



Synthetic Aperture Radar (SAR) Imaging Formation Fundamentals

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ESA–MOST China Dragon 4 Cooperation

2019 ADVANCED INTERNATIONAL TRAINING COURSE IN LAND REMOTE SENSING

中欧科技合作“龙计划”第四期 **2019年陆地遥感高级培训班**





合成孔径雷达
Synthetic Aperture Radar (SAR)





Earth Observation Systems

Optical & Microwave

Microwave Imaging

- * Imagery
- * 300MHz-300GHz

Synthetic Aperture Radar (SAR)

RADARSAT-1 FINE mode
Vancouver 8m / 45Km

Active

- + Day-and-Night, All-weather
- Signal Proc., Image Interpretation

1951	Carl Wiley	SAR Concept		
1957	Willow Run (ERIM)	1st fully focused SAR image		
1978	NASA	SEASAT-A	2D res.	↓
1990s	ESA	ERS-1		
	NASDA	JERS-1		
	CSA	RadarSat-1		
1996		EUSAR		
2000~	NASA/DLR/ASI	SRTM	DEM	↓
	ESA	ENVISAT-1/ASAR		
2006		CRS-1		
2007~	JAXA	ALOS/PALSAR	Scat. Class.	↓
	OHB	SAR-LUPE		
	CSA	RadarSat-2		
	DLR/ASTRIUM	TerraSAR-X / Tandem-X		
	ESA	BiomassSAR	Para. Retr.	↓

SAR	Band	Resolution	Swathwidth	Year
ERS-1	C	25m	100km	1991
JERS-1				1992
ERS-2	C	25m	100km	1995
RadarSAT-1	C	10m-100m	50km-500km	1995
EnviSAT/ASAR	C	25m-1km	100-400km	2002
ALOS-1/PALSAR	L	10m-100m	70km-360km	2006
ALOS-2				2014
CRS-1	L			2006
TerraSAR-X	X	1m-16m	10km-100km	2007
TanDEM-X	X/2			2010
COSMO/Skymed	X/4	1m-100m	11km-200km	2007-
RadarSAT-2	C	3m-100m	10km-500km	2007
RadarSAT-2 Constellation	C/3			2019
HJ-1-C	S	5m-20m	40km-100km	2012
Sentinal-1a	C	5m-100m	80km-400km	2014
GF-3	C	1m-500m	10km-650km	2016
Sentinal-3b	C	5m-100m	20km-400km	2018



Texture



@ open source



Geometry



@ TerraSAR-X/DLR

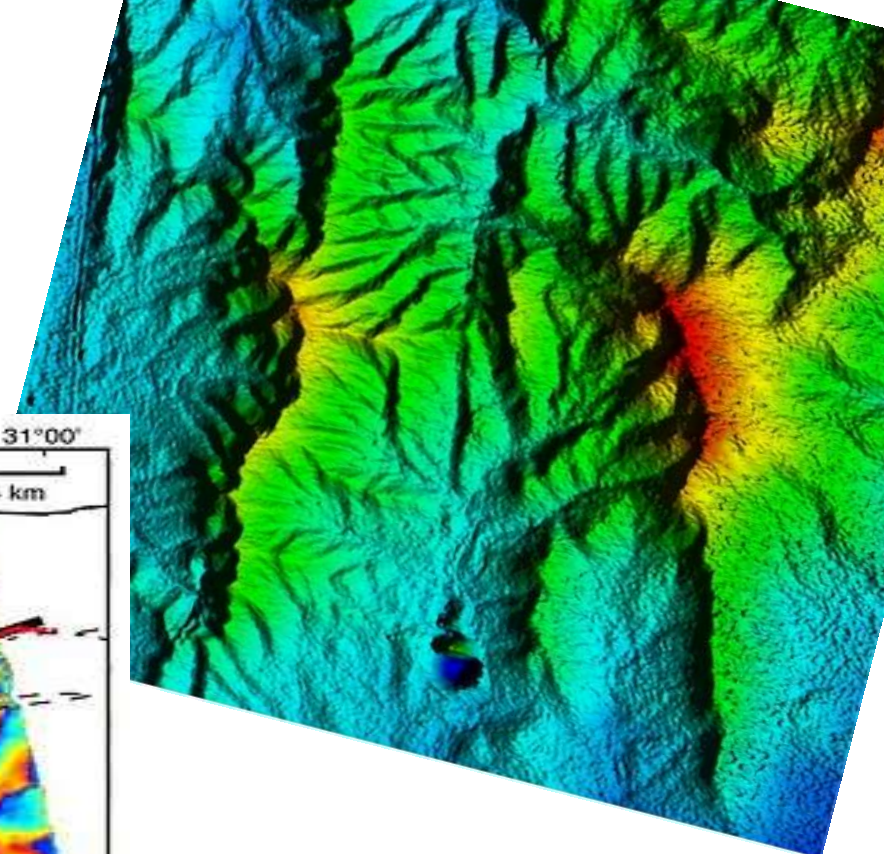
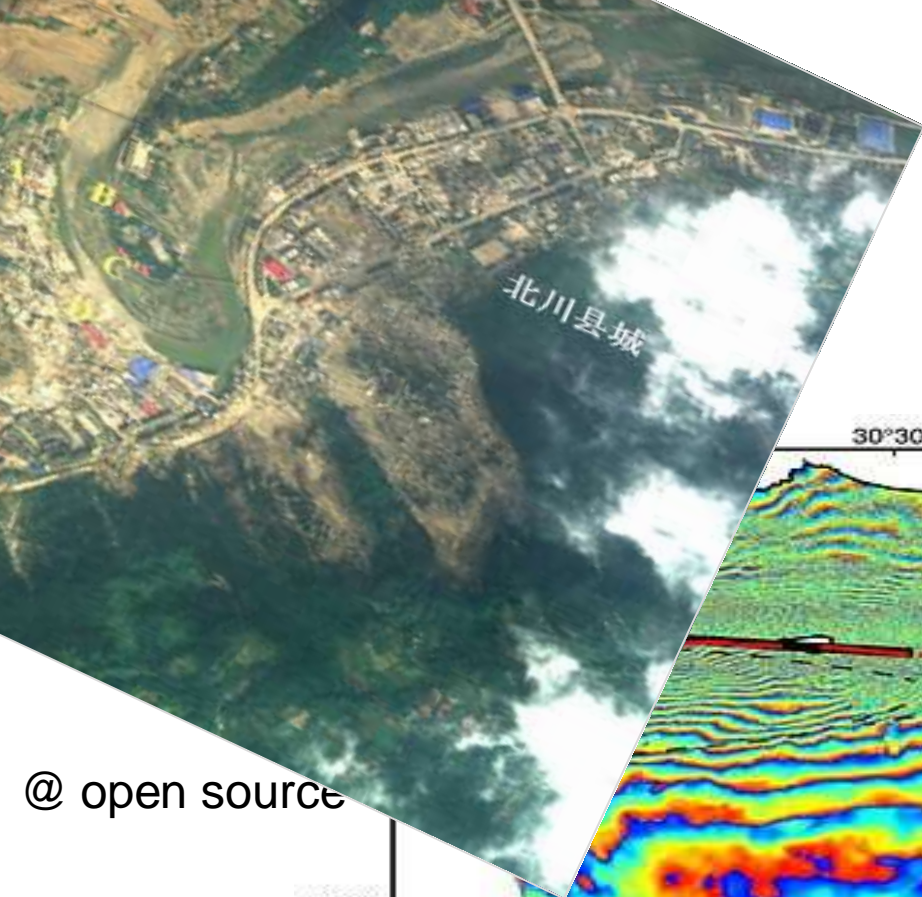


EM Scattering

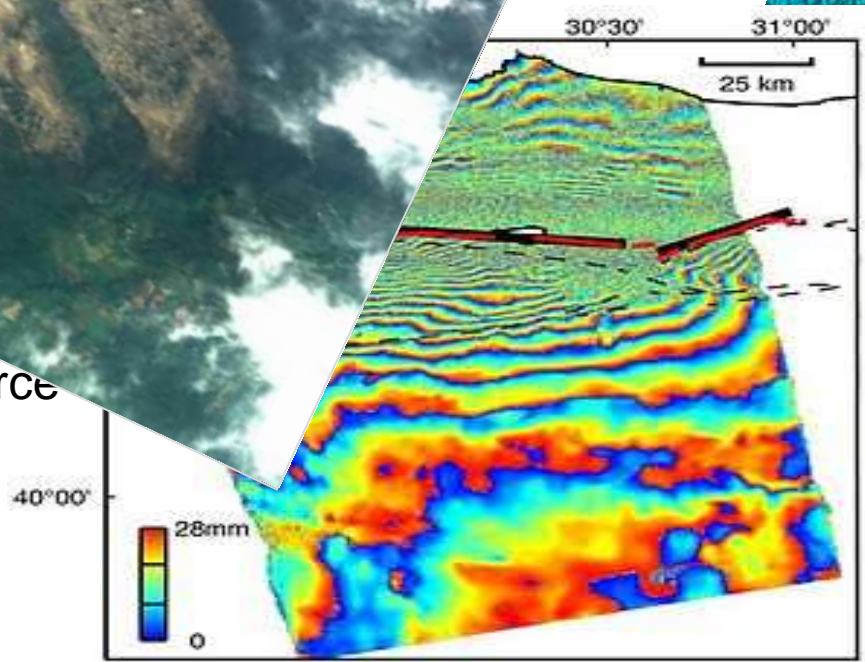


@ FSAR/DLR

@ PolSARPro

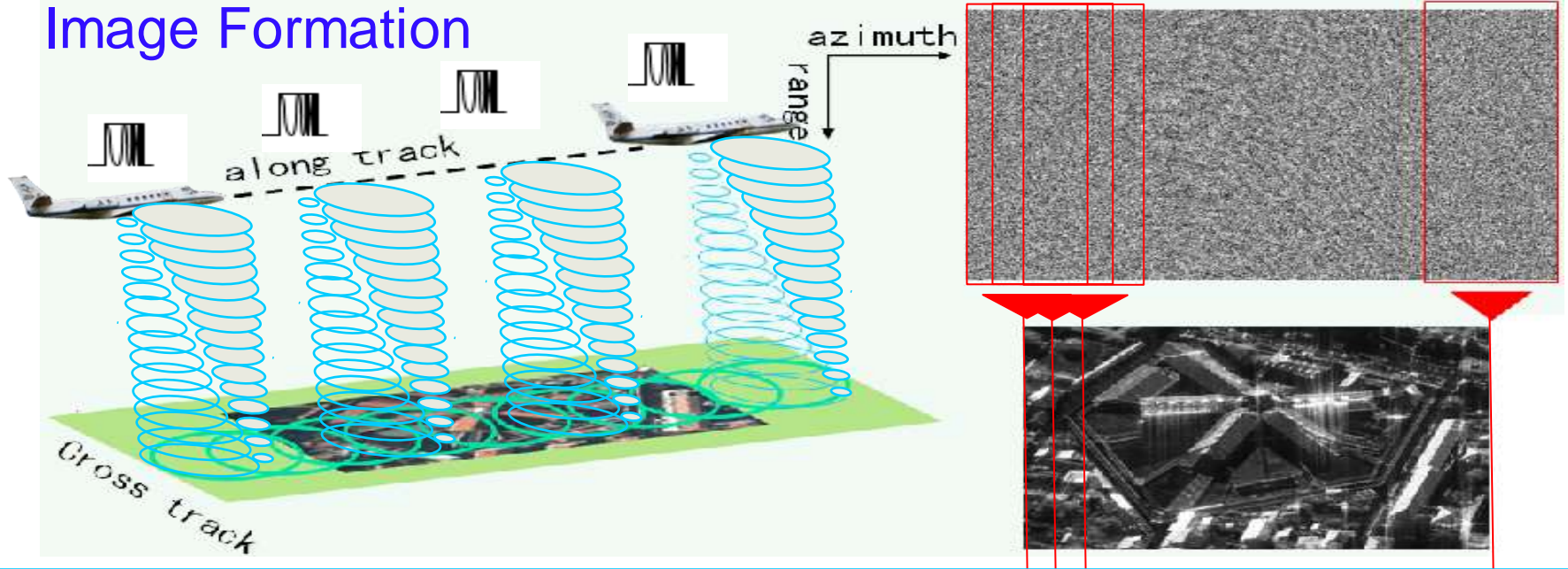


@ open source



Coherence
ie Interferometry, deformation

Image Formation



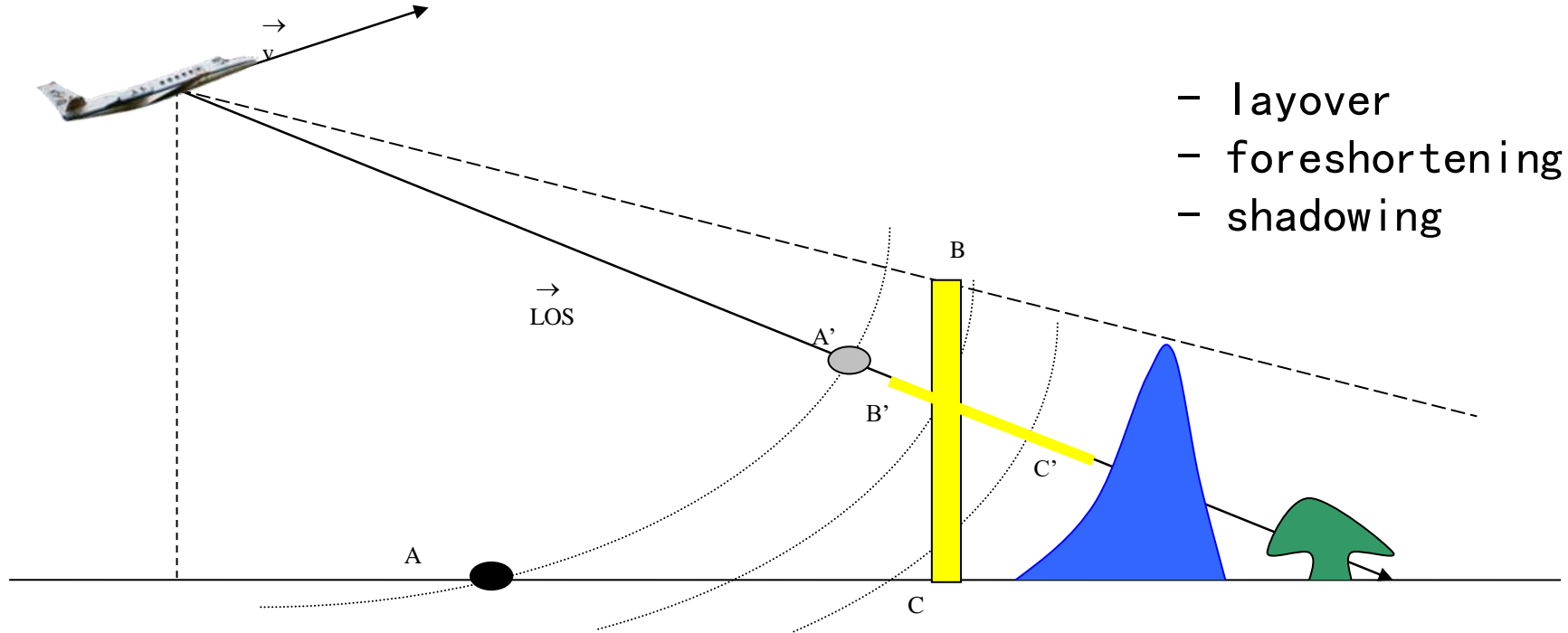
1 Data Acquisition :

Flight Path , EM T/R , Coherent accumulation in Synthetic Aperture or Time

2 Signal Processing :

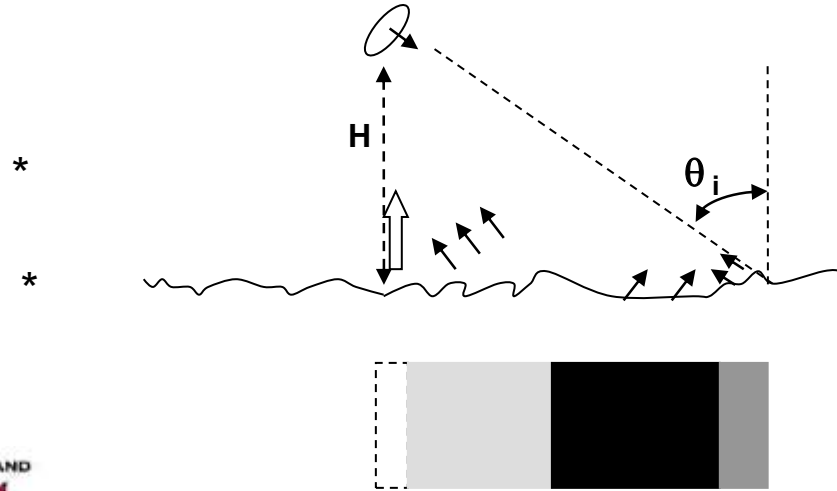
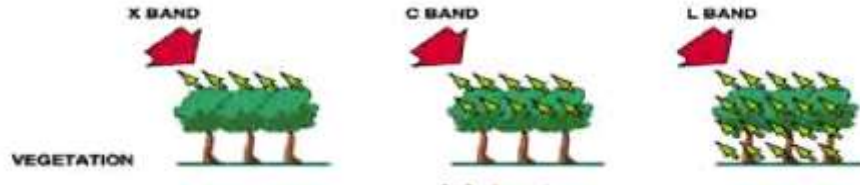
two-dimensional de-convolution by matched-filtering technique

Geometry



Data Acquisition - RCS

- shape
- material
- surface roughness
- dielectric constant
- incidence angle
- frequency
- polarimetry...



@PoISARPro

Imagery

- shape
- material
- surface rough.
- dielectric const
- incidence angle
- frequency
- polaritry

Target

System



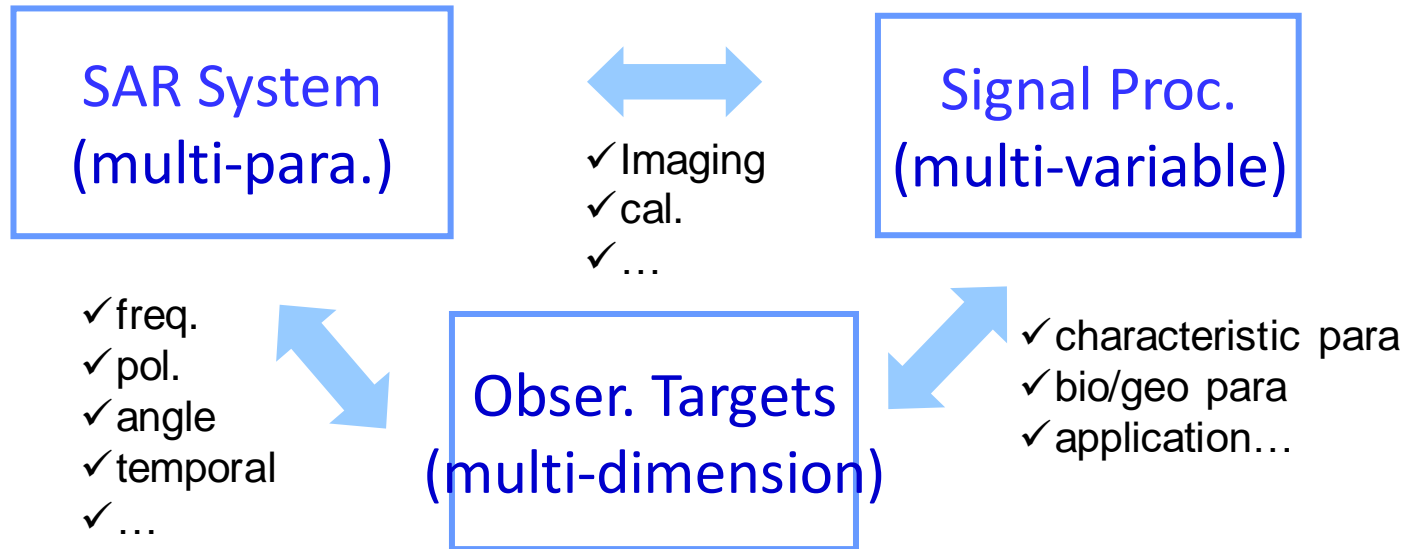
from visual interpretation to qualitative/quantitative parameter retrieval :
scattering mechanism, observation mode, signal processing, applications...



合成孔径雷达多维度观测
**Multidimensional Space Joint-observation
in Synthetic Aperture Radar (SAR)**



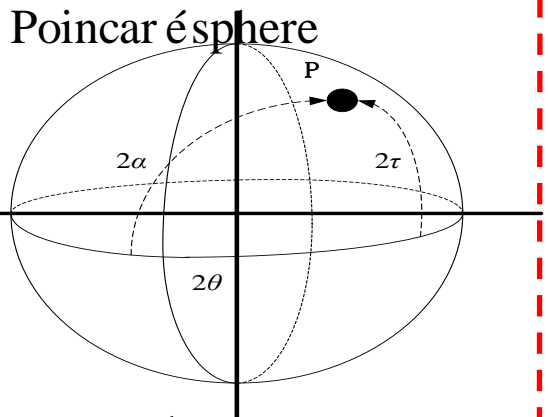
Multi-dimensional Space Joint-observation



Modeling Space

Pol.

Poincaré sphere



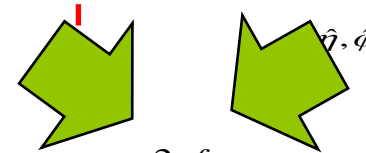
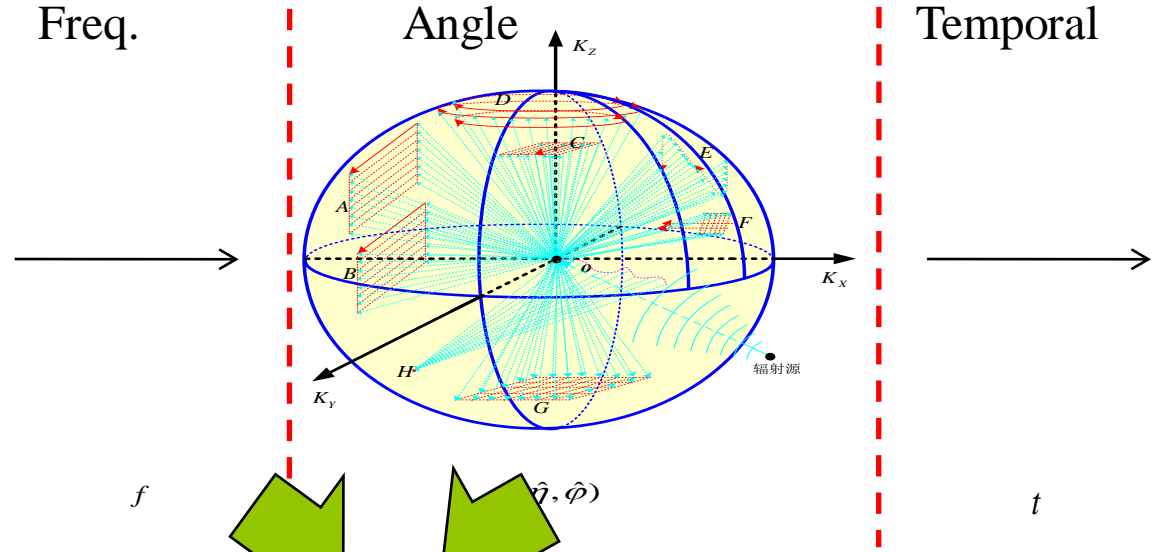
$$\hat{\mathbf{p}} = \frac{1}{\sqrt{2}} \begin{bmatrix} e^{j\delta_{\hat{m}}} & e^{j\delta_{\hat{m}_{\perp}}} \end{bmatrix}^T$$

$$\mathbf{E}_{(\hat{\mathbf{p}}, \hat{\mathbf{p}}_{\perp})} = \mathbf{U}_{2(\hat{\mathbf{m}}, \hat{\mathbf{m}}_{\perp}) \rightarrow (\hat{\mathbf{p}}, \hat{\mathbf{p}}_{\perp})} \mathbf{E}_{(\hat{\mathbf{m}}, \hat{\mathbf{m}}_{\perp})}$$

Freq.

Angle

Temporal

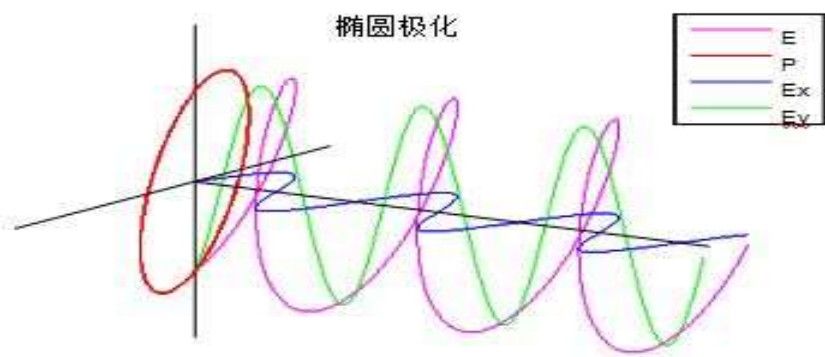
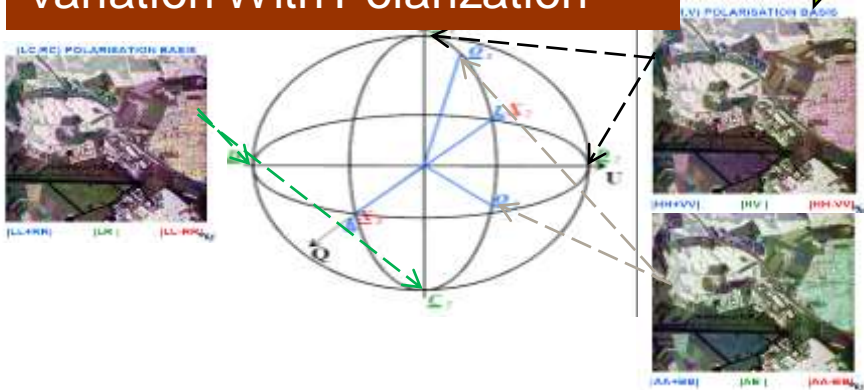


$$\mathbf{k} = \frac{2\pi f}{c} (\hat{\boldsymbol{\eta}}, \hat{\boldsymbol{\varphi}}) \quad \mathbf{k} \text{ 球, 3D 波束域}$$

Polarimetry

$$\Pi(h_v, \chi, \dots) = A^{-1}(\vec{\sigma}_0(\hat{p}, f, \hat{k}, t, r))$$

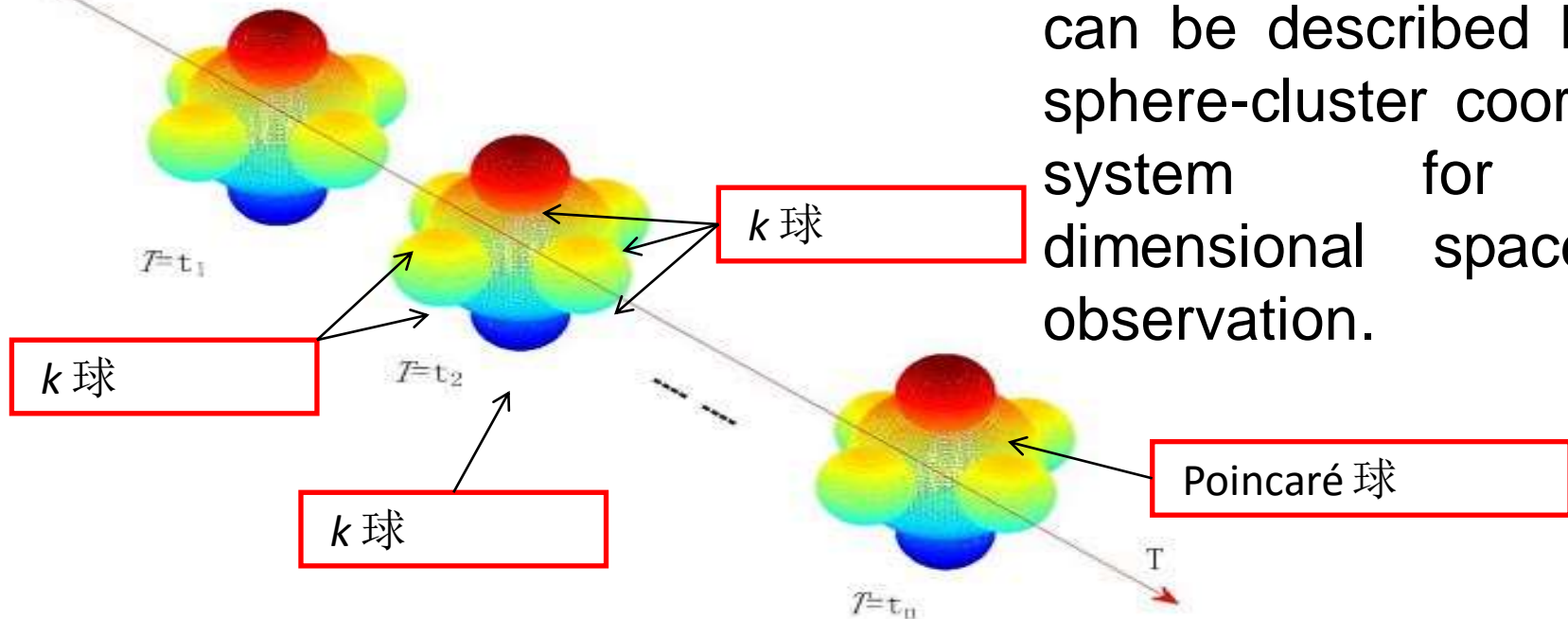
Interferometry Phase
Variation With Polarization
Frequency Response
Variation With Polarization



- perfect base
- coherent

Pol. ~ basic observation base

coordinate sys.



Scattering mechanism can be described by the sphere-cluster coordinate system for multi-dimensional space joint observation.

Signal modeling ~ monochromatic EM plane wave

$$\langle E(\hat{\mathbf{p}}_{i1}, f_{i2}, \hat{\mathbf{a}}_{i3}, t_{i4}) E^*(\hat{\mathbf{p}}_{j1}, f_{j2}, \hat{\mathbf{a}}_{j3}, t_{j4}) \rangle = \sum_{k=1}^K \alpha_k(\hat{\mathbf{p}}_{i1}, \hat{\mathbf{p}}_{j1}) \cdot \beta_k(f_{i2}, f_{j2}) \cdot \gamma_k(\hat{\mathbf{a}}_{i3}, \hat{\mathbf{a}}_{j3}) \cdot \delta_k(t_{i4}, t_{j4})$$

where

$$\alpha_k(\hat{\mathbf{p}}_{i1}, \hat{\mathbf{p}}_{j1}) = \langle E(\hat{\mathbf{p}}_{i1}, f_{i2}, \hat{\mathbf{a}}_{i3}, t_{i4}) E^*(\hat{\mathbf{p}}_{j1}, f_{j2}, \hat{\mathbf{a}}_{j3}, t_{j4}) \rangle \Big|_{f, \hat{\mathbf{a}}, t}$$

$$\beta_k(f_{i2}, f_{j2}) = \langle E(\hat{\mathbf{p}}_{i1}, f_{i2}, \hat{\mathbf{a}}_{i3}, t_{i4}) E^*(\hat{\mathbf{p}}_{j1}, f_{j2}, \hat{\mathbf{a}}_{j3}, t_{j4}) \rangle \Big|_{\hat{\mathbf{p}}, \hat{\mathbf{a}}, t}$$

$$\gamma_k(\hat{\mathbf{a}}_{i3}, \hat{\mathbf{a}}_{j3}) = \langle E(\hat{\mathbf{p}}_{i1}, f_{i2}, \hat{\mathbf{a}}_{i3}, t_{i4}) E^*(\hat{\mathbf{p}}_{j1}, f_{j2}, \hat{\mathbf{a}}_{j3}, t_{j4}) \rangle \Big|_{\hat{\mathbf{p}}, f, t}$$

$$\delta_k(t_{i4}, t_{j4}) = \langle E(\hat{\mathbf{p}}_{i1}, f_{i2}, \hat{\mathbf{a}}_{i3}, t_{i4}) E^*(\hat{\mathbf{p}}_{j1}, f_{j2}, \hat{\mathbf{a}}_{j3}, t_{j4}) \rangle \Big|_{\hat{\mathbf{p}}, f, \hat{\mathbf{a}}}$$



$$\begin{aligned} & \langle E(\hat{\mathbf{p}}_{i1}, f_{i2}, \hat{\mathbf{a}}_{i3}, t_{i4}) E^*(\hat{\mathbf{p}}_{j1}, f_{j2}, \hat{\mathbf{a}}_{j3}, t_{j4}) \rangle \\ &= \sum_{k=1}^K \alpha_k(\hat{\mathbf{p}}_{i1}, \hat{\mathbf{p}}_{j1}) \cdot \beta_k(f_{i2}, f_{j2}) \cdot \gamma_k(\hat{\mathbf{a}}_{i3}, \hat{\mathbf{a}}_{j3}) \cdot \delta_k(t_{i4}, t_{j4}) \end{aligned}$$

$$\Leftrightarrow \mathbf{W} = \langle \mathbf{E} \mathbf{E}^* \rangle = \sum_{k=1}^K \mathbf{P}_k \otimes \mathbf{F}_k \otimes \mathbf{A}_k \otimes \mathbf{T}_k$$

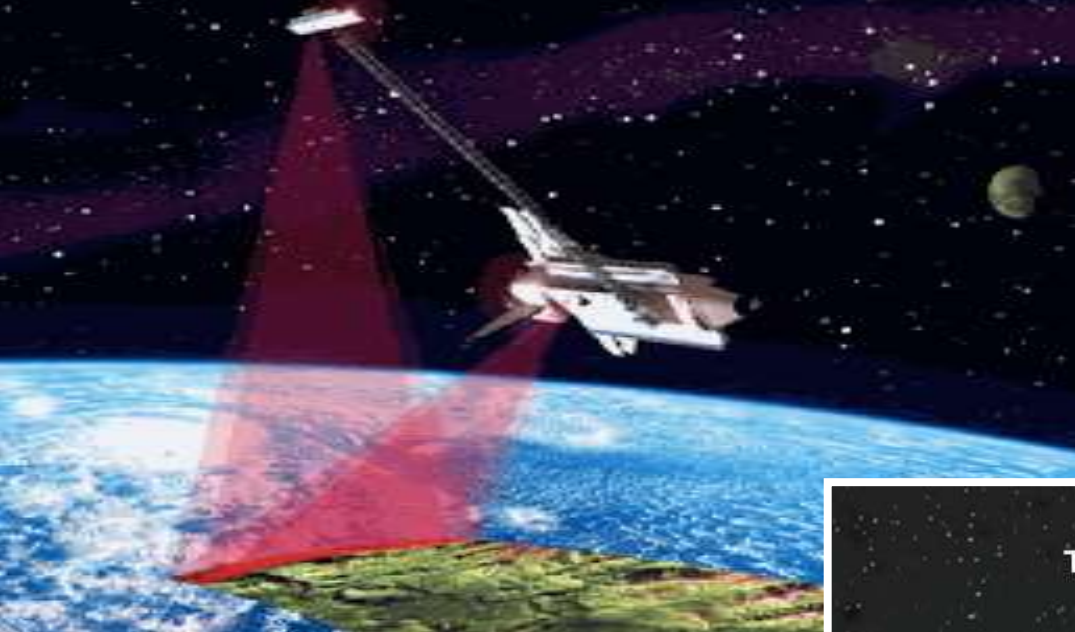
$\mathbf{P}_k, \mathbf{F}_k, \mathbf{A}_k, \mathbf{T}_k$: covariance matrix of k -th SM in polarizations $\hat{\mathbf{p}}_{i1}, \hat{\mathbf{p}}_{j1}$
 frequencies f_{i2}, f_{j2} , angles $\hat{\mathbf{a}}_{i3}, \hat{\mathbf{a}}_{j3}$, and times t_{i4}, t_{j4}

⊗ Kronecker Products



从干涉、极化到极化干涉
**Interferometric SAR(InSAR), polarimetric SAR(PoSAR),
and Polarimetric SAR Interferometry(PolInSAR)**





InSAR

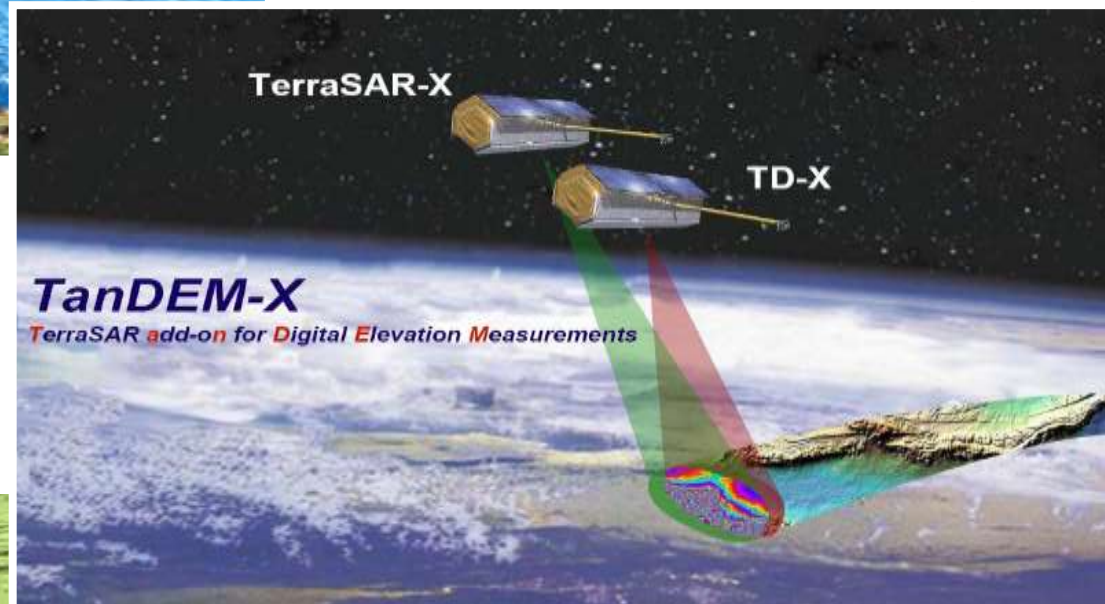
TanDEM-X:

BMBF/DLR/ASTRIUM

SRTM: NASA/DLR/ASI

X/C 2000

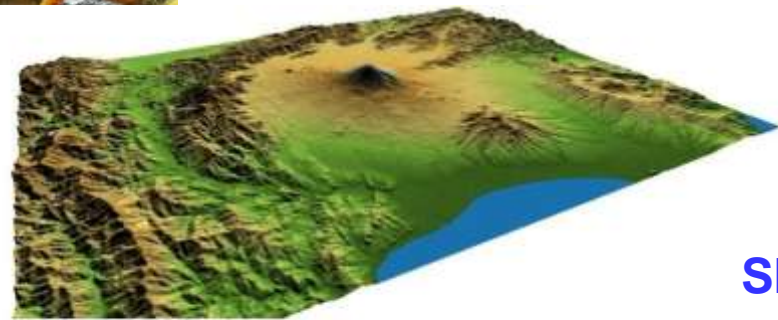
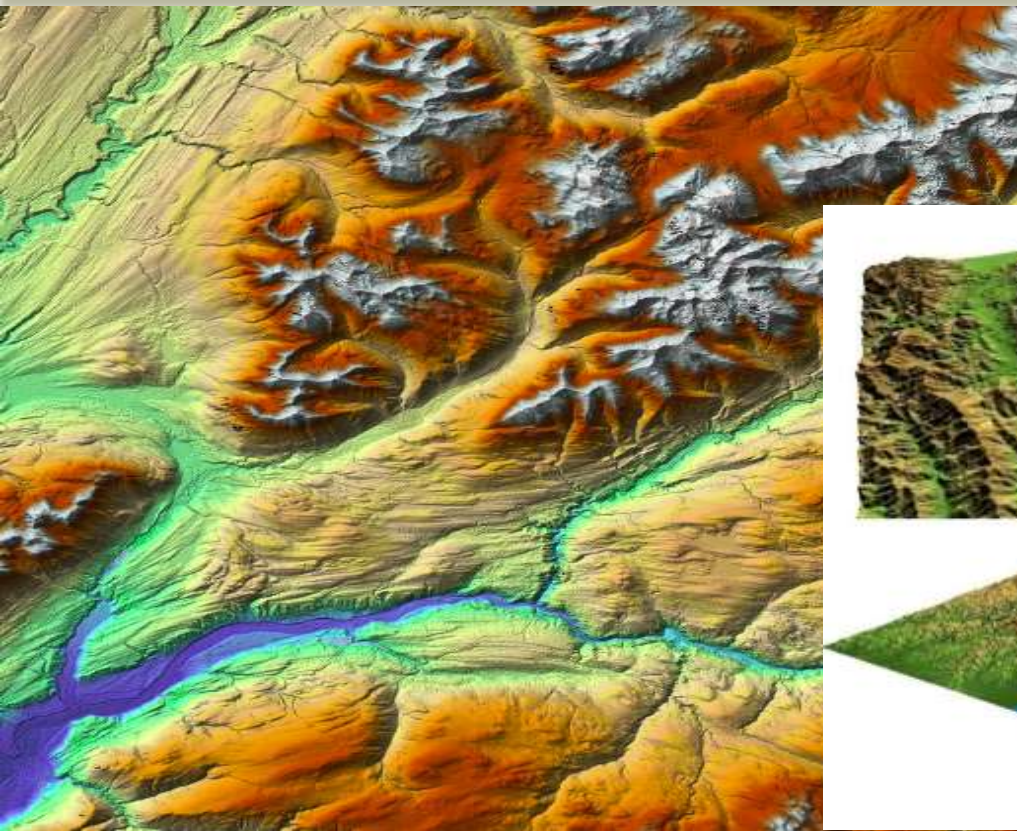
11days 80% 90/30m





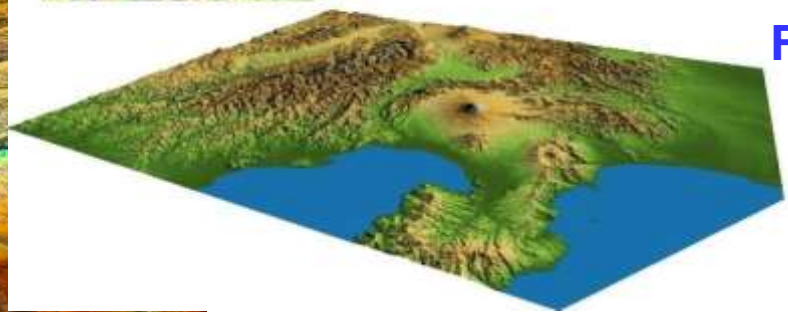
TanDEM-x 2010 InSAR

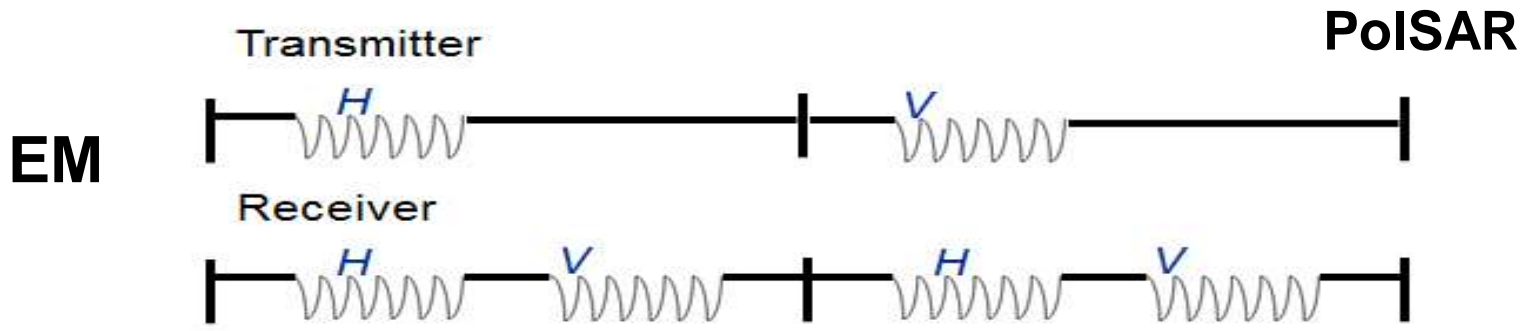
Alaska 2m



SRTM 2000

Fuji 90m





HH



HV



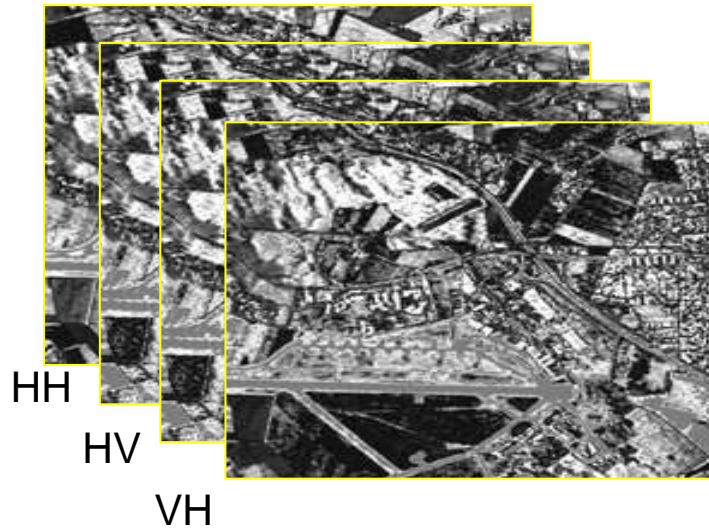
VH



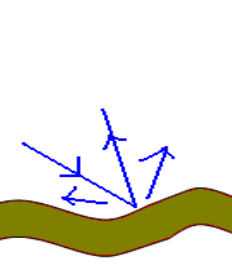
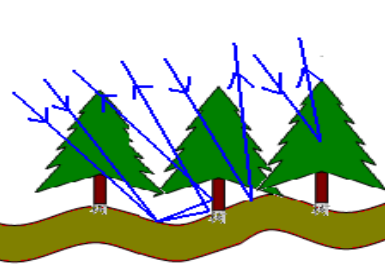
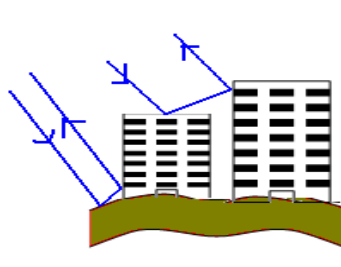
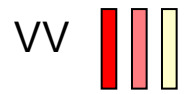
VV

@ESAR DLR





PoISAR



@ESAR DLR





PoISAR

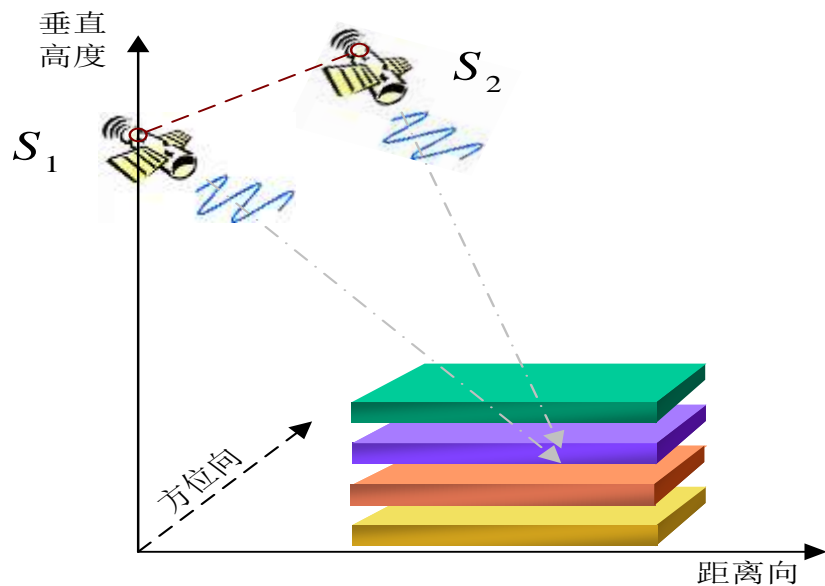
B: single scatter

R: double scatter

G: volume scatter

@PoISARpro

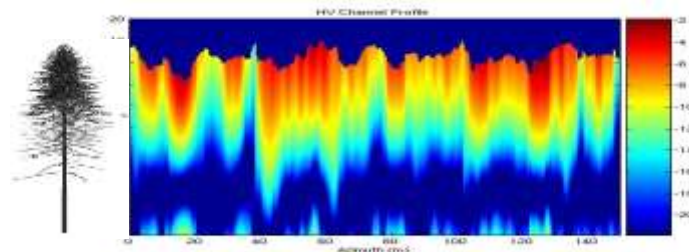
Pauli DeComp



PolInSAR

POLSAR , InSAR ~ POLInSAR

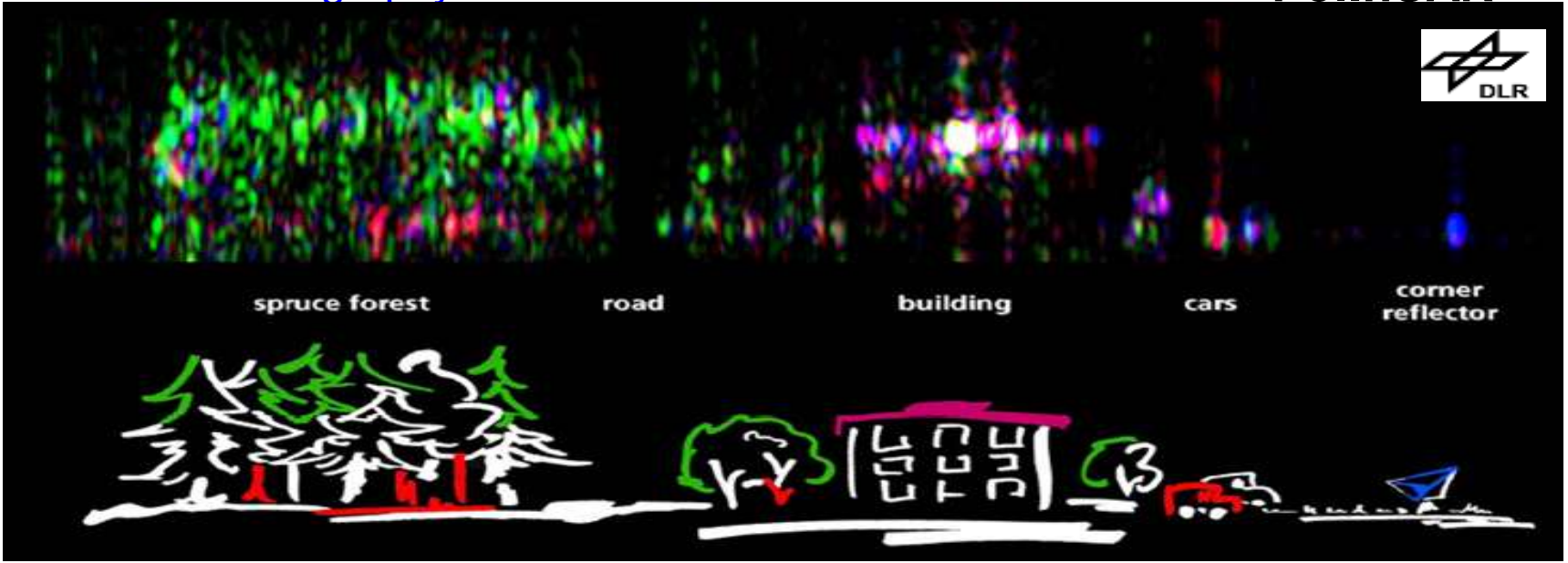
- interferometric accuracy from pol.
- new info. ~ scattering center distribution along height
- new appl.
~ profile ~ tree height,



@W. Boener, K. P. Papathanassiou, E. Pottier, S. R. Cloude, Yamaguchi ... etc.

POLSAR Tomography = Multi-Baseline POLInSAR

PolInSAR



POLSAR : scattering mechanism, ie SS/DB/VS

MB POLInSAR : resolution along height

-> 3D distribution of scattering centers

@E-SAR/L 2000

R: HH-VV

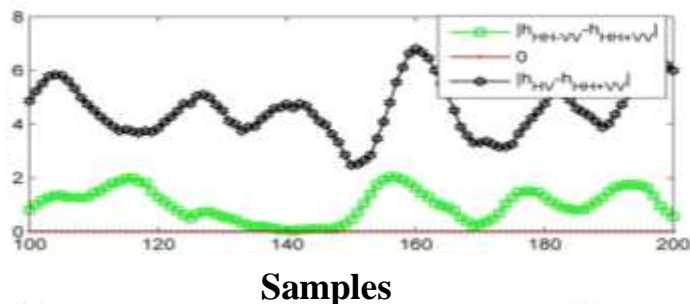
G: 2xHV

B: HH+VV

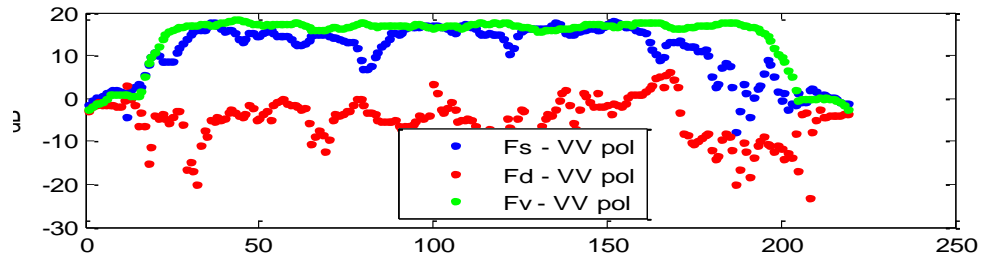
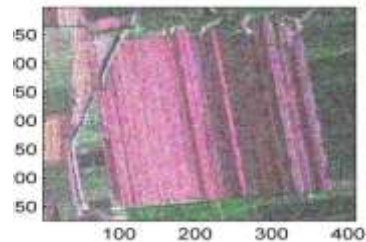
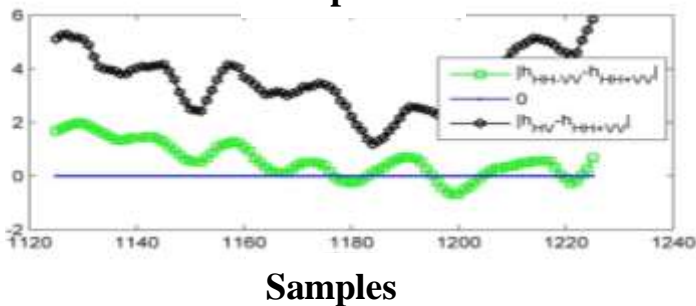


PolInSAR

$\Delta Z /$
m



$\Delta Z /$
m



Test Site: Changzhi, Shanxi
IECAS 2011

@PolSARProSIM*

L-band, 220*240, Hedge, 10m



PolInSAR

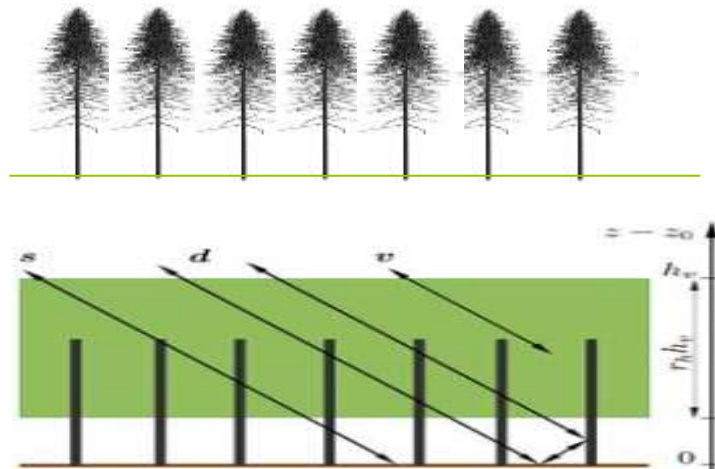
Vegetation Area Study

- ie. agriculture monitoring
- ie. forestry clear cut
- ie. type classification
- ie. forestry regrowth
- ie. vegetation height
- ie. biomass estimation
- ...

Freq. penetration

PolSAR

PolInSAR





问题讨论
Discussions



SAR Multidimensional Space Joint-observation

- Data acquisition:

working mode, T/R, relative motion...

? new concept radar

- signal modeling:

pol/freq/angle/temporal -> multi-dimension signal

? tensor, K product

- Image formation:

high dimensional, complex data -> phase/characteristics preserving

? coherent, incoherent

- Para retrieval:

bio/geo para retrieval -> empirical/semi-empirical, forward/inverse model

-> inverse/ill-conditioned problem

? Experimental, generalizability

- Computation Technique:

big data(HRWS, multi-channel, modes...) -> descent method @application

? CS/LR

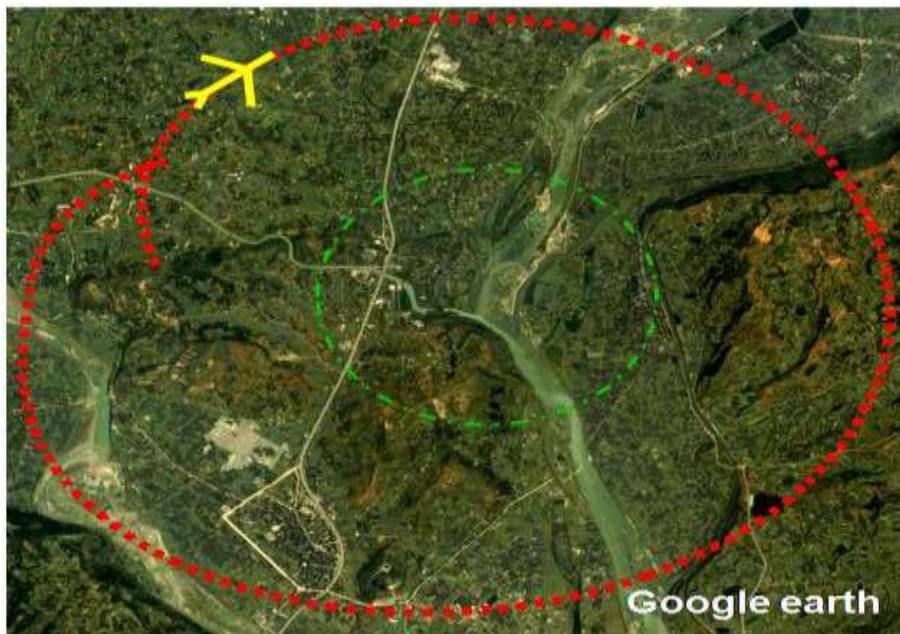
high performance computation -> complex multiply, fast FFT, memory...

? lens/lens array proc.

- Image characterization and information representation:

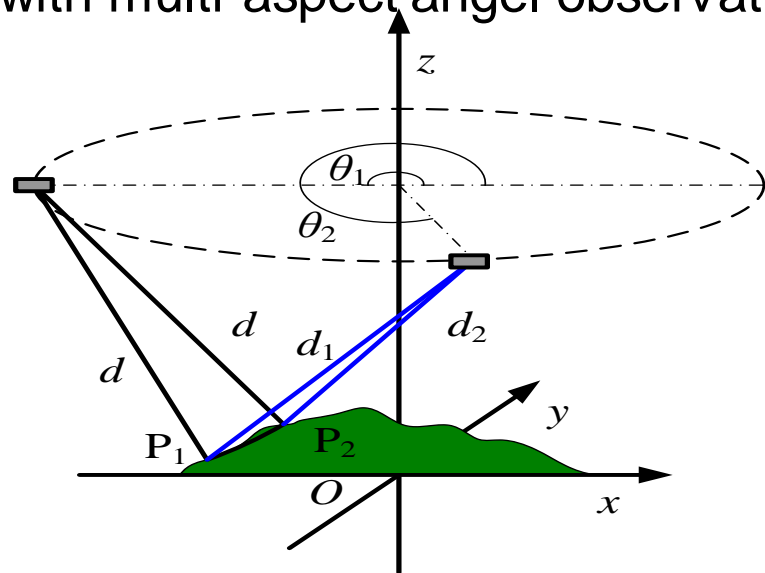
new info. mining, mechanism tokening, visualization... ? AI

Circular SAR



IECAS P-Band QP r=3km Aug. 2011 Sichuan P.R. China

SAR with multi-aspect angle observation



- multi-aspect info.
- 3D imaging
- moving target monitoring

.....



SAR with multi-aspect angle

SAR





Circular SAR



SAR with multi-aspect angle



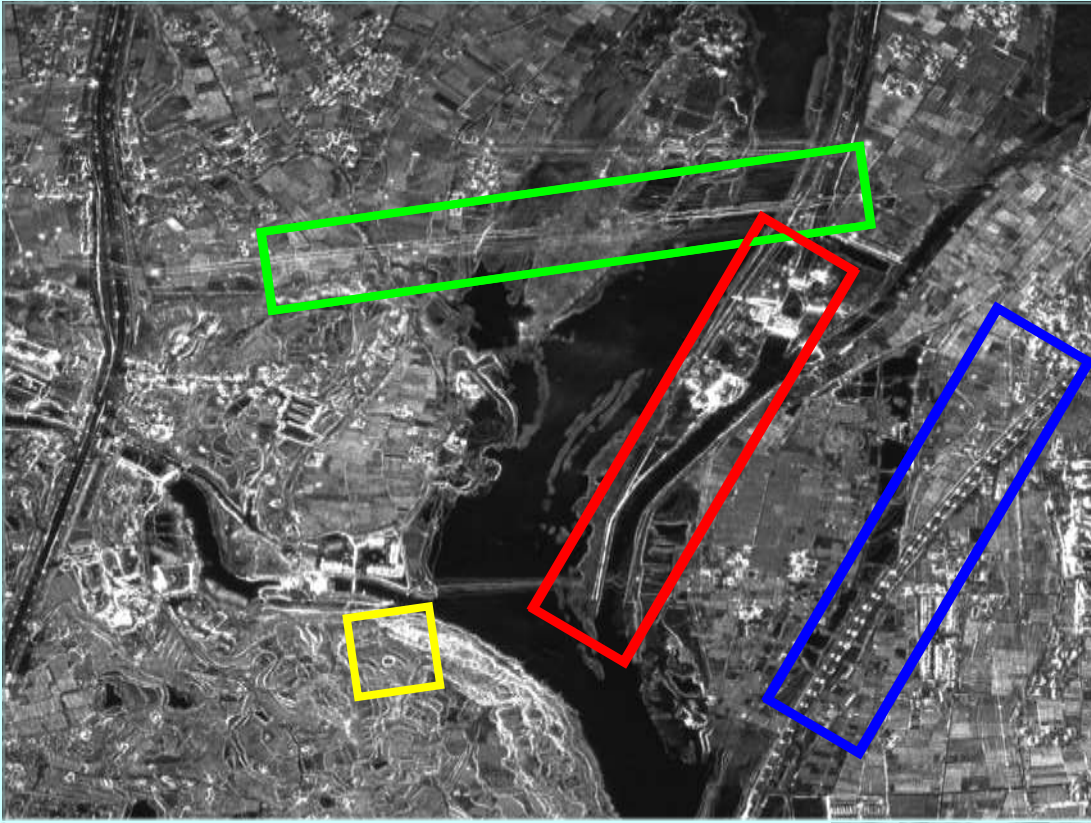


Circular SAR



SAR with multi-aspect angle
IKONOS

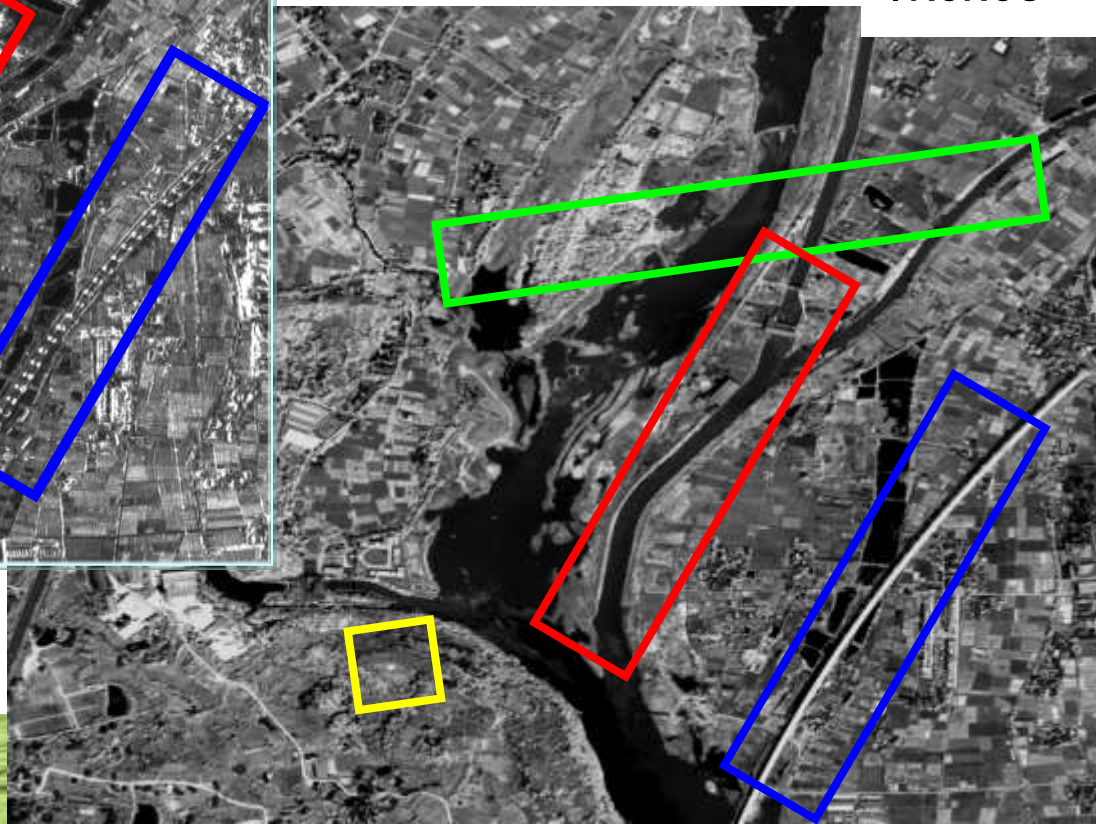


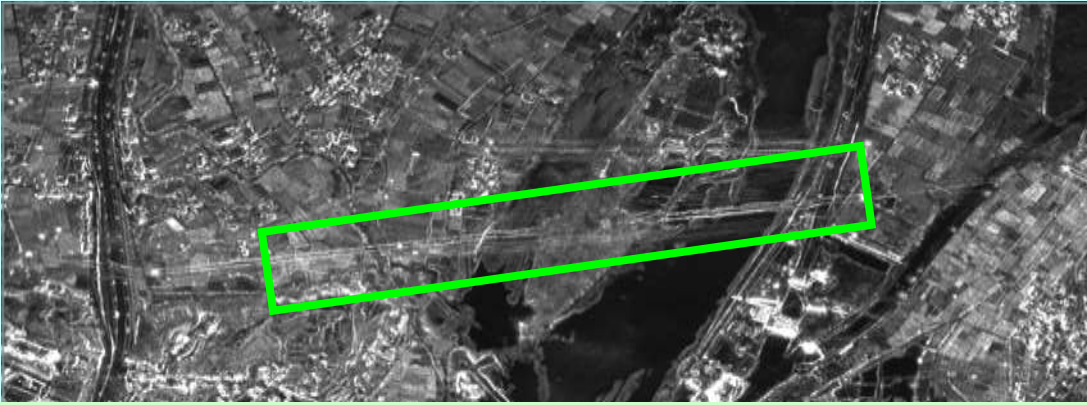


Circular SAR



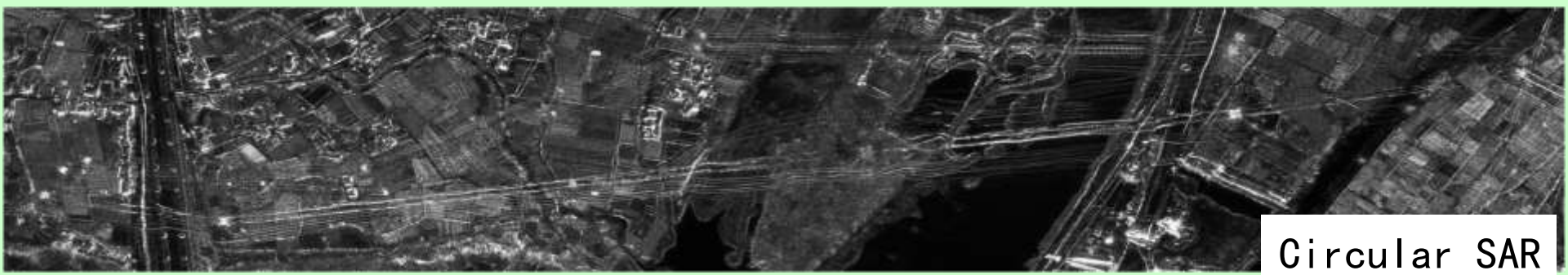
SAR with multi-aspect angle
IKONOS



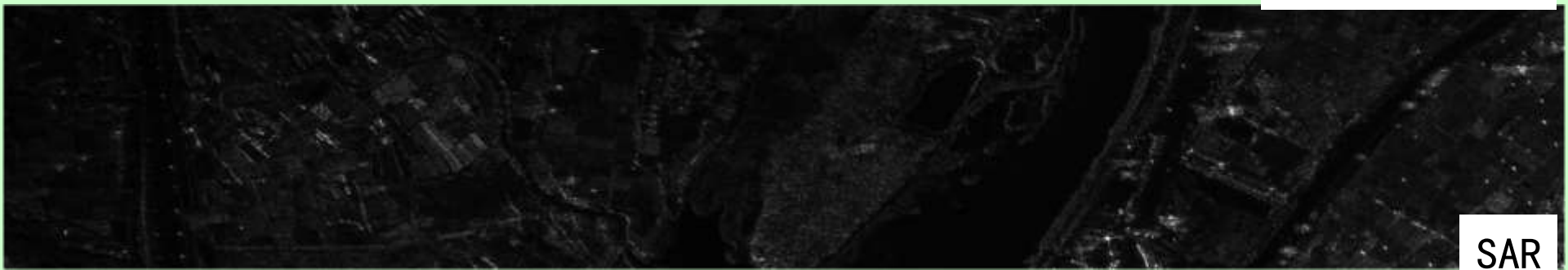


SAR with multi-aspect angle

power line



Circular SAR

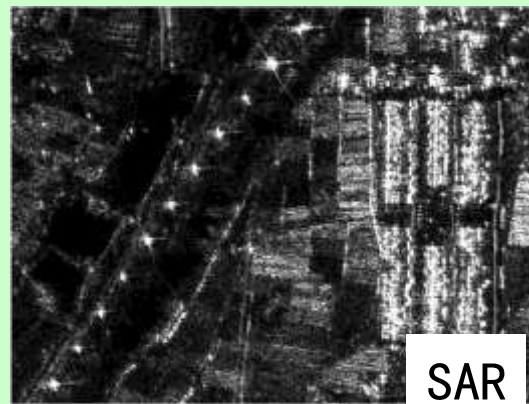


SAR



SAR with multi-aspect angle

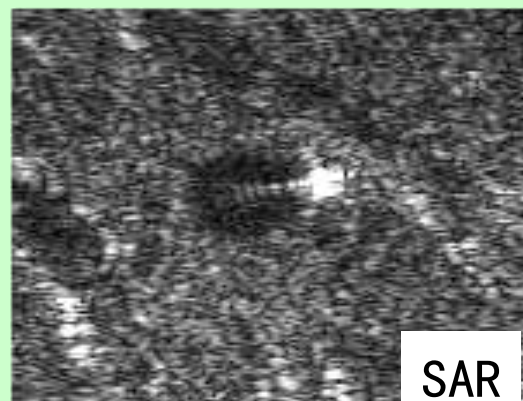
Elevated railway
(under construction)





SAR with multi-aspect angle

irrigation pool



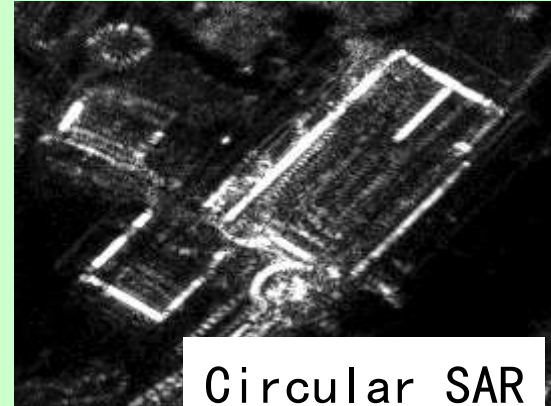


SAR with multi-aspect angle

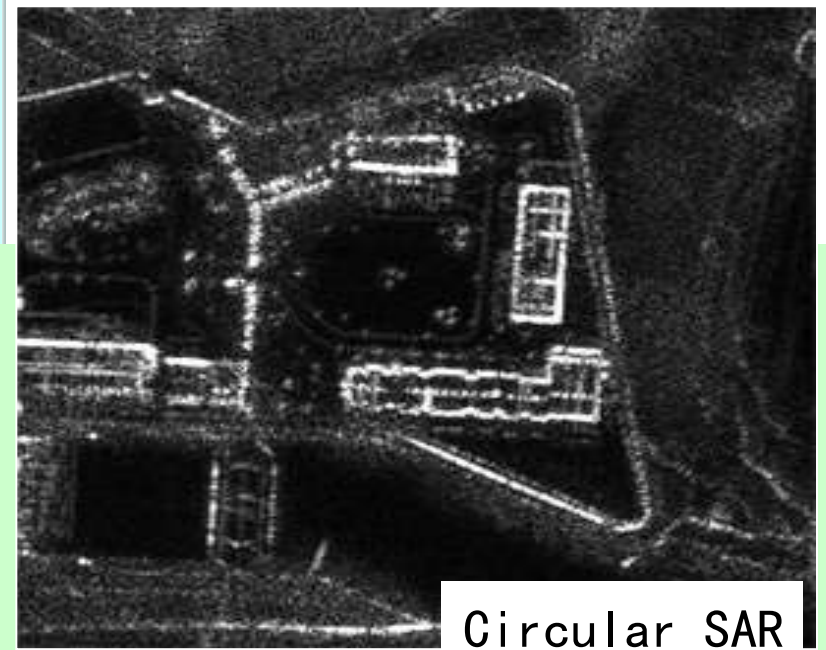
building area



IKONOS



Circular SAR



Circular SAR

SAR with multi-aspect angel

terrace field farm land

SAR

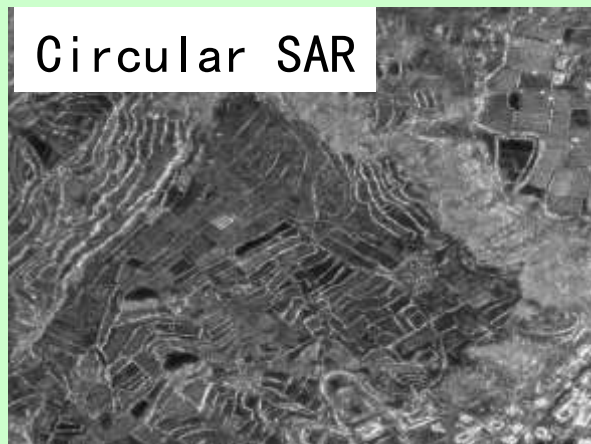
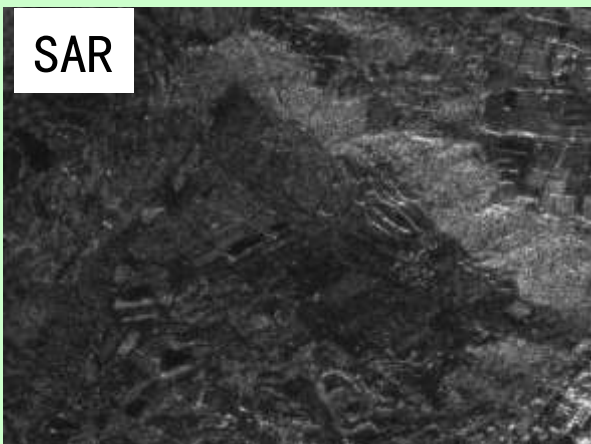
Circular SAR

IKONOS

SAR

Circular SAR

IKONOS

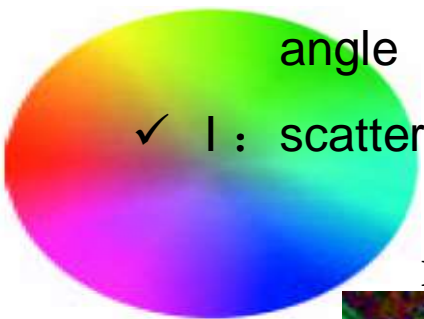


HIS coding

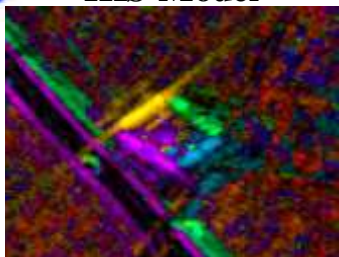
- ✓ H: scattering direction
- ✓ S: scattering consistency

angle

- ✓ I : scattering intensity




HIS Model





Summary

- SAR technology: from EO to complex media target detection, understanding and applications
 - SAR system: from radar to the overall information system, including scattering mechanism, data acquisition, signal proc., information extraction and etc.
 - SAR with multidimensional space joint-observation: challenge facing theoretical modeling, methodology, system realization and applications
- 



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ESA–MOST China Dragon 4 Cooperation

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中欧科技合作“龙计划”第四期 **2019年陆地遥感高级培训班**

