2V_a}{\lambda}\sin[\theta(t)] \cong$$

$$\cong -\frac{2V_a}{\lambda}\cdot\theta(t) \cong -\frac{2V_a}{\lambda}\cdot\frac{V_a t}{R_0}$$



Doppler chirp

$$f_{d,MAX} = \frac{2V_a}{\lambda}\sin(\theta_A) \cong \frac{2V_a}{\lambda}\cdot\theta_A$$

$$f_{d,MIN} = -\frac{2V_a}{\lambda}\sin(\theta_C) \cong -\frac{2V_a}{\lambda}\cdot\theta_C$$

Doppler frequency bandwidth

$$B_{d\,AZ} = f_{d,MAX} - f_{d,MIN} = \frac{2V_a}{\lambda}\cdot(\theta_A + \theta_C) = \frac{2V_a}{\lambda}\cdot\Delta\theta$$

Frequency approach to SAR (3/3)

- Signal as a function of the azimuth time (slow-time) with frequency bandwidth:

$$B_{d\,AZ} = \frac{2V_a}{\lambda}\Delta\theta$$

- After pulse compression the resolution is azimuth time is given by:

$$\delta t_a = \frac{1}{B_{d\,AZ}} = \frac{\lambda}{2V_a\Delta\theta}$$

- The relationship between azimuth space and azimuth time is given by the platform velocity:

$$x_a = V_a t_a$$

- Azimuth spatial resolution after azimuth chirp compression:

$$\delta x_a = V_a \delta t_a = \frac{V_a}{B_{d\,AZ}} = \frac{\lambda}{2\Delta\theta}$$

In general azimuth resolution depends on the overall observation angle $\Delta\theta$

ISAR image formation (1/2)

GOAL: formation of high resolution 2D images of man-made targets (ground, air and ship targets, usually non-cooperative) to feed ATR (Automatic Target Recognition) procedures.

⇓

ISAR techniques

- ❑ wide bandwidth is transmitted to achieve fine range resolution;
- ❑ coherently processing the echoes returned from the target at different aspect angles gives fine cross-range resolution.

- **Target model**: rigid body with dominant scatterers with constant complex reflectivity;
- **Target motion**: decomposed as the translation of a reference point and the rotation of the rigid body around the reference

1. **Translation** ⇒ to be compensated: <u>Motion compensation</u> techniques for ISAR;
2. **Rotation** ⇒ to be exploited: <u>ISAR image formation techniques</u>.

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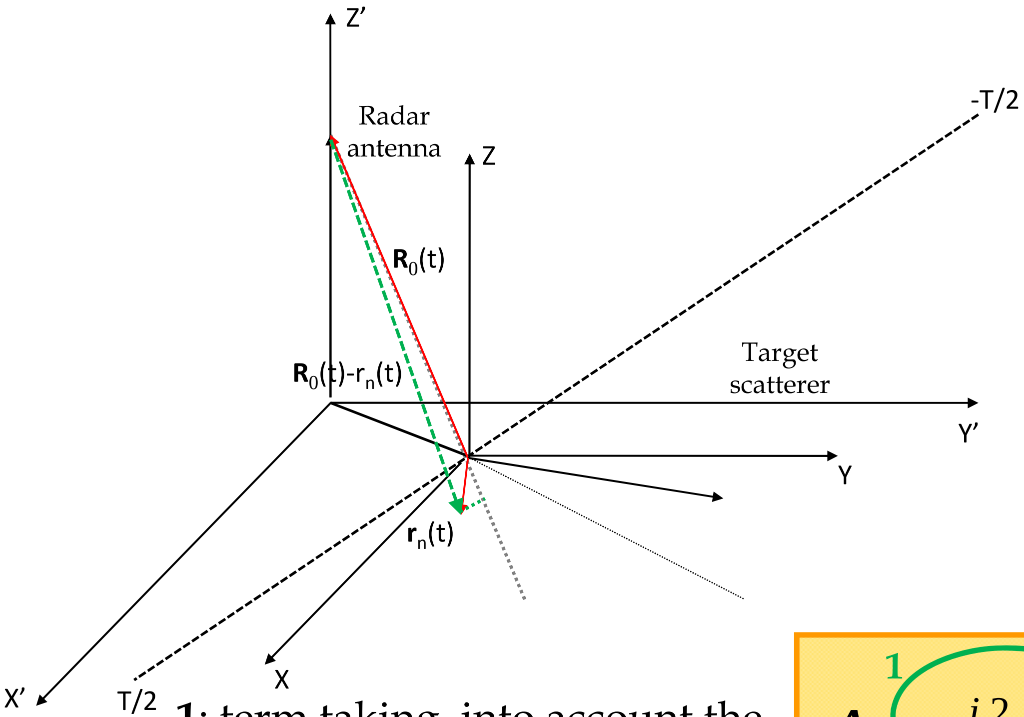
MAIN PROBLEM: target motion is unknown and needs to be estimated directly from the acquired radar signal.

ISAR image formation (2/2)



- Transmitting at frequency $f_0 = c/\lambda$ the radar echo from the n-th scatterer (0-th scatterer as the reference point)

$$A_n e^{j2\pi f_0 \left(t - \frac{2|\mathbf{R}_0(t) - \mathbf{r}_n(t)|}{c}\right)}$$

- In the hypothesis distance radar-target much larger than target size, i.e. $|\mathbf{R}_0(t)| >> |\mathbf{r}_n(t)|$

$$\left|\mathbf{R}_0(t) - \mathbf{r}_n(t)\right| \approx \left|\mathbf{R}_0(t)\right| - \hat{\mathbf{r}}_0(t) \cdot \mathbf{r}_n(t)$$

$$A_n \underbrace{e^{j2\pi f_0 t}}_{1} \underbrace{e^{-j\frac{4\pi}{\lambda}|\mathbf{R}_0(t)|}}_{2} \underbrace{e^{j\frac{4\pi}{\lambda}\hat{\mathbf{r}}_o(t) \cdot \mathbf{r}_n(t)}}_{3}$$

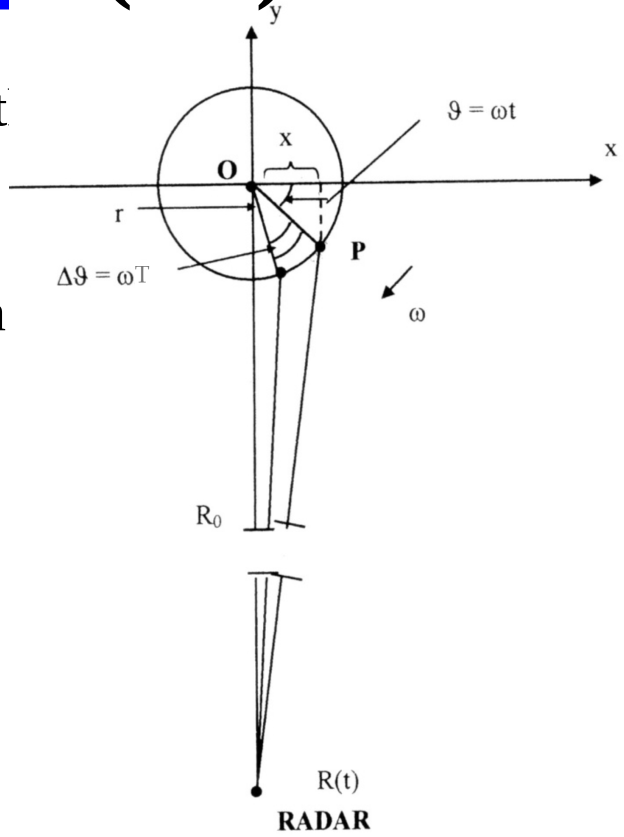
1: term taking into account the carrier frequency: common to all the scatterers.

2: phase of the reference point taking into account the translational motion: common to all the scatterers → to be compensated.

3: term taking into account the rotational motion: different for every scatterer → to be exploited.

Frequency approach to ISAR (1/2)

- Point scatterer P rotates around the fulcrum O wit angular velocity ω
- The distance of the radar from the fulcrum in much higher than the distance of the point P from the fulcrum



⬇

$$\left|\mathbf{R}_0(t)-\mathbf{r}_P(t)\right| \approx \left|\mathbf{R}_0(t)\right| - \hat{\mathbf{r}}_0(t)\cdot\mathbf{r}_P(t) = R_0 - r\sin(\theta_0+\omega t)$$

⬇

- Point scatterer P is interested by a Doppler frequency given by:

⬇

$$f_d(t) = -\frac{2}{\lambda}\frac{d}{dt}\left[R_0 - r\sin(\theta_0+\omega t)\right] = \frac{2\omega}{\lambda} r\cos(\theta_0+\omega t) = \frac{2\omega}{\lambda}x(t)$$

Frequency approach to ISAR (2/2)

- In the observation time T centered around t=0 the scatterer Doppler frequency can be expressed as:

$$f_d(t) = \frac{2\omega}{\lambda} x(t) \approx \frac{2\omega}{\lambda} \left[r\cos(\theta_0) + \omega r \sin(\theta_0) t + \ldots \right] = \frac{2\omega}{\lambda} x_0 + \frac{2\omega^2}{\lambda} y_0 t + \ldots$$

- Depending on target size (i.e. r) and processed time the scatterer Doppler frequency can be assumed constant during time aperture (i.e. first order term negligible $\Rightarrow$ as unfocused SAR) or linearly varying with time t (i.e. first order term not negligible $\Rightarrow$ as focused SAR);
- Two scatterers P^1-P^2 located at x_0^1-x_0^2 will show Doppler frequencies

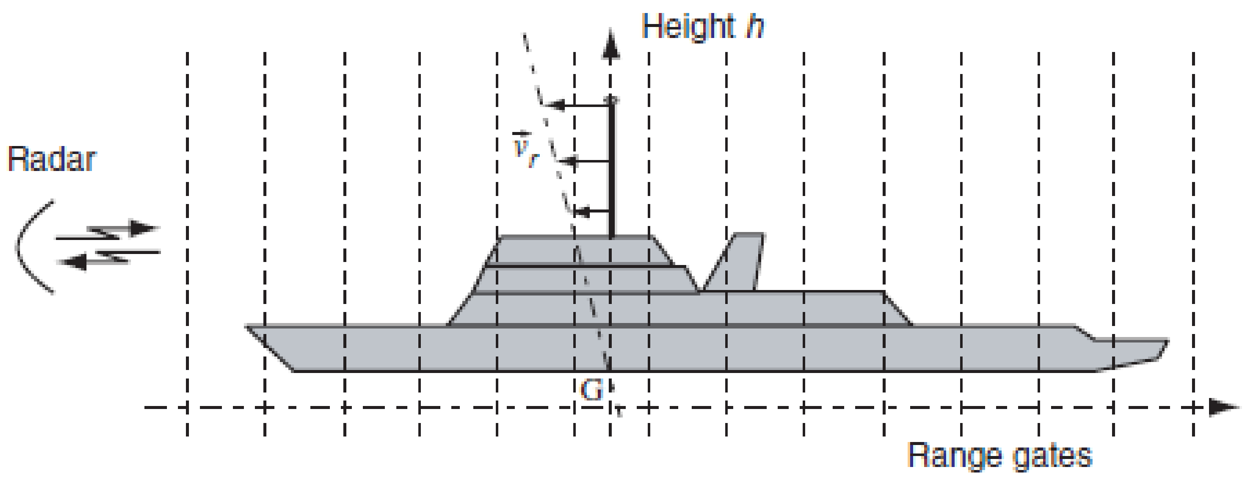
$$f_d^1 = \frac{2\omega}{\lambda} x_0^1 \quad \& \quad f_d^2 = \frac{2\omega}{\lambda} x_0^2$$

- Filter bank (FFT) with resolution $\Delta f_d = \frac{1}{T}$ to obtain the cross range resolution

$$\Delta x = \frac{\lambda}{2\omega} \Delta f_d = \frac{\lambda}{2\omega T} = \frac{\lambda}{2\Delta\theta}$$

- ❑ Achievable resolution depends on target motion and observation time;
- ❑ Image scaling (Hz → m) requires the knowledge of the target rotation rate.

Frequency approach to ISAR (2/2)



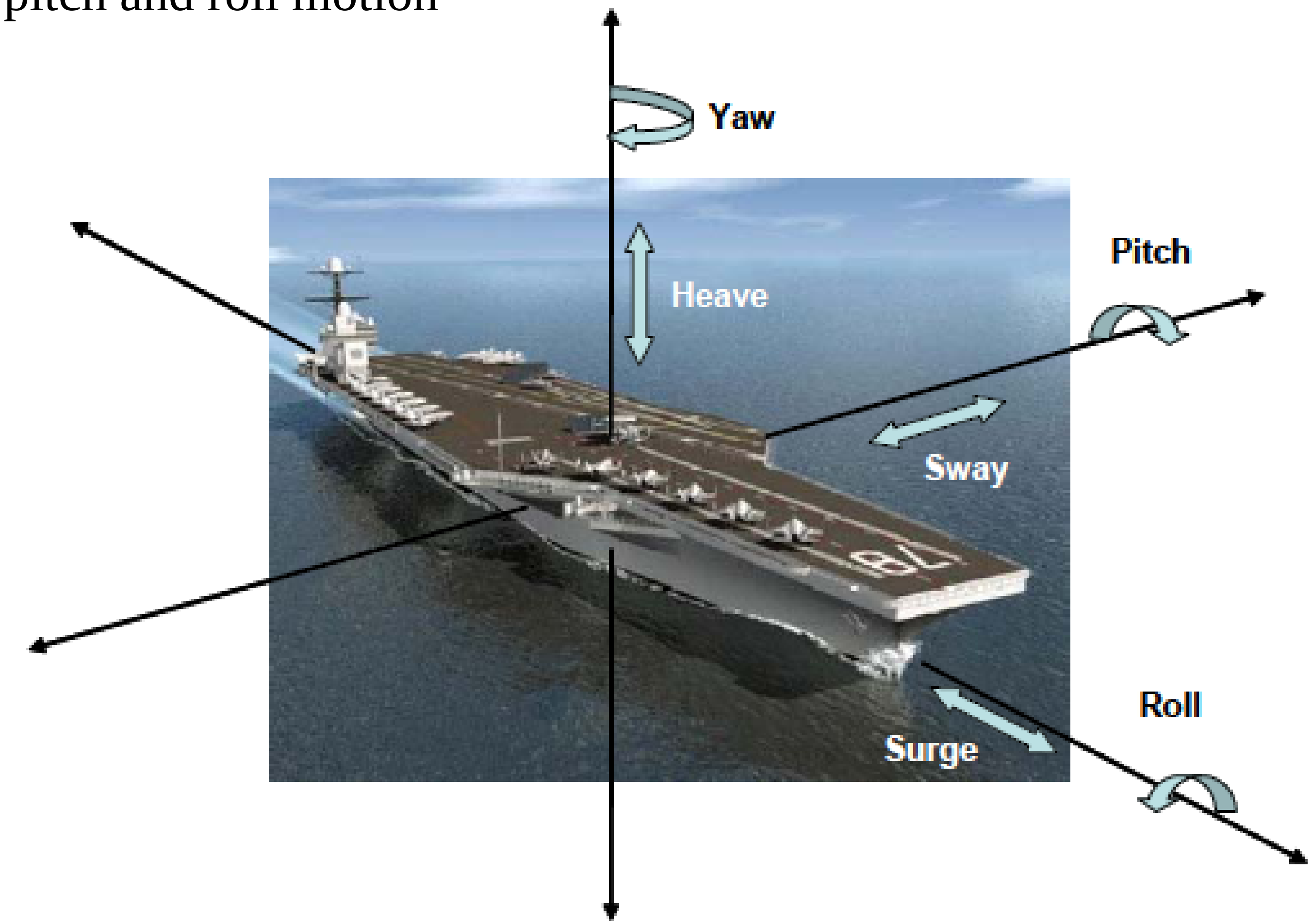
For example by analyzing the Doppler frequency of signals received in one range gate, it is possible to measure the height of the target reflectors relative to the center of rotation. Two possibilities:

• Rotation speed known: the height measurement is an absolute measurement

• Rotation speed is unknown: the measurement is relative. The scale factor along the height axis remains undetermined in the case of observation of an uncooperative target, and must be estimated from the data.

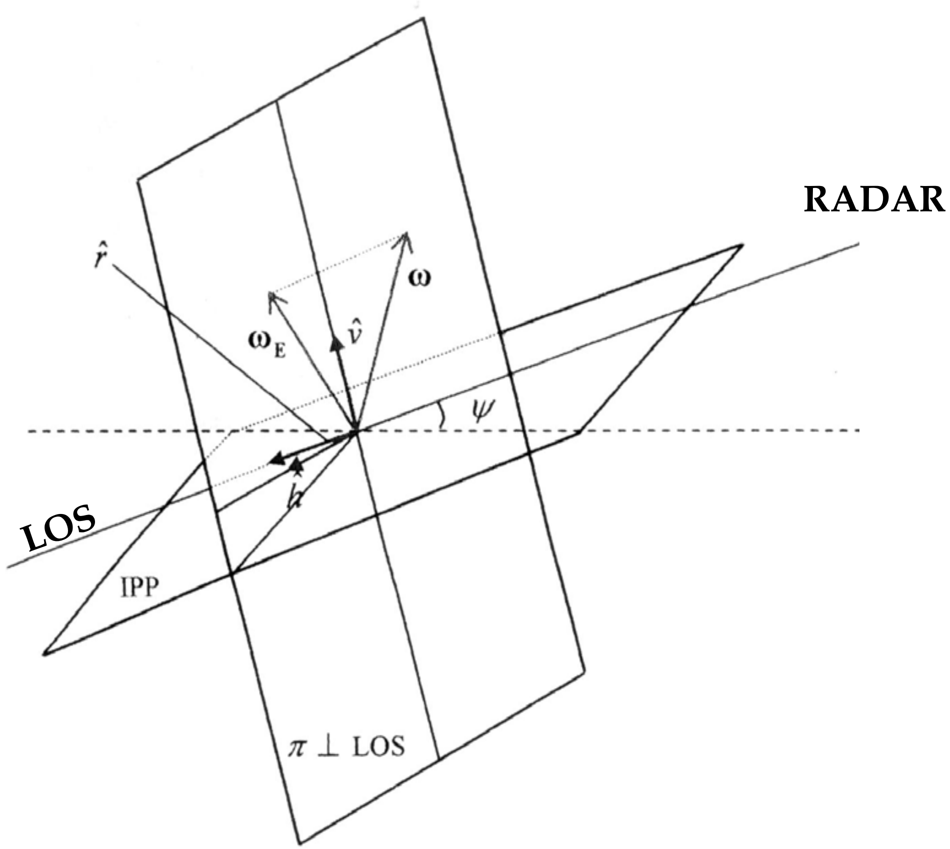
ISAR: Image Projection Plane (1/4)

- Target with a complex motion: the actual rotation vector ω accounts for the yaw, pitch and roll motion

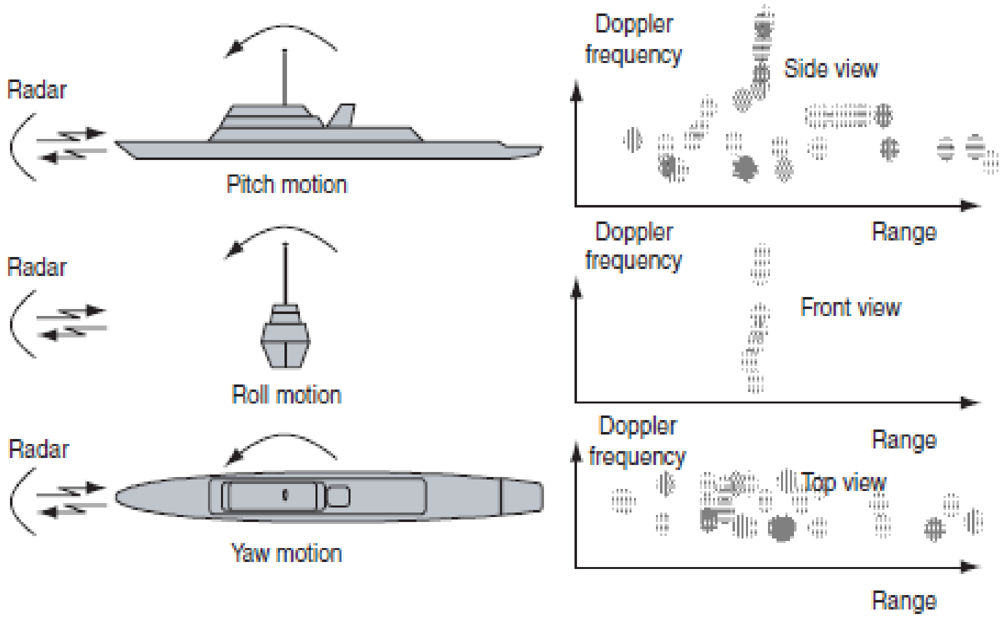


ISAR: Image Projection Plane (2/4)

- The effective rotation vector $\boldsymbol{\omega}_E$ is the projection of $\boldsymbol{\omega}$ orthogonal to the Line of Sight (LOS)
- The image plane is the slant range/doppler frequency plane, containing the LOS and orthogonal to $\boldsymbol{\omega}_E$ → Image Projection Plane (IPP)

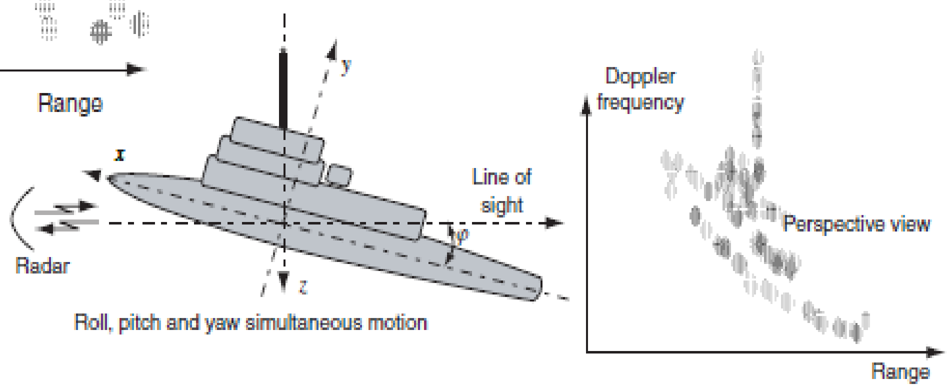


ISAR: Image Projection Plane (3/4)



Projection Plane in Relation to the Rotation Axis of the Target and the Direction of Observation

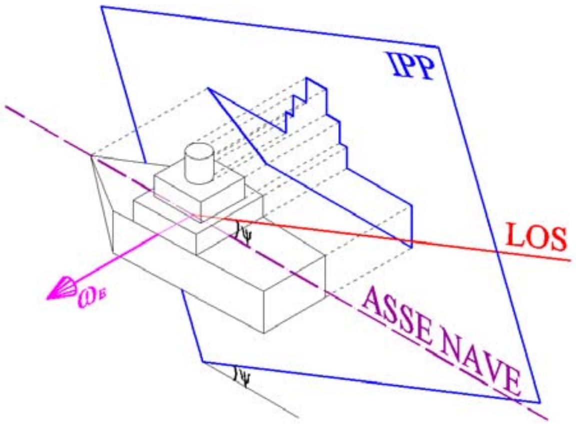
Projection Plane: General Case

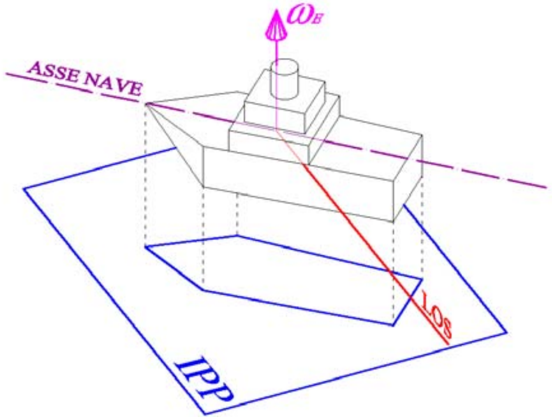


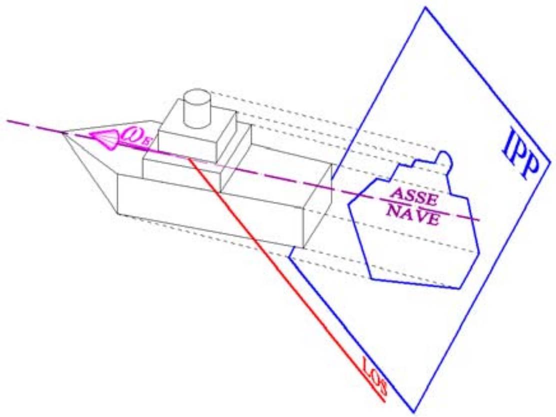
Different ISAR projections with the same acquisition geometry ⇒ characteristics highly suitable for classification & recognition purposes

ISAR: Image Projection Plane (4/4)

Horizontal rotation component ω_h	Vertical rotation component ω_v	Horizontal&vertical rotation components
⇓	⇓	⇓
Side-view image	**Top-view image**	**Mixed (top&side) image**







Radar image focusing (SAR&ISAR)

The variation of the distance radar antenna-imaged scatterer with slow-time t_a (i.e. transmitted pulse) affects

- **delay of the echo:** $R(t_a)-R_0$ comparable with range resolution ⇒ Range Cell Migration (RCM): undesired effect to be compensated before azimuth processing;
- **phase of the echo:** $R(t_a)-R_0$ comparable with wavelength ⇒ Doppler (Azimuth) Chirp: desired effect to be exploited to achieve fine azimuth resolution

Observation: <u>focusing requires the knowledge of the acquisition geometry</u> (relative motion between antenna and imaged scene: known for SAR and a priori unknown for ISAR)

Focusing scheme of principle