ISPRA
Istituto Superiore per la Protezione e la Ricerca Ambientale

Sistema Nazionale per la Protezione dell'Ambiente

SUMMER SCHOOL WORKSHOP

ACTION 2020-2-21: COPERNICUS FOR CULTURAL HERITAGE

Cyprus University of Technology

DLR

SAR change detection and InSAR techniques for study and conservation of cultural heritage, with a focus on ASI's COSMO-SkyMed constellation

Deodato Tapete

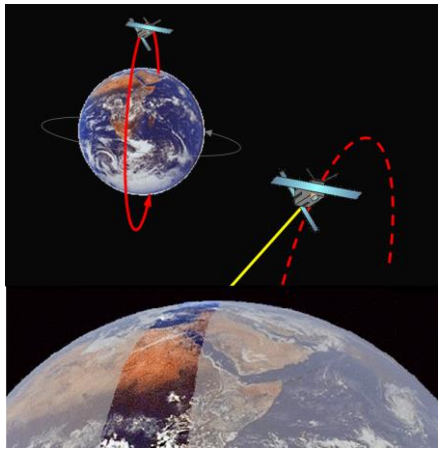
Italian Space Agency (ASI)

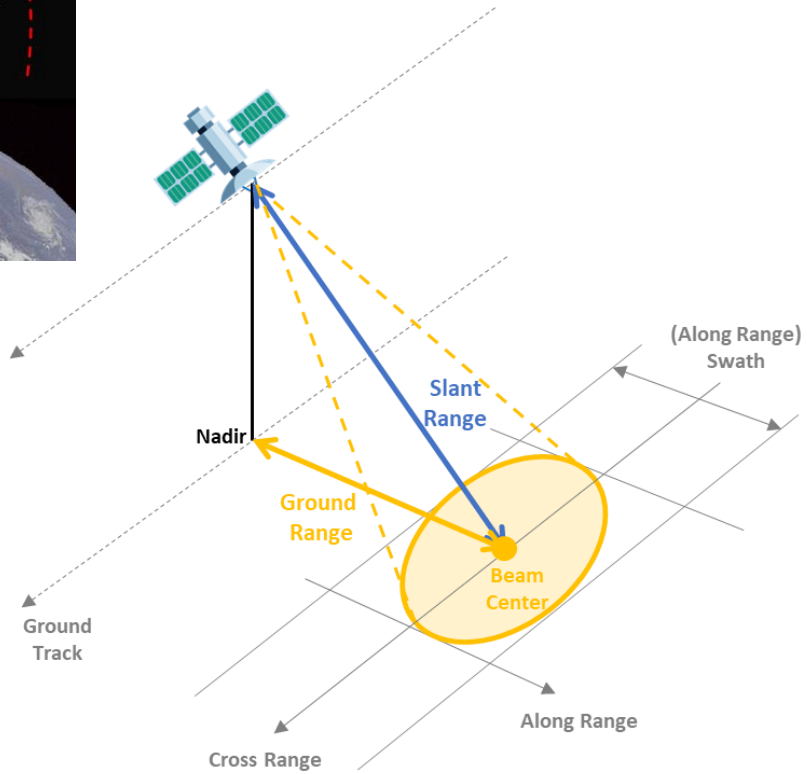
13-16.06.2023

PARCO REGIONALE DELL'APPIA ANTICA

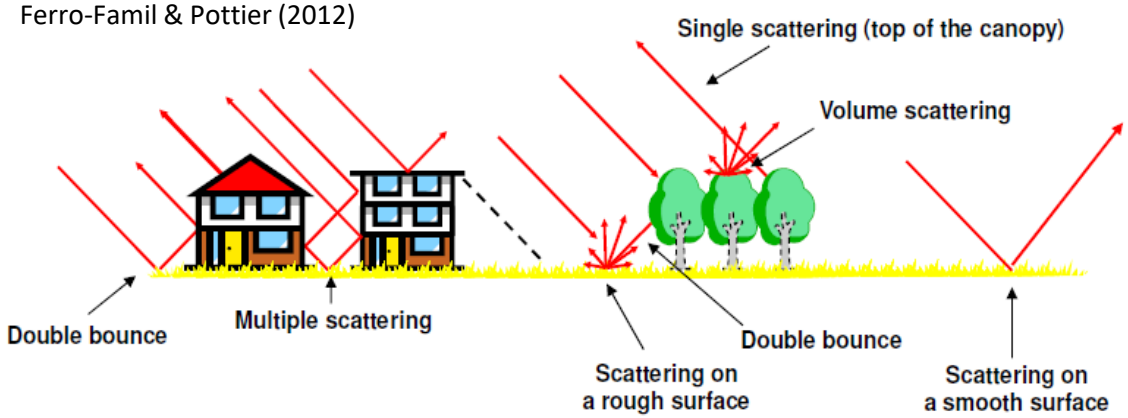
Ex Cartiera Latina - Via Appia Antica, 42

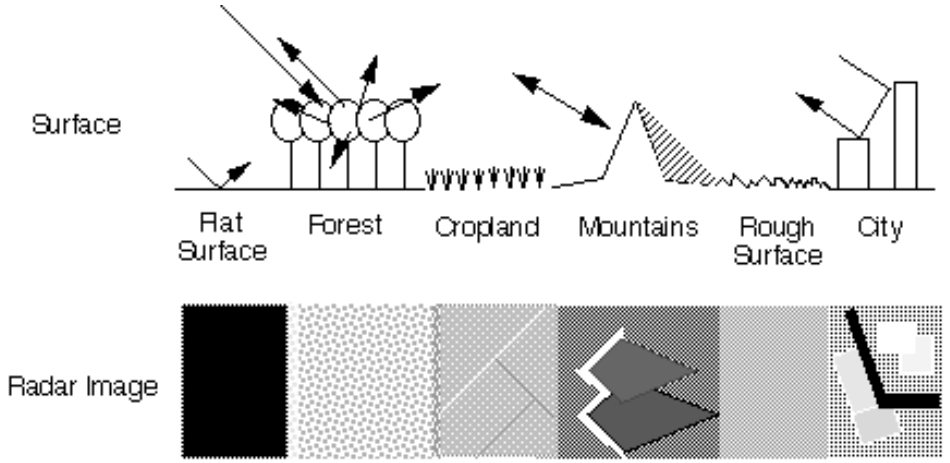
Radar imaging (quick recap of the basics)





Ferro-Famil & Pottier (2012)





ESA Earthnet Online (2013)

Radar imaging (quick recap of the basics)

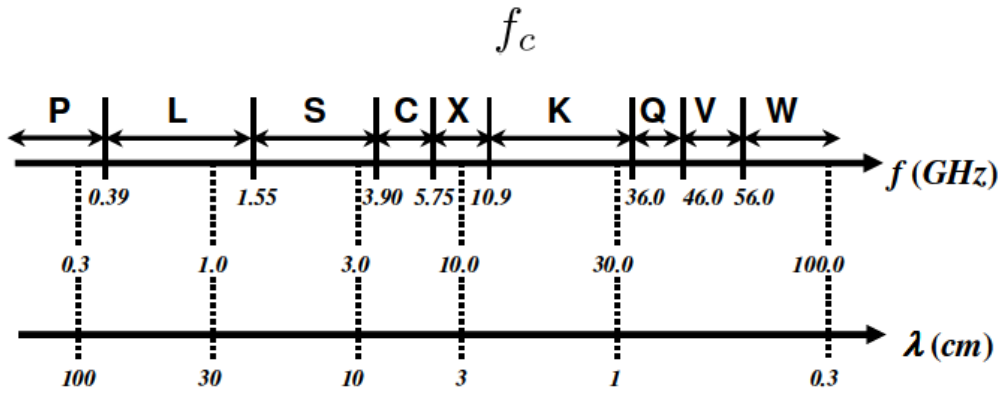
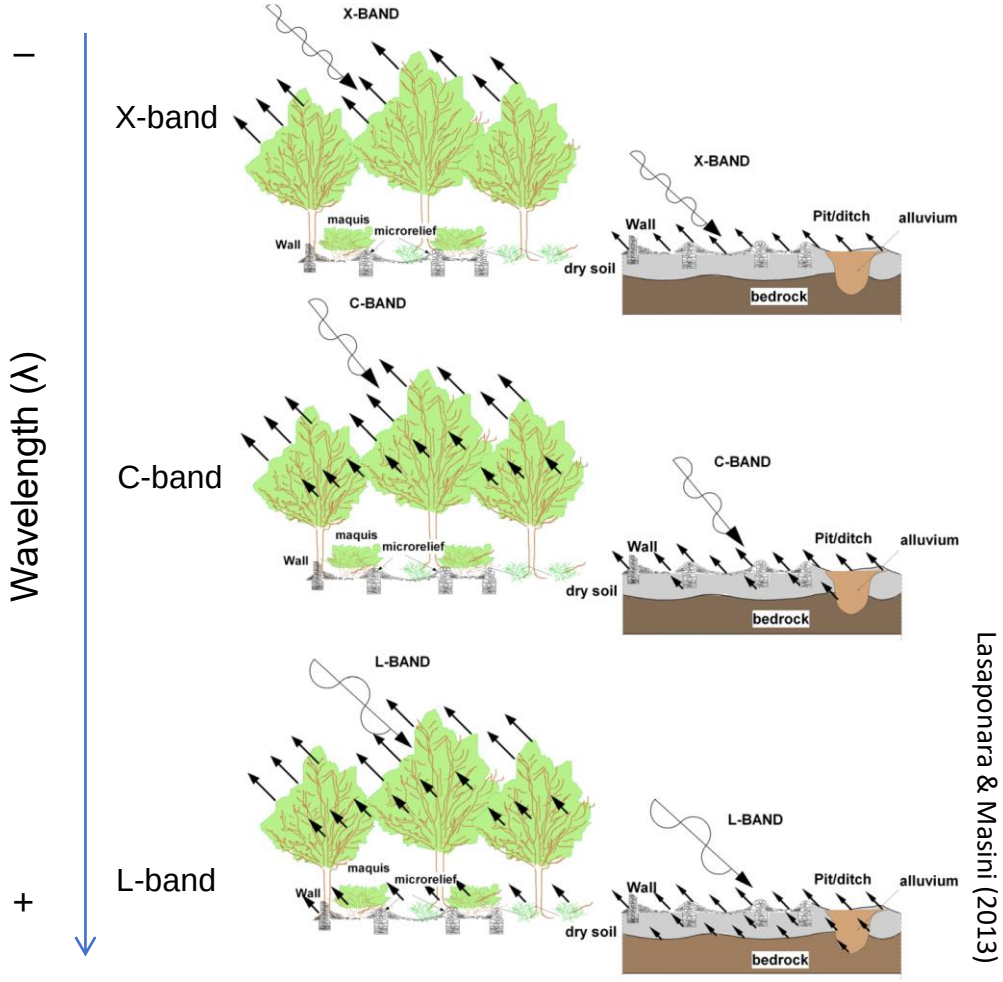


Table 1. SAR bands and frequencies.

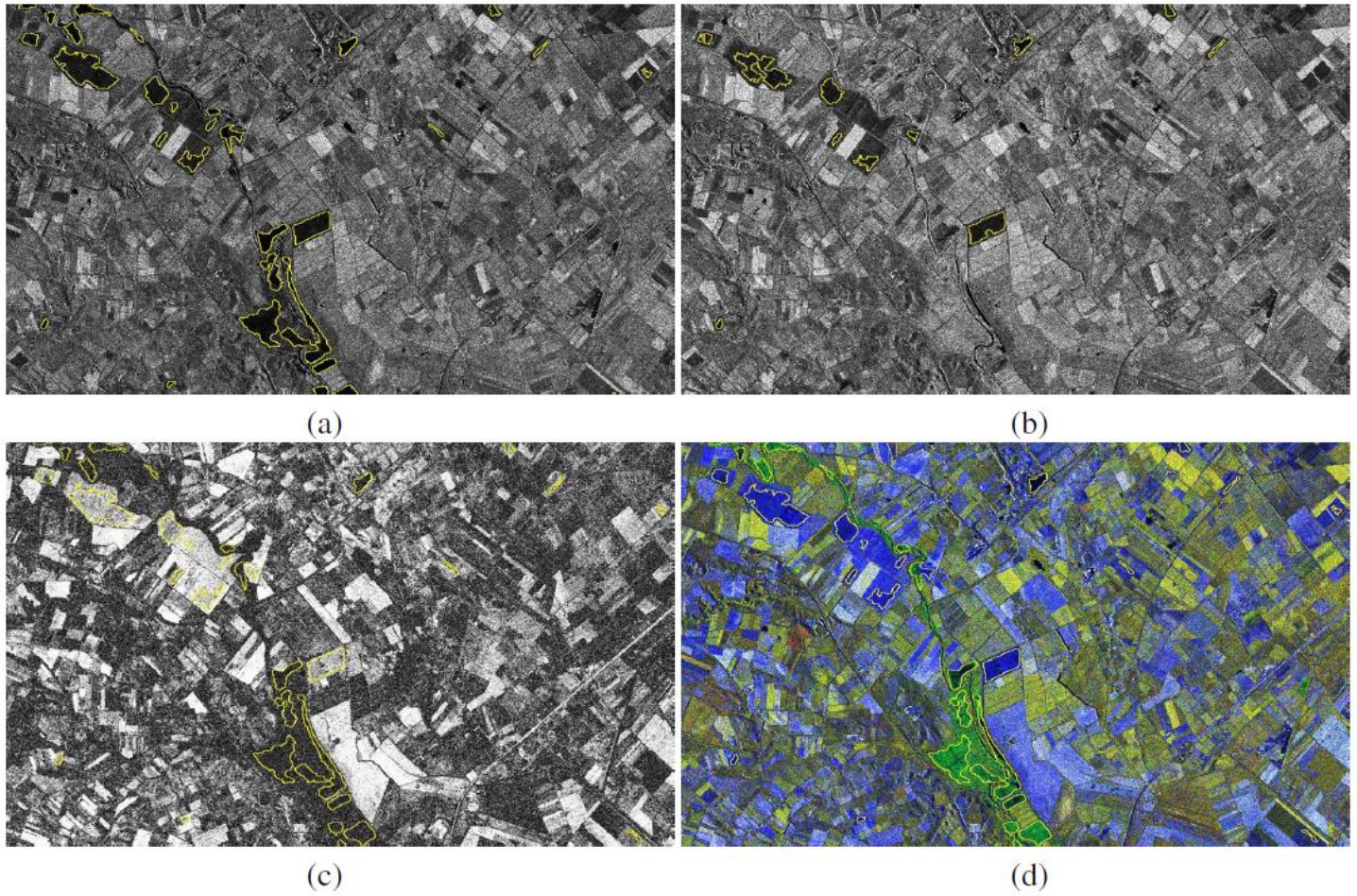
Name	Nominal frequency range	Wavelength range	Specific bands used in SARs
VHF	30–300 MHz	10–1 m	138–144 MHz, 216–225 MHz
P (UHF)	300–1000 Mhz	100–30 cm	420–450 MHz, 890–942 MHz
L	1–2 GHz	30–15 cm	1.215–1.4 GHz
S	2–4 GHz	17–7.5 cm	2.3–2.5 GHz, 2.7–3.7 GHz
C	4–8 GHz	7.5–3.75 cm	5.25–5.925 GHz
X	8–12 GHz	3.75–2.5 cm	8.5–10–68 GHz
Ku	12–18 GHz	2.5–1.67 cm	13.4–14.0 GHz, 15.7–17.7 GHz
K	18–27 GHz	1.67–1.11 cm	24.05–24.25 GHz
Ka	27–40 GHz	1.11–0.75 cm	33.4–36.0 GHz
V	40–75 GHz	0.75–0.40 cm	59–64 GHz
W	75–110 GHz	0.40–0.27 cm	76–81 GHz 92–100 GHz
Millimetre	110–300 GHz	2.7–1.0 mm	



SAR-based change detection

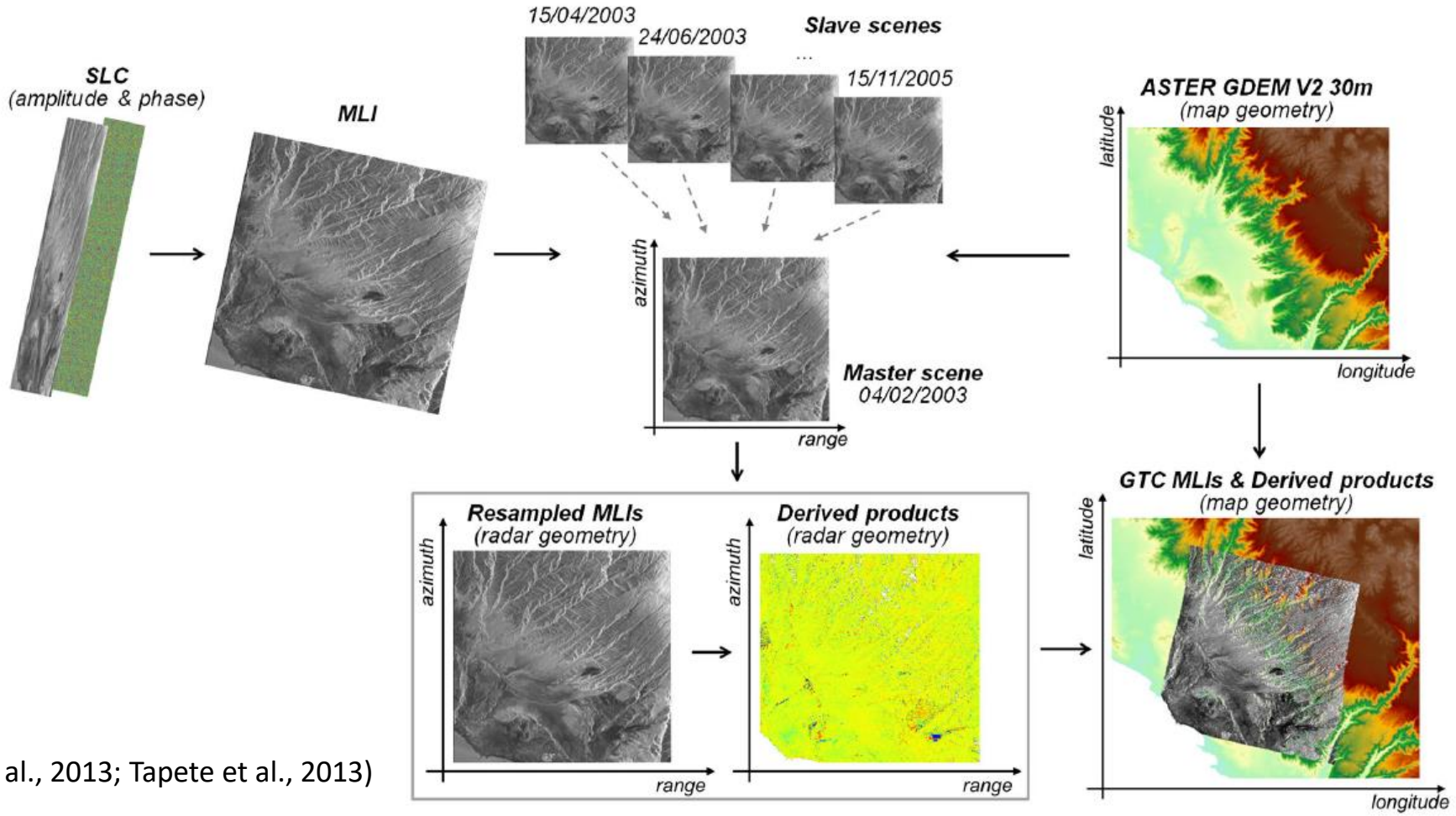
- Multi-temporal coherence
- Amplitude-based approaches
- DInSAR (interferograms)

$$\gamma(coherence) = \frac{\left|\sum_{i=1}^{N} C_M^{(n)} \cdot C_S^{*(n)}\right|}{\sqrt{\sum \left|C_M^{(n)}\right|^2 \cdot \sum \left|C_S^{(n)}\right|^2}}$$



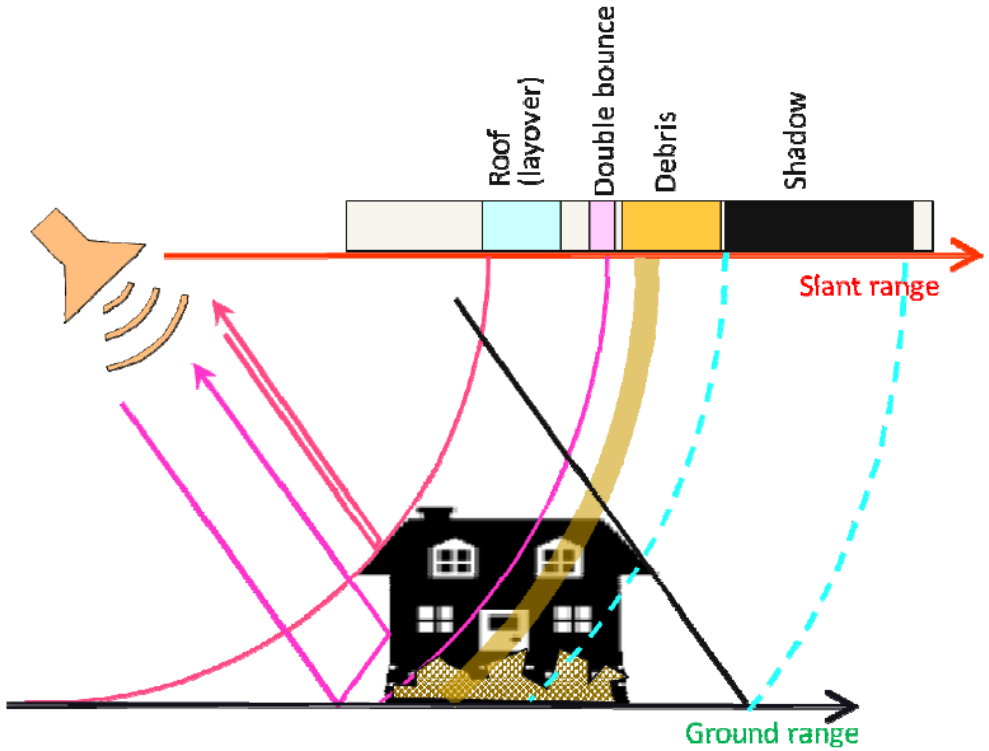
COSMO-SkyMed Stripmap SAR amplitude: (a) 03/11/2010, (b) 04/11/2010; (c) coherence map; (d) RGB combination of (a), (b) and (c) (Refice et al., 2014)

SAR-based change detection

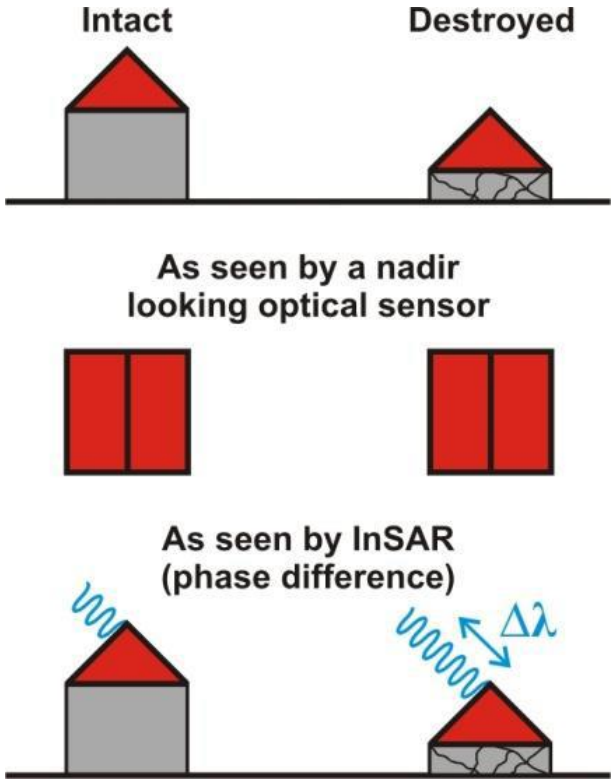


(Cigna et al., 2013; Tapete et al., 2013)

SAR-based change detection – e.g. earthquake damages



(Anniballe et al., 2015)



Phase difference between the pre- and post-disaster SAR images allows discrimination between intact and destroyed buildings (Plank, 2014).

SAR-based change detection – e.g. earthquake damages

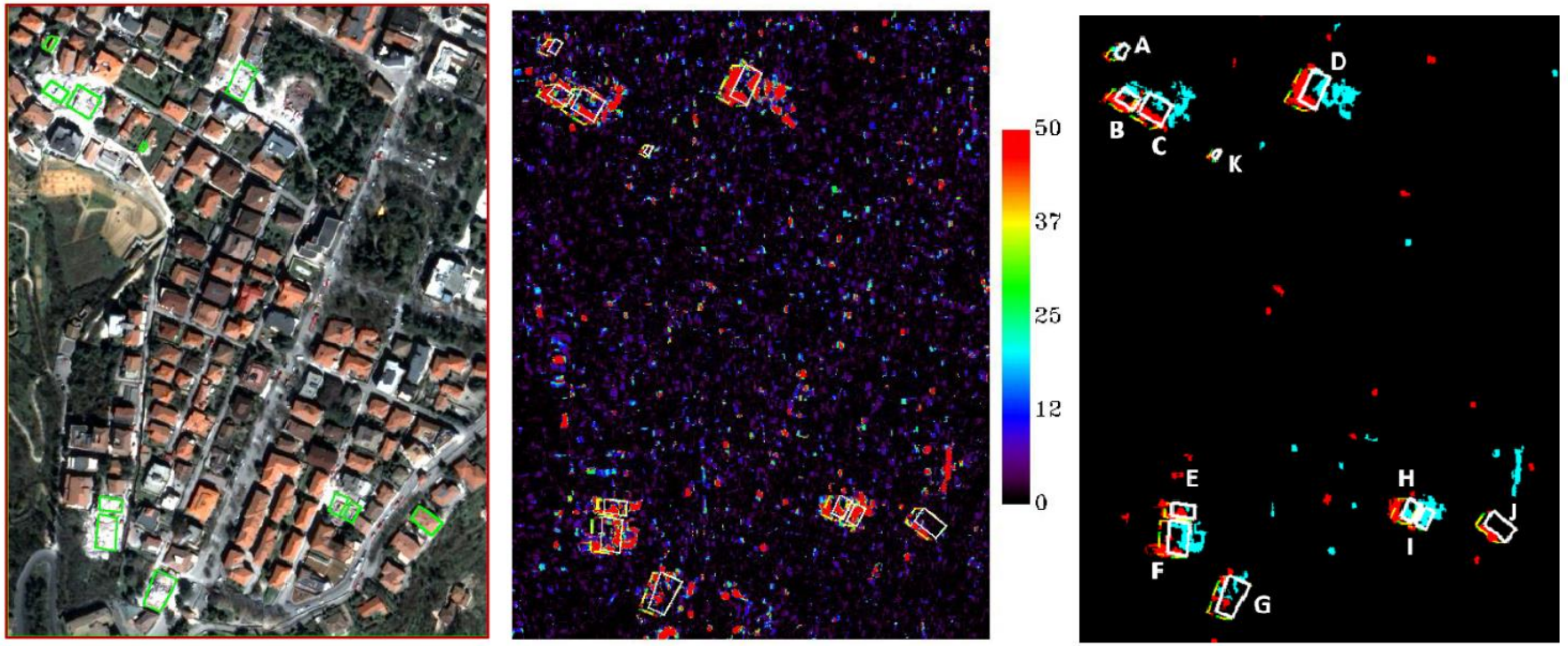
a) b)

2009 L'Aquila earthquake: a) Post-seismic optical image (QuickBird 08/04/2009) and b) RGB composite of pre- (Red) and post-event (Green and Blue) COSMO-SkyMed Spotlight SAR images (05 and 21/04/2009). Green polygons indicate severely damaged buildings (Anniballe et al., 2015).

SAR-based change detection – e.g. earthquake damages

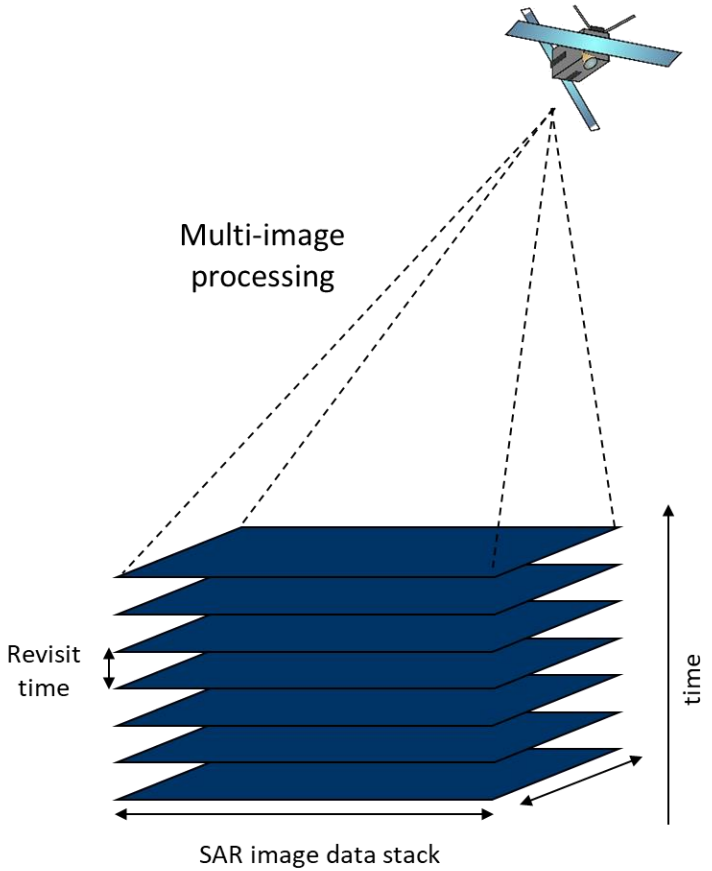
Based on where layover areas (hence double-bounce) were previously located, collapsed buildings are detected by combining two change features:

- Kullback-Leibler (KL) divergence – measure of statistical similarity (Inglada & Mercier, 2007)
- Backscattering intensity ratio – decrease/increase of radar backscatter

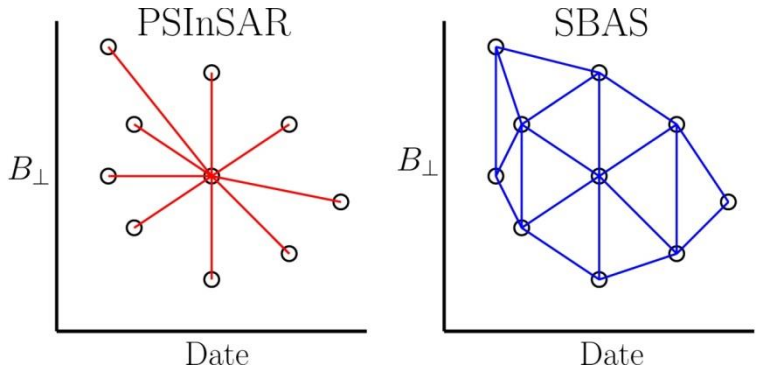


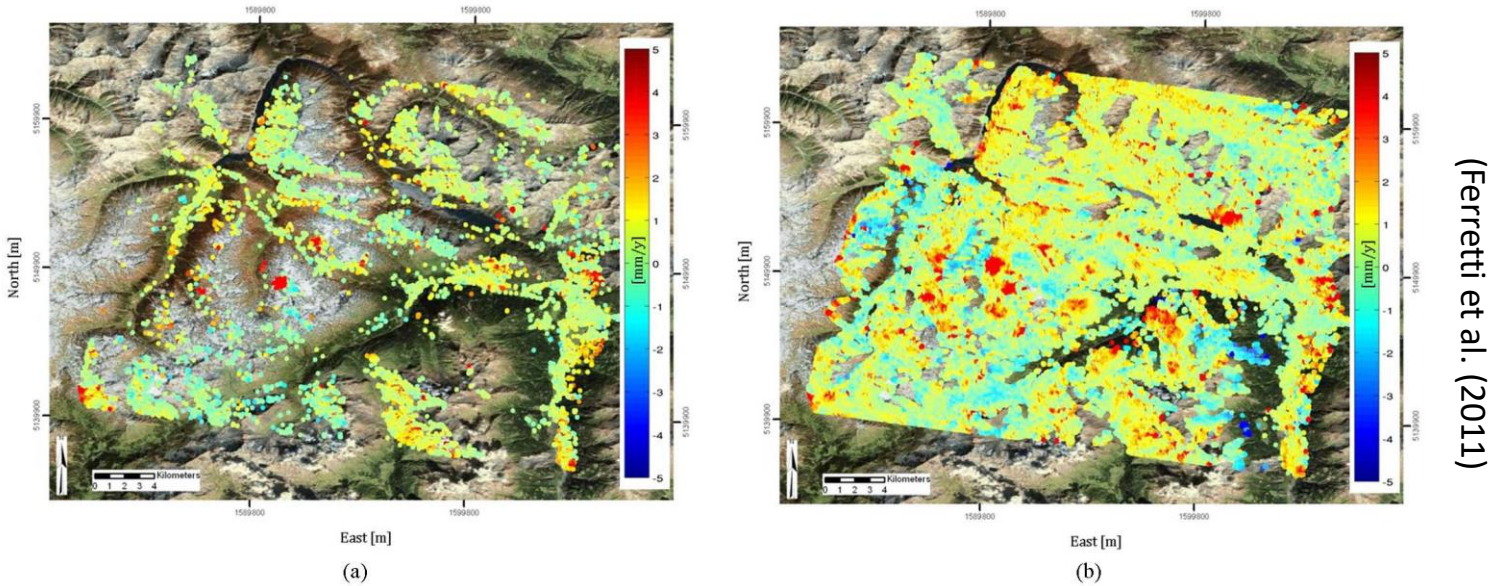
2009 L'Aquila earthquake: a) Post-seismic Quickbird image; b) KL divergence map using pre- and post-event COSMO-SkyMed images; c) areas with high KL and associated decrease (red) or increase (cyan) of the backscatter (Anniballe et al., 2015).

Multi-interferogram approaches (time series analysis)



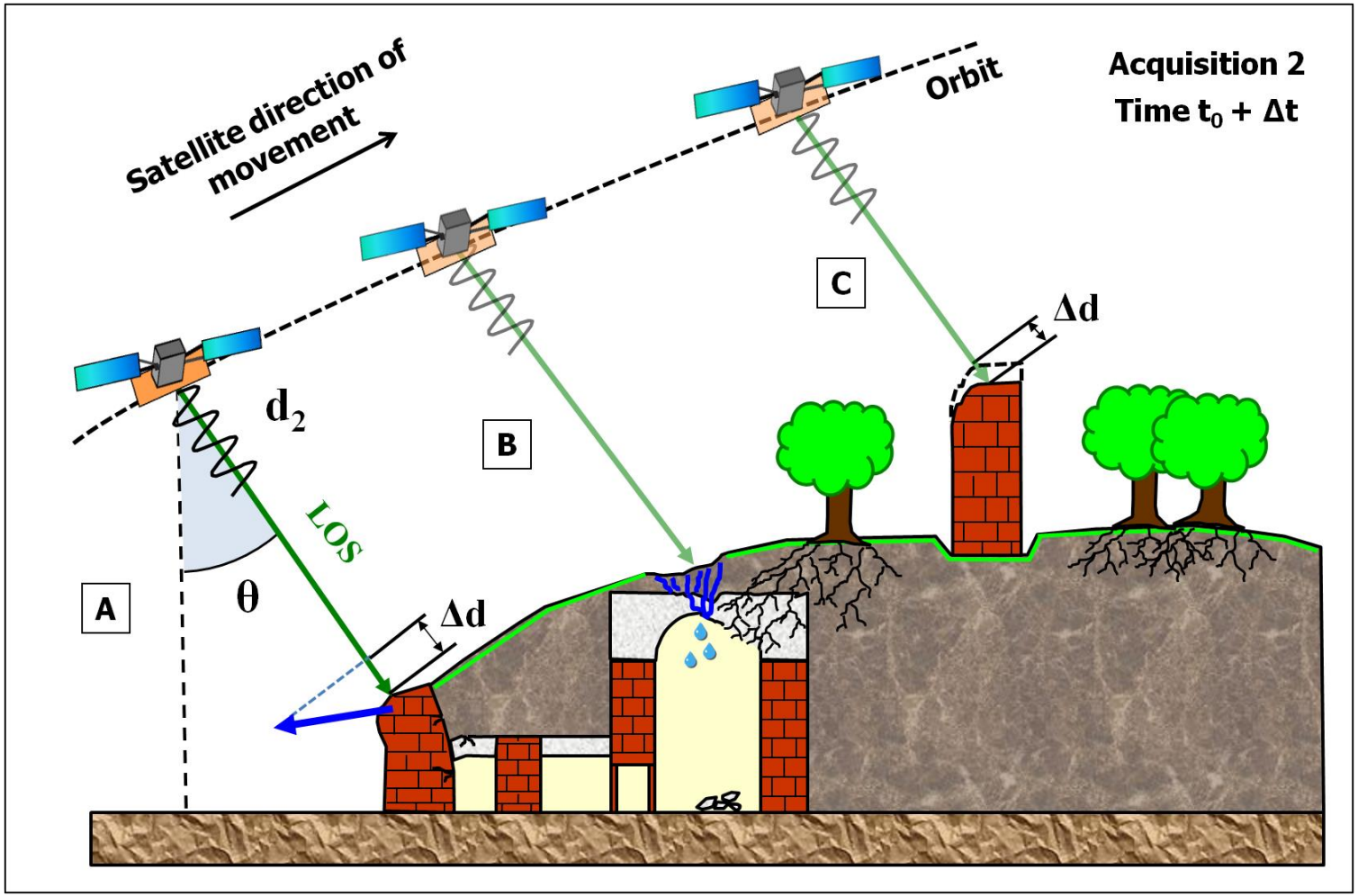
- Small Baseline Subset (SBAS)
- Persistent Scatterer Interferometry (PSI)





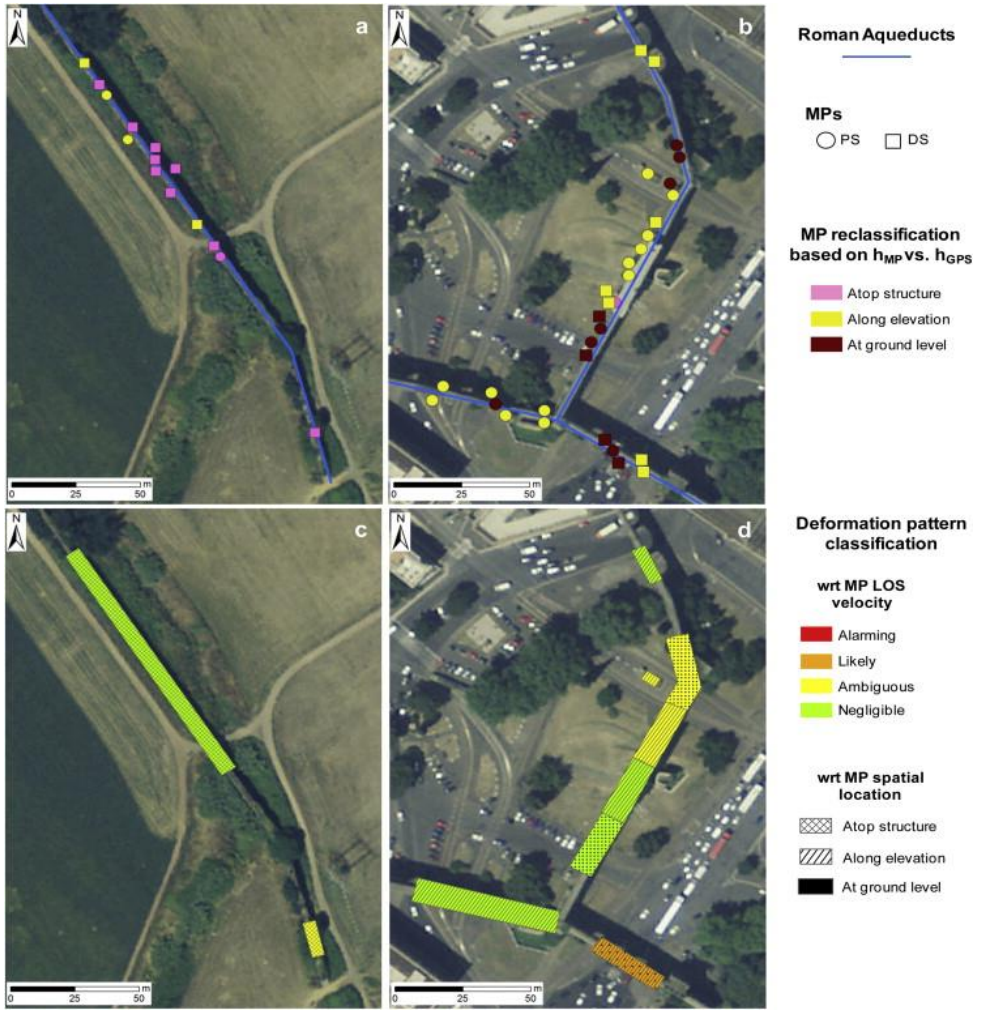
(Ferretti et al. (2011)

Multi-interferogram approaches applied to cultural heritage



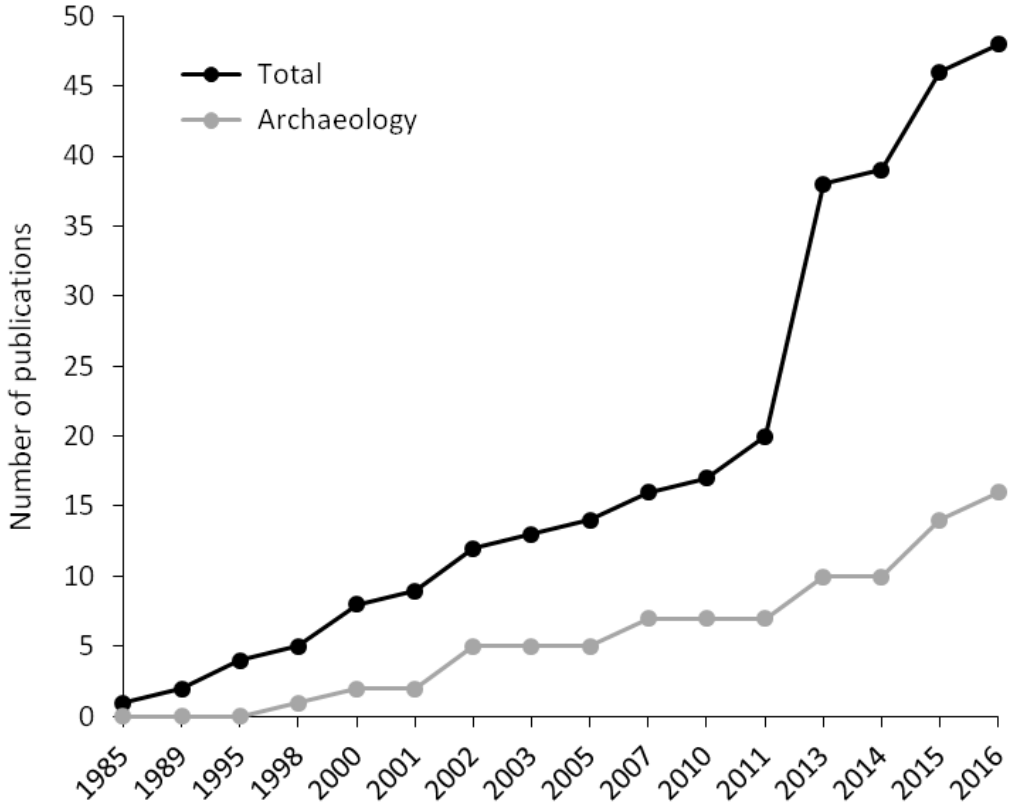
Tapete et al. (2012)

Multi-interferogram approaches applied to cultural heritage

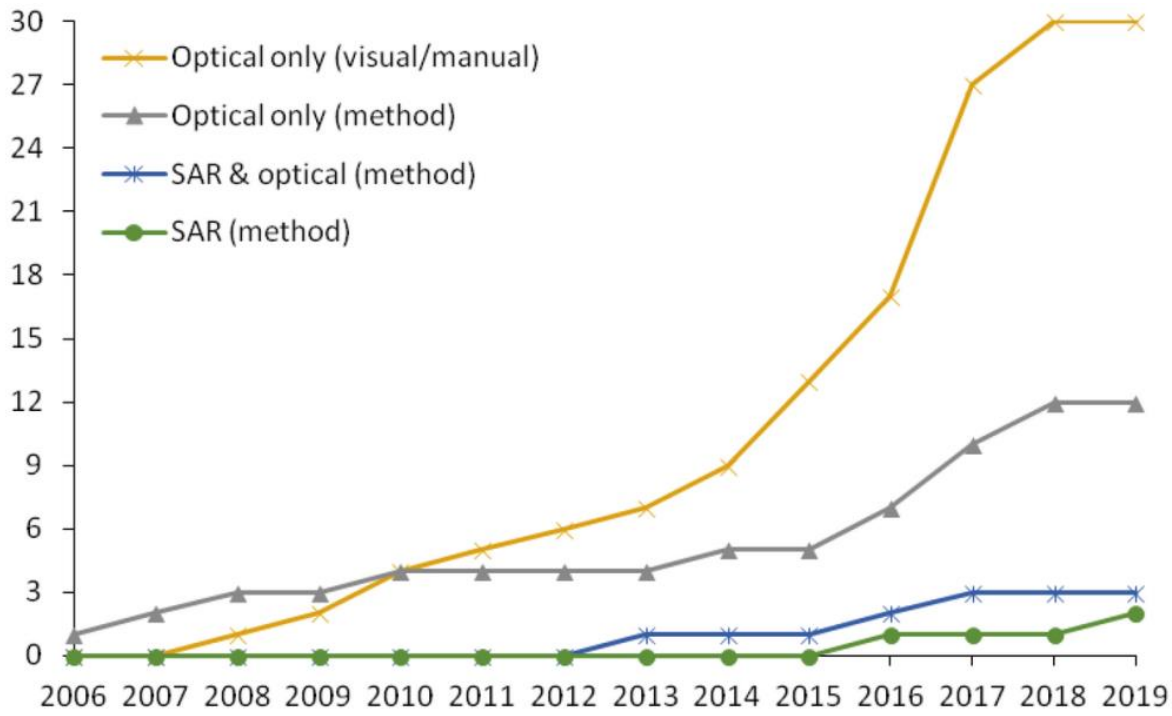


Tapete et al. (2015)

Exploitation of SAR technologies for cultural heritage



Tapete & Cigna (2017)



Tapete & Cigna (2019b)

COSMO-SkyMed Mission

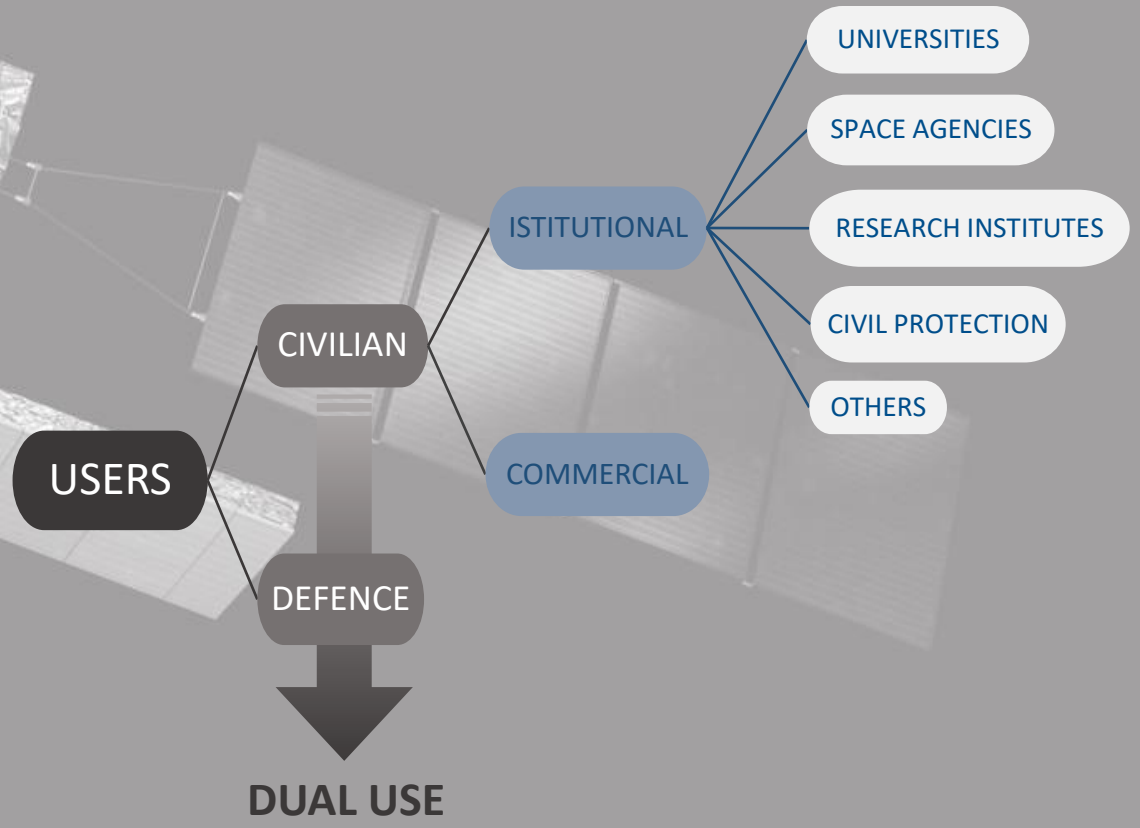
COSMO-SkyMed is the Italian end-to-end System for Earth Observation, commissioned and funded by:

Italian Space Agency

Italian Ministry of Defence

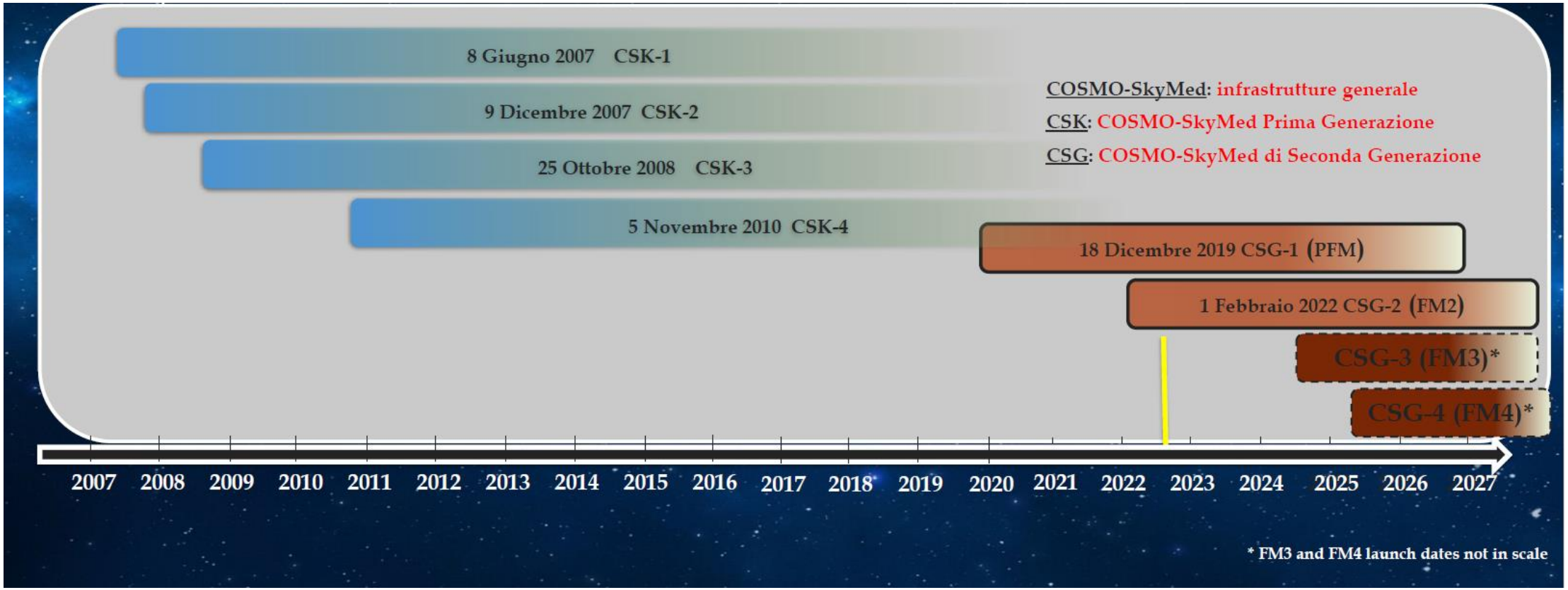
And with the primary objective to simultaneously fulfill the applicative needs of different typologies of Users

- Emergencies
- Ocean and ice
- Coastlines and inland waters
- Forestry and agricultural resources
- Technical cartography and Urban planning
- Security applications

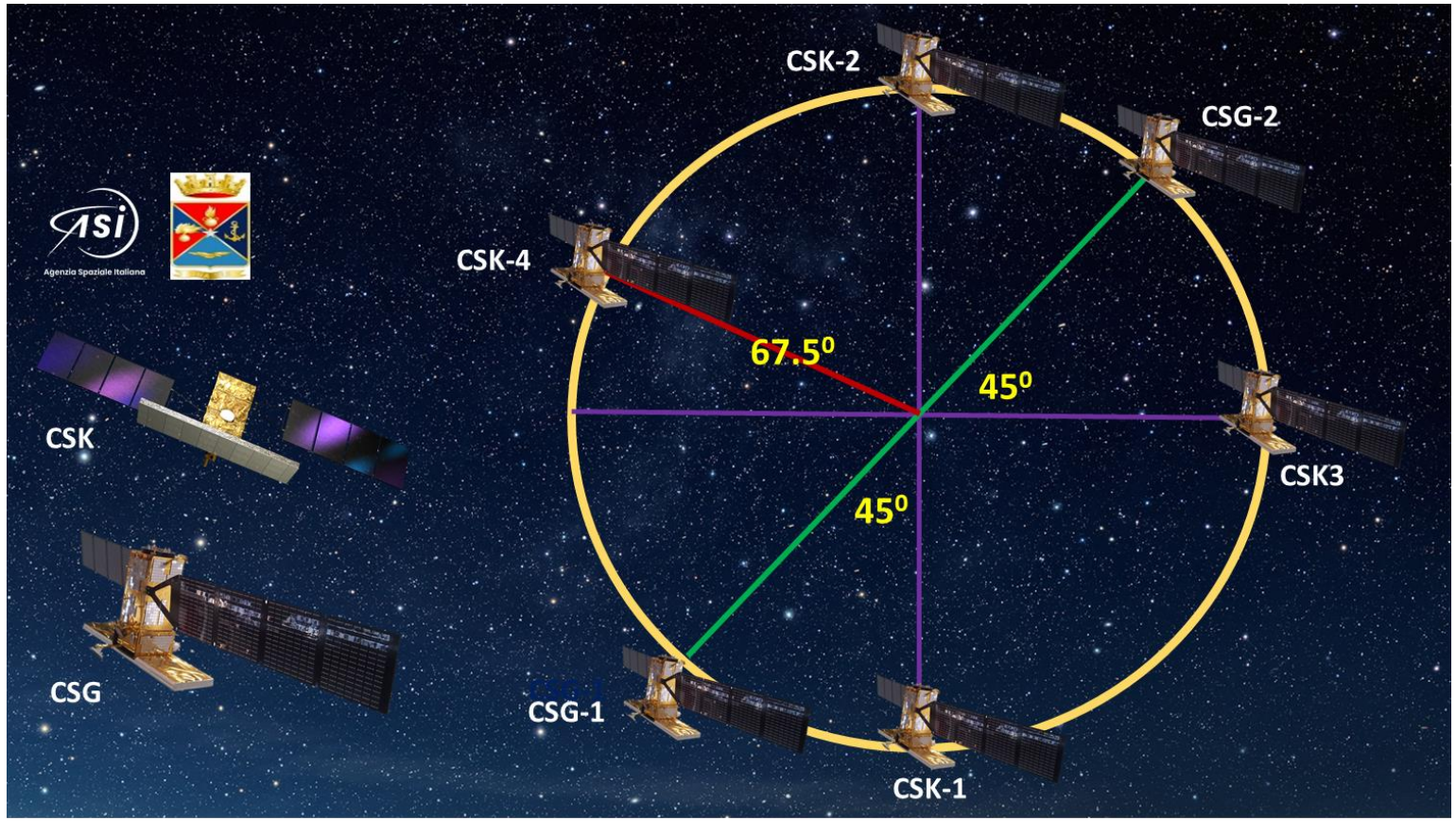


COSMO-SkyMed evolution

COSMO-SkyMed Second Generation (CSG) ensures operational continuity of First Generation satellites
Nominal operational lifetime of CSG satellites: 7 years

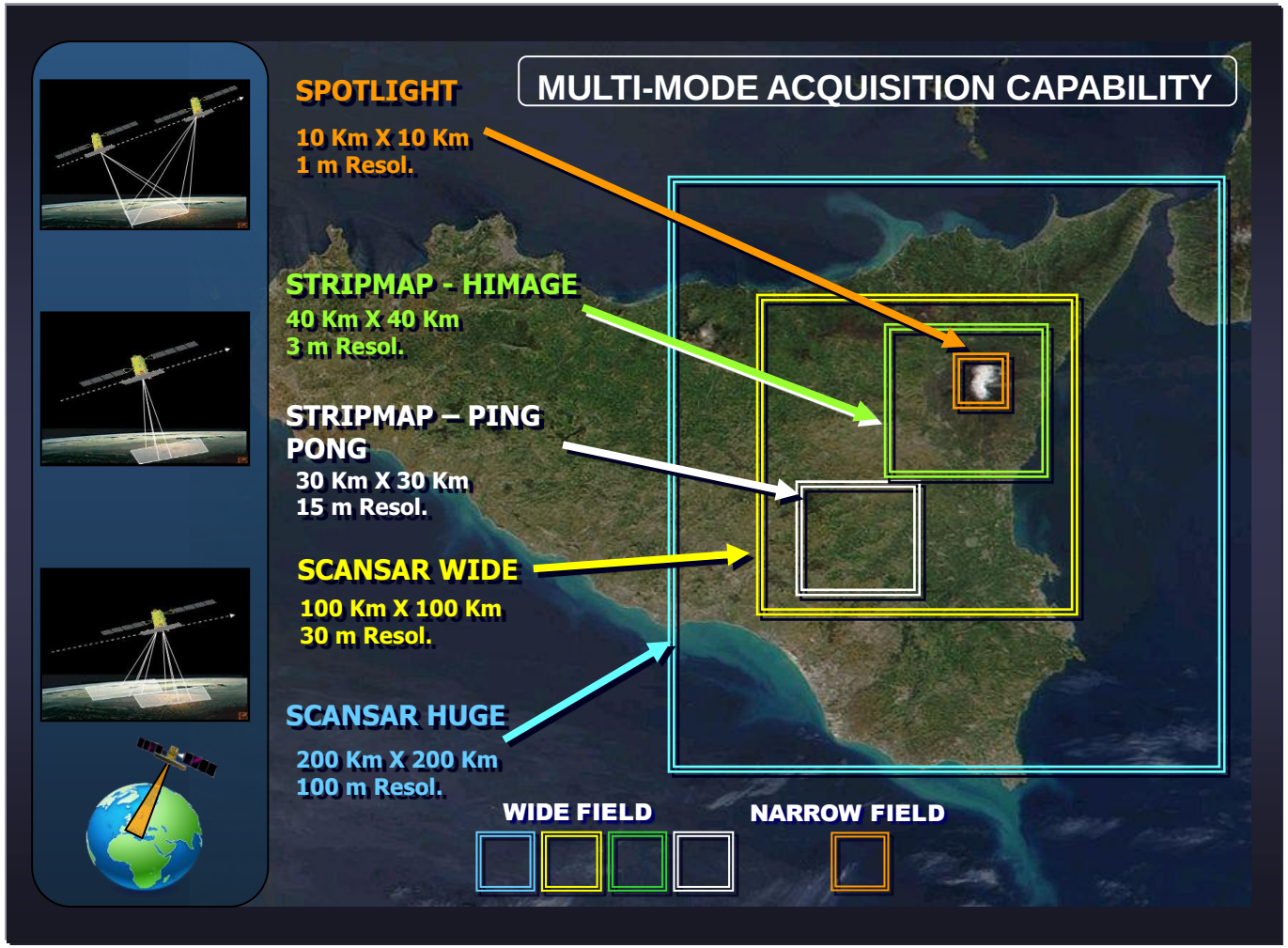


ASI's COSMO-SkyMed constellation



COSMO-SkyMed constellation – Orbital Parameters	
Orbit Type	SSO
Inclination	97.86°
Revolutions/day	14.8125
Orbit Cycle	16 days
Eccentricity	0.00118
Argument of Perigee	90°
Semi Major Axis	7003.52 km
Nominal Height	619.6 km
Nominal LTAN	6:00 A.M.
Deployment	Progressive

CSK acquisition modes



Usefulness for cultural heritage applications:

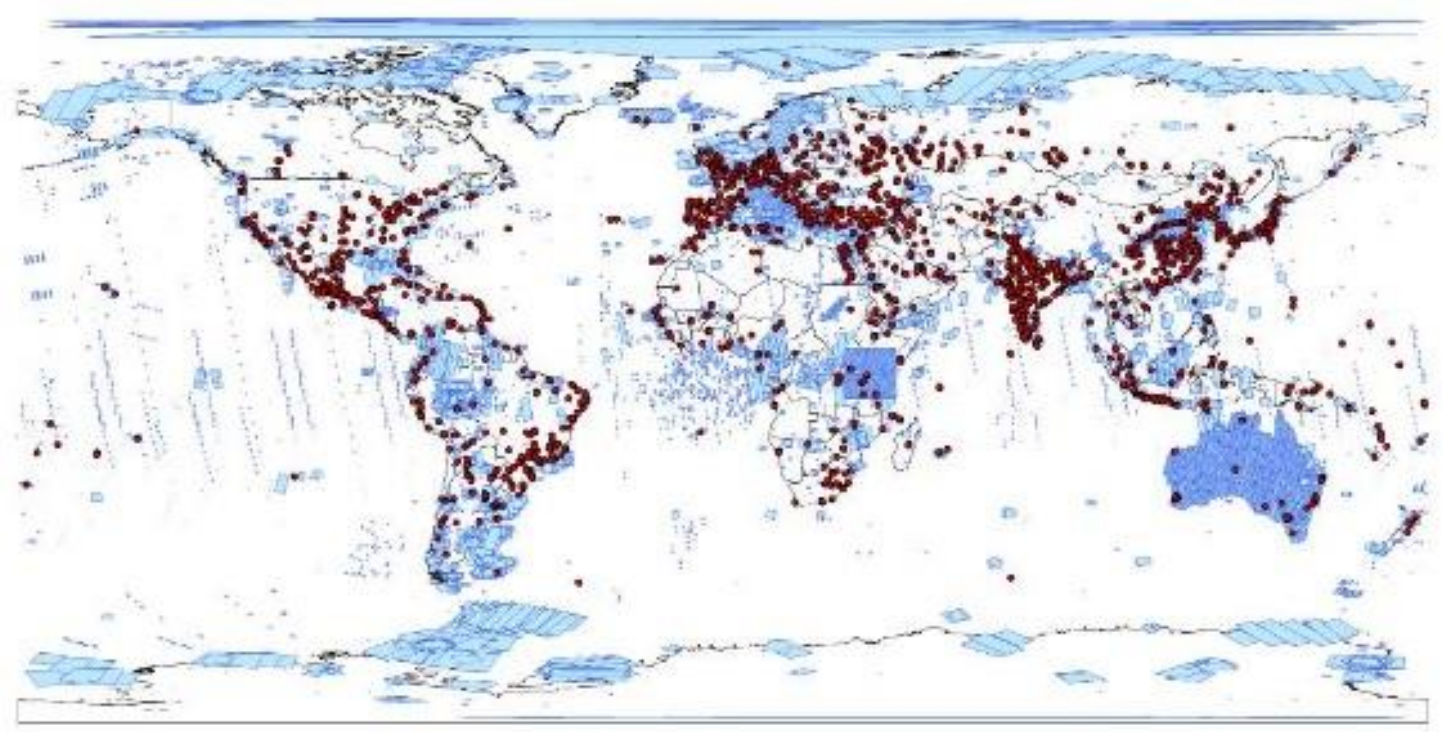
- Best modes
  - StripMap (best trade-off between high spatial resolution and areal coverage)
  - Spotlight (e.g. local/site-scale investigations and fine archaeological mapping)

- Most suited data format
  - Level 1A, single-look complex slant products (SCS) – for interferometric analysis and users who want to process on their own;
  - Level 1C/1D, geocoded ellipsoid-corrected (GEC) and geocoded terrain-corrected (GTC) products – ready to use e.g. in GIS, for users who do not need necessarily to process

CSK Background Mission

- Started in May 2011 and meant to build image catalogue for interferometric applications and maximize the system exploitation during the operational lifetime of the constellation
- Usefulness for cultural heritage apps especially for long-term monitoring, change detection, disaster/incident mapping

Typology	Frequency of observation	Number of Sites
Cities (population >100.000 units)	16 days	748
Extended cities (>500.000 units)		222
UNESCO sites		96
Volcanoes		74
Infrastructures		2
Oil & Gas mining		6



CSG Acquisition modes - overview

Standard Acquisition Modes

- Spotlight-1A
- Spotlight-1B
- Spotlight-2A
- Spotlight-2B
- Spotlight-2C
- Stripmap
- Ping-Pong
- Stripmap Quad-Pol
- ScanSAR-1
- ScanSAR-2

Non-Standard Operational Acquisition Modes

- DI2S Spotlight 1 Multi-Swath
- DI2S Spotlight 2 Multi-Swath
- Spotlight on theatre (offline)
- Spotlight Quad-Pol

NEW

Total daily imaging profile per satellite (wideband mode)	
SAR Mode	**Daily**
Spotlight-1 [num]	31
Spotlight-2 [num]	46
Stripmap Dual Pol [min]	36.19

- Defence mode
- Non-Standard **Operational** Modes: the system shall be designed to meet the required performances
- **Offline**: acquisition mode which is not available on the user interface, but managed with an offline tool at the User Ground Segments

Agenzia Spaziale Italiana

STRIP	CSK			CSG		
	Max resolution (Az. x Ra.)	Polarization	Scene size (Az. x Ra.)	Max resolution (Az. x Ra.)	Polarization	Scene size (Az. x Ra.)
HIMAGE	3 x 3 m	Single	40 x 40 Km	3 x 3 m	Single / Dual	40 x 40 Km
Ping Pong	15 x 15 m	Alternating	30 x 30 Km	12 x 5 m	Alternating	40 x 40 Km
Quad Pol				3 x 3 m	Quad	40 x 15 Km

SCAN	CSK			CSG		
	Max resolution (Az. x Ra.)	Polarization	Scene size (Az. x Ra.)	Max resolution (Az. x Ra.)	Polarization	Scene size (Az. x Ra.)
Wide	23 x 13,5	Single	100 x 100			
Huge	38 x 13,5	Single	200 x 200			
ScanSAR-1				20 x 4	Single / Dual	100 x 100
ScanSAR-2				40 x 6	Single / Dual	200 x 200

SPOT	CSK			CSG		
	Max resolution (Az. x Ra.)	Polarization	Scene size (Az. x Ra.)	Max resolution (Az. x Ra.)	Polarization	Scene size (Az. x Ra.)
Spotlight-2	1 x 1 m	Single	10 x 10 Km			
Spotlight-2A				0,3 x 0,5 m	Single / Dual	3,5 x 7 Km
Spotlight-2B				0,6 x 0,6 m	Single / Dual	10 x 10 Km
Spotlight-2C				0,8 x 0,8 m	Single / Dual	5 x 10 Km

Agenzia Spaziale Italiana

CSG Improvements in Acquisition Modes

NOT STA… MODES

CSG HIMAGE mode:

- A Quad-Pol mode introduced

CSG Spotlight standard mode:

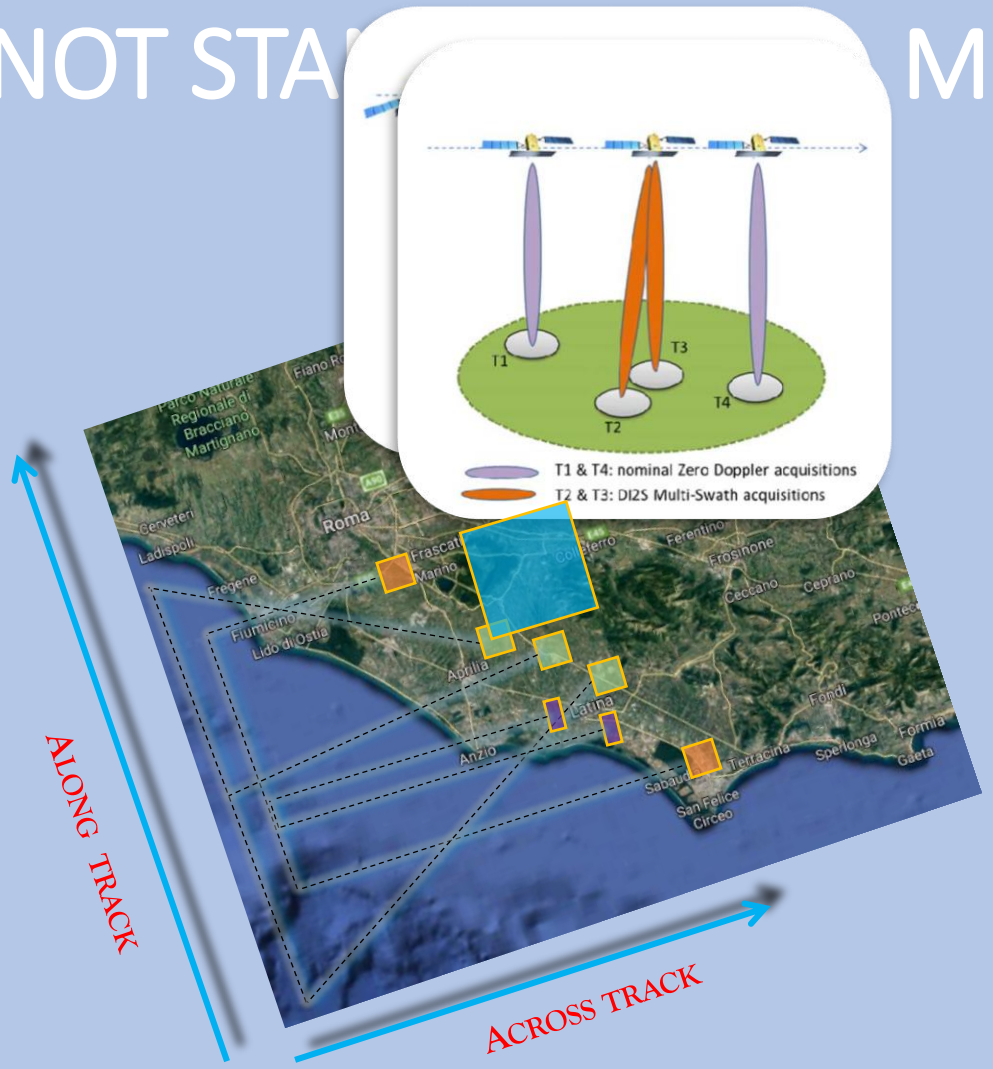
- Improved resolution
- Separation between spotlight images is ~100 km

CSG Theatre mode:

- The platform agility allows to perform pitch maneuvers
- **More images in a theatre region** can be acquired

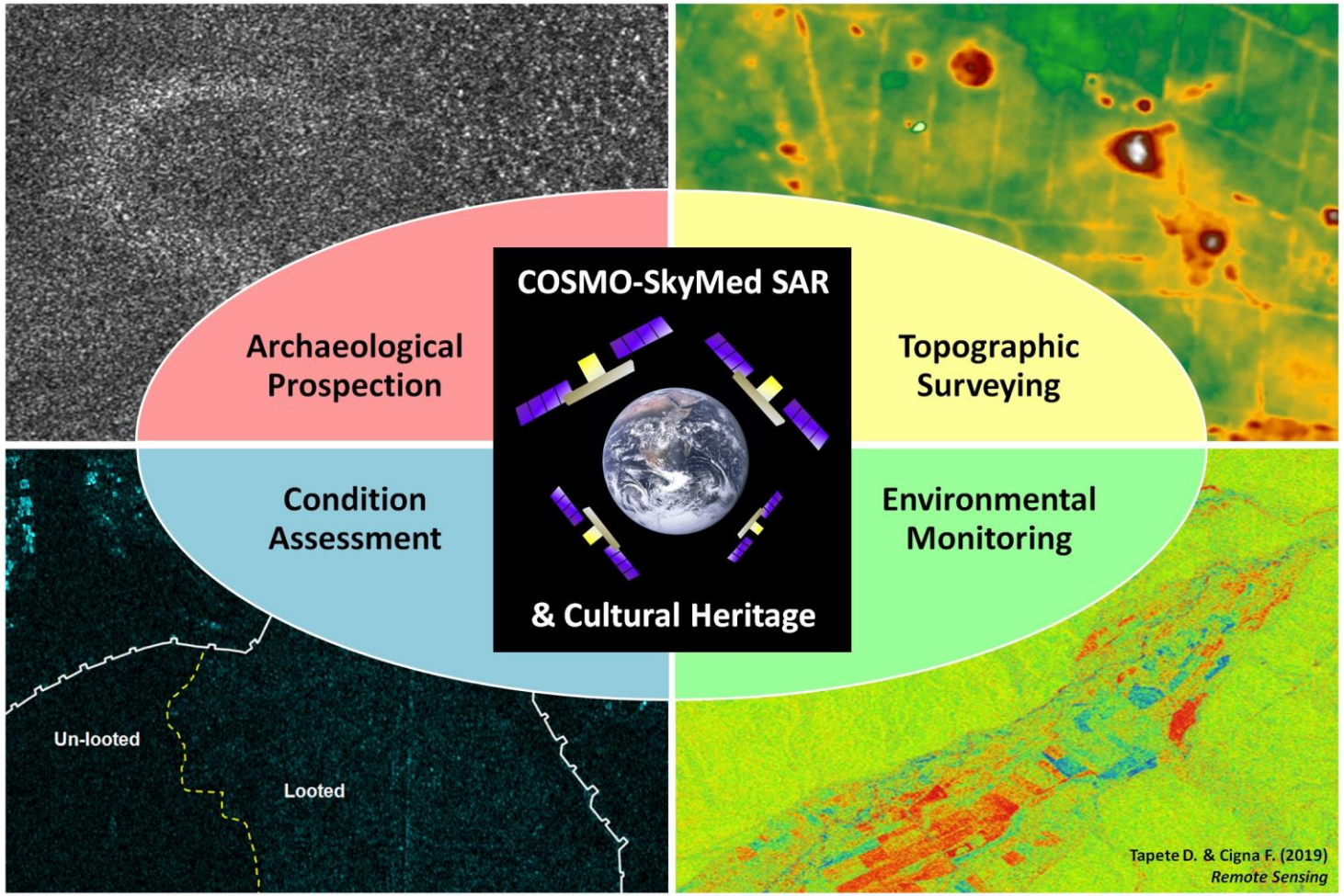
CSG DI2S:

- The SAR instrument capabilities allows to acquire **two targets** almost simultaneously (using double PRF)
- The swath is reduced in range



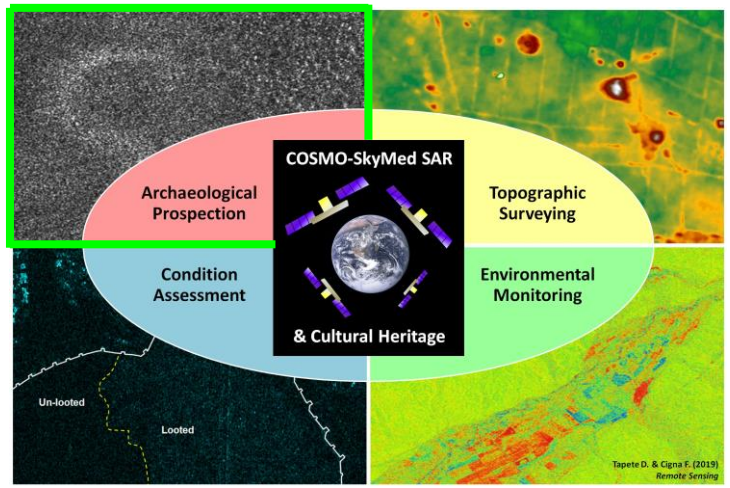
Agenzia Spaziale Italiana

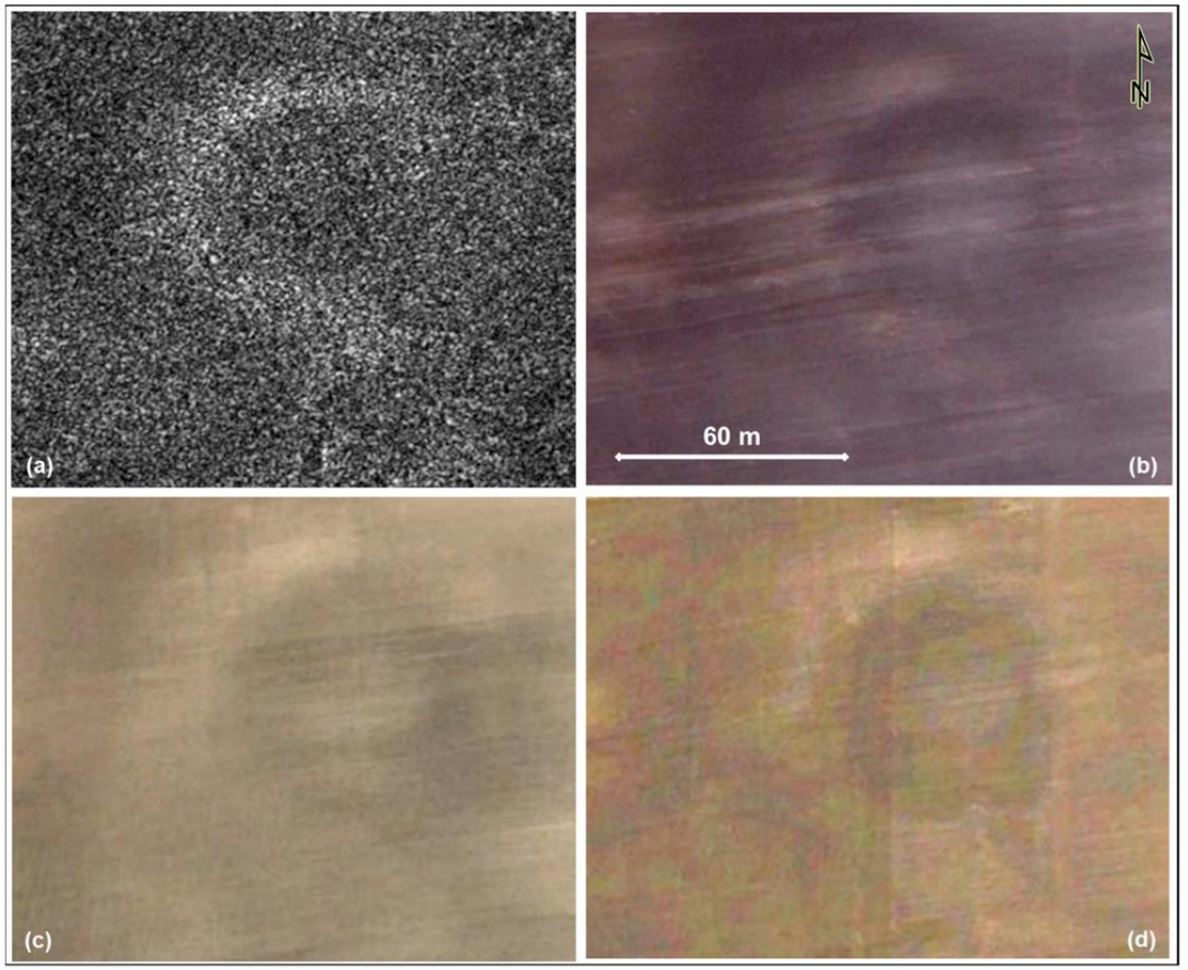
COSMO-SkyMed for cultural heritage



Tapete & Cigna (2019a)

COSMO-SkyMed for cultural heritage (prospection)

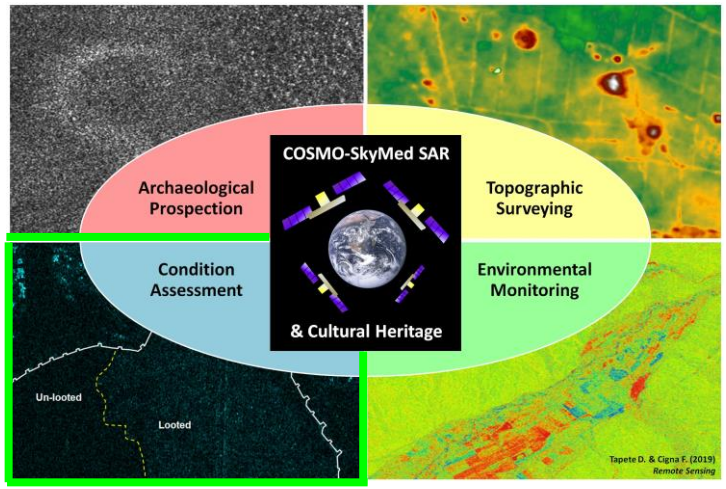


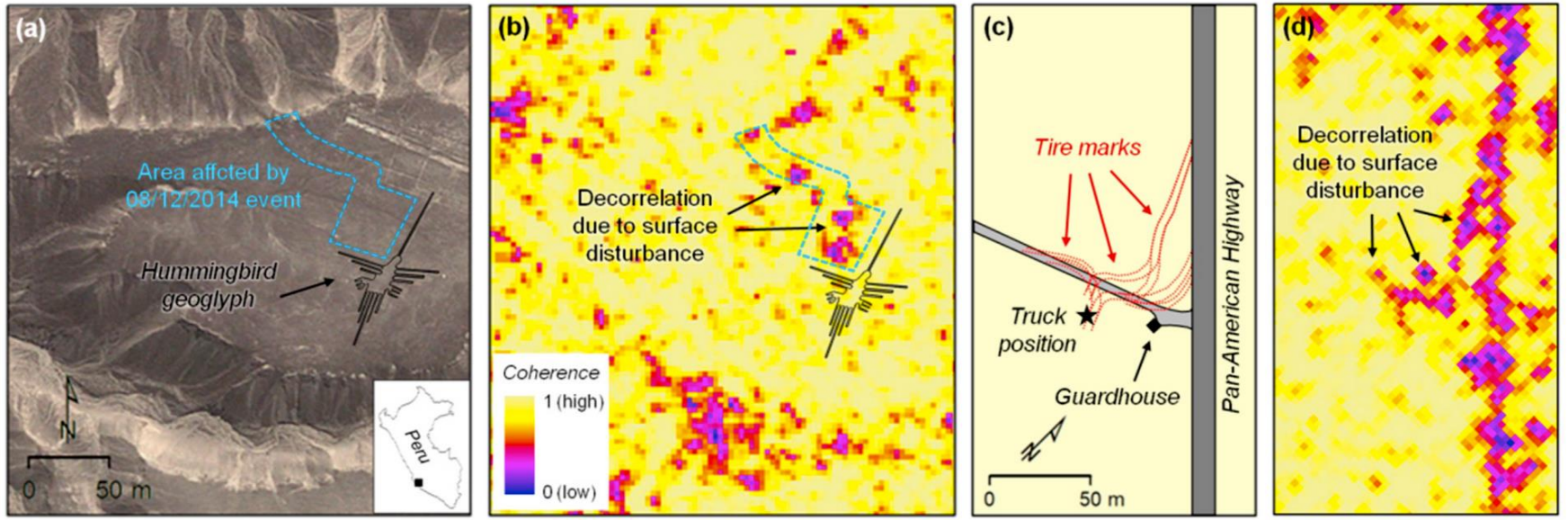


(**a**) Backscattering anomaly in bare ground observed in a COSMO-SkyMed Enhanced Spotlight image at 1-m ground resolution acquired in the summer with an incidence angle of 39°. The soil/damp mark is also visible in very high resolution optical satellite imagery (Google Earth © DigitalGlobe) acquired in (**b**) summer, (**c**) autumn and (**d**) winter.

Tapete & Cigna (2019a)

COSMO-SkyMed for cultural heritage (damage assessment)



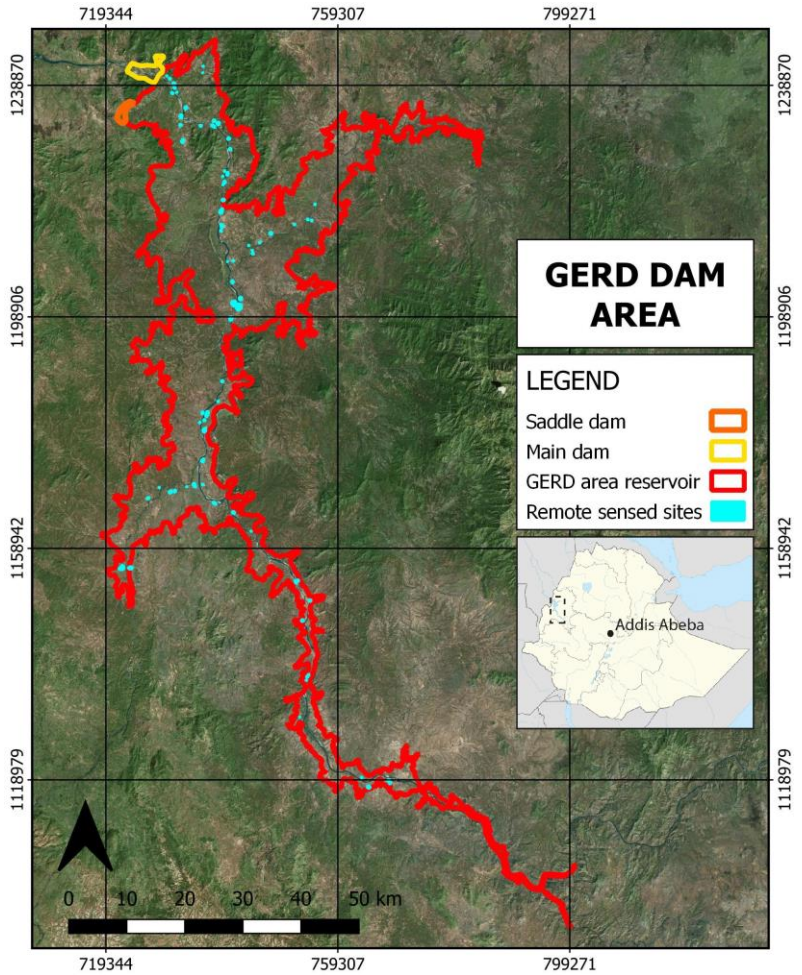


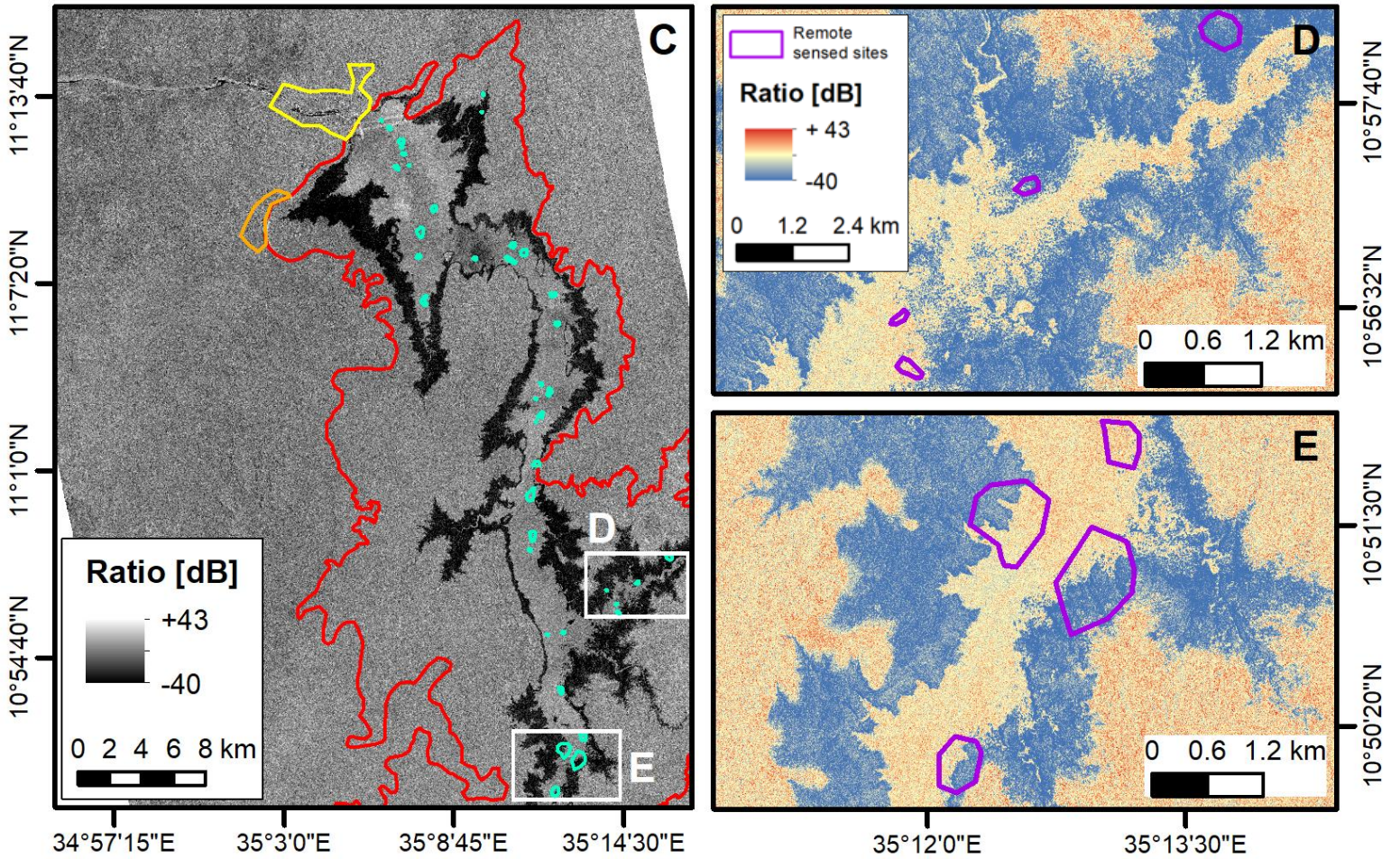
(**a**) Area affected by the surface disturbance event occurred on 08/12/2014 at the Hummingbird geoglyph in Nasca, Peru (Google Earth image © 2018 DigitalGlobe) and (**b**) COSMO-SkyMed StripMap Himage (~3 m ground resolution) InSAR coherence from cross-event pair 10/07/2014–12/04/2015 with 14 m perpendicular baseline; (**c**) sketch of the "plowing" event occurred on 27/01/2018 when a truck drove off the Pan-American Highway, and (**d**) COSMO-SkyMed StripMap Himage InSAR coherence from cross-event pair 13/12/2017–30/01/2018 with 19 m perpendicular baseline.

Cigna & Tapete (2018)

COSMO-SkyMed for cultural heritage (risk/impact assessment)

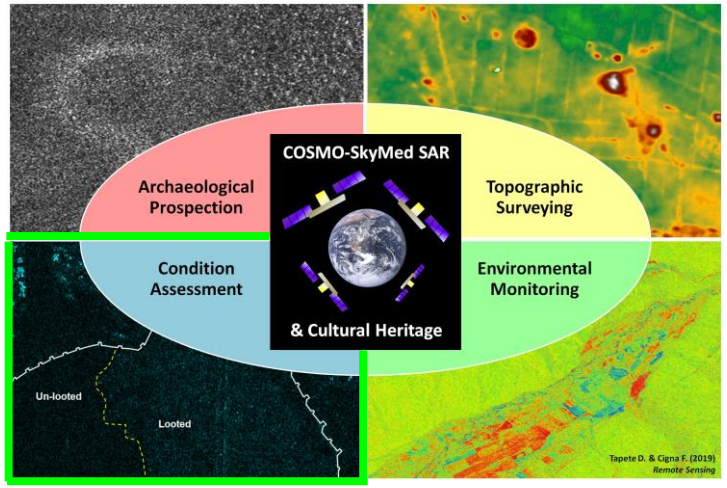
Post dam construction
05-30/05/2021-05/10/2021

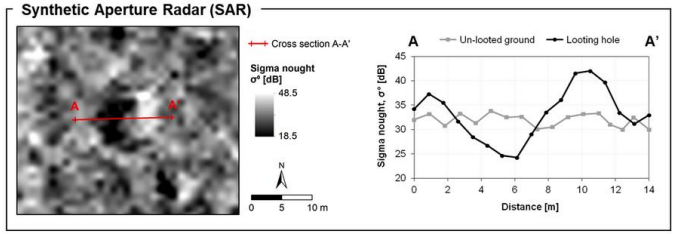


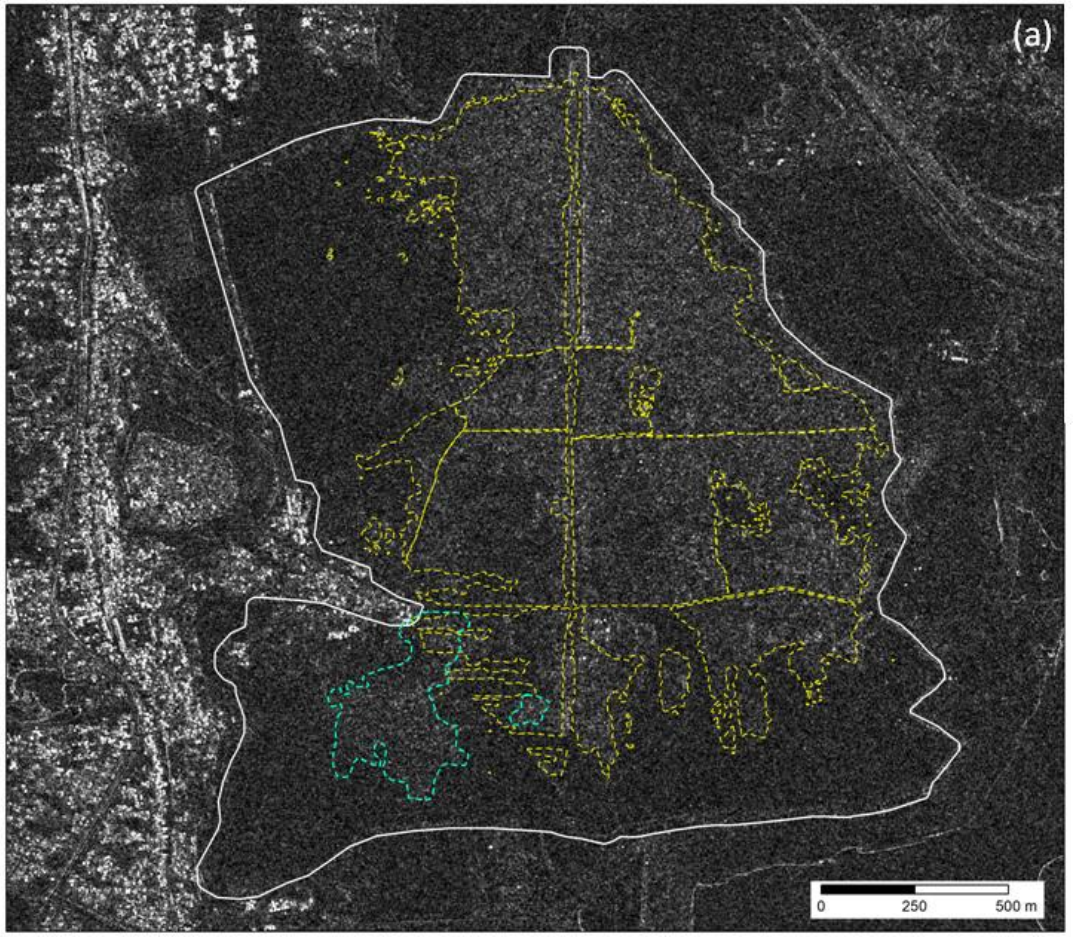


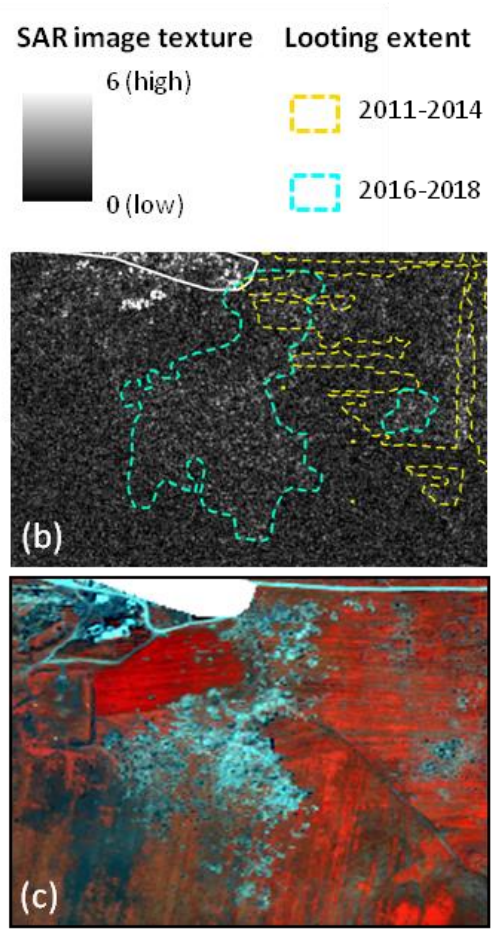
Zaina & Tapete (2022)

COSMO-SkyMed for cultural heritage (looting detection)



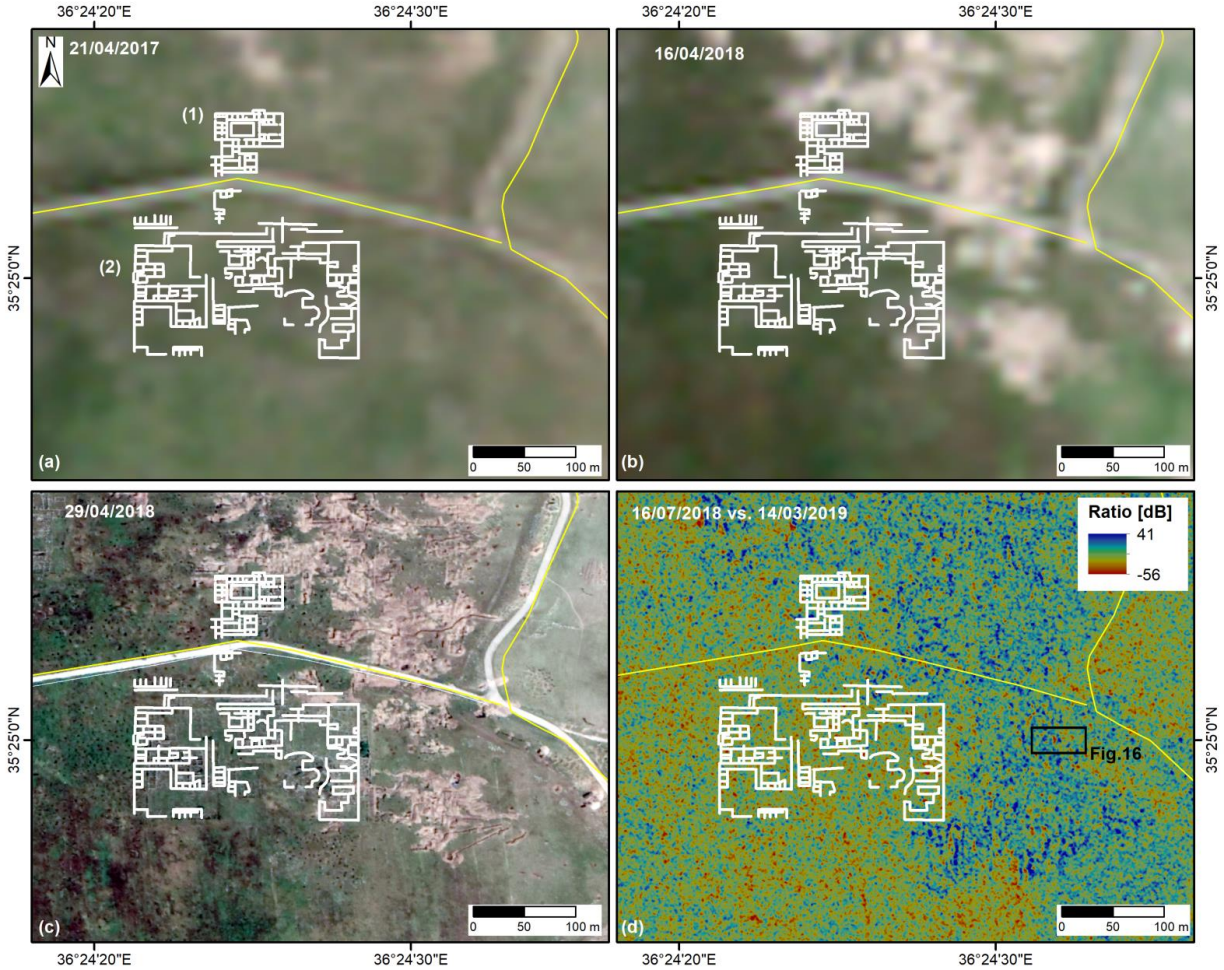


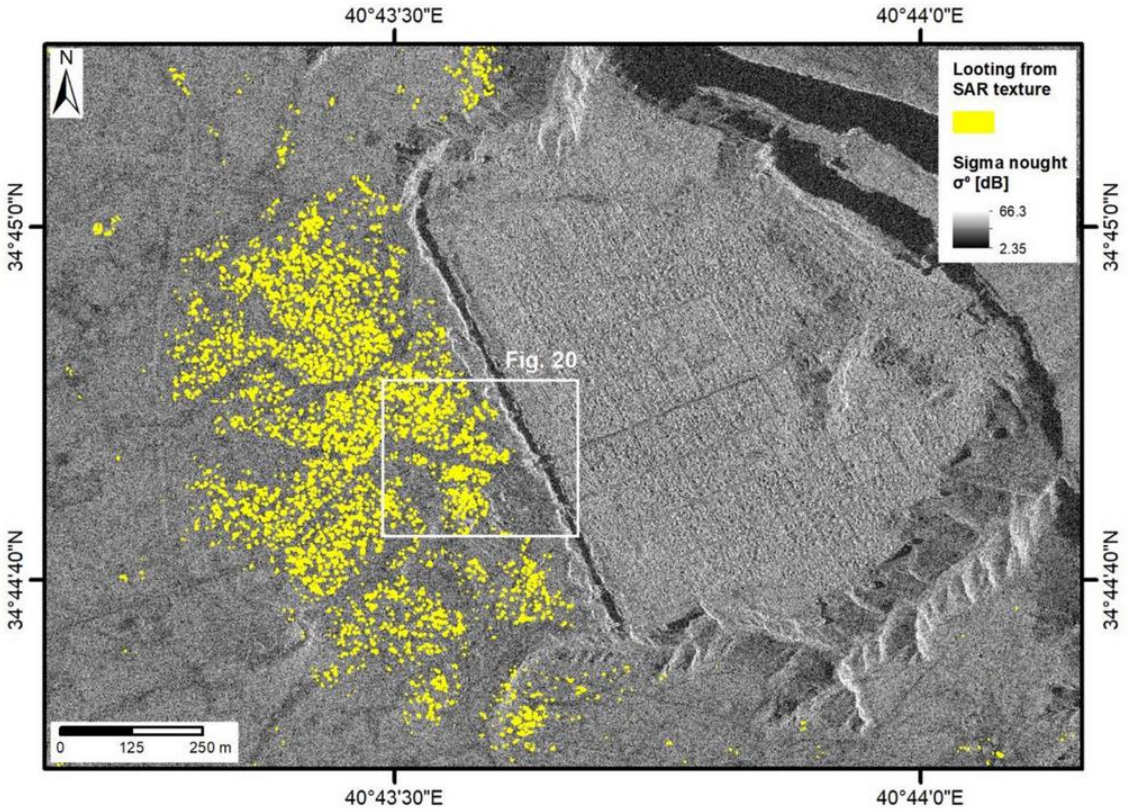




Tapete & Cigna (2019a)

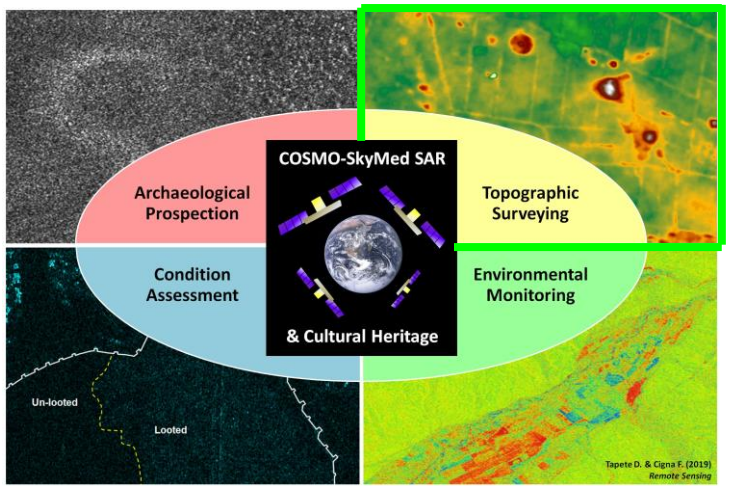
COSMO-SkyMed for cultural heritage (looting monitoring)



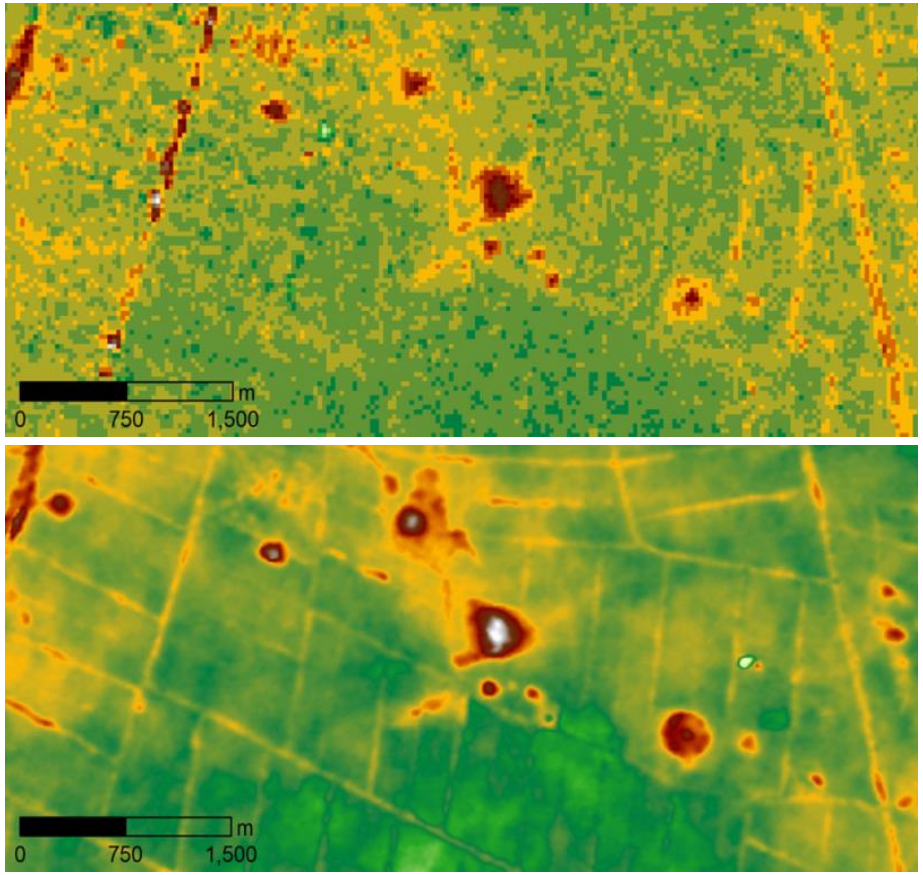


Tapete & Cigna (2019a)

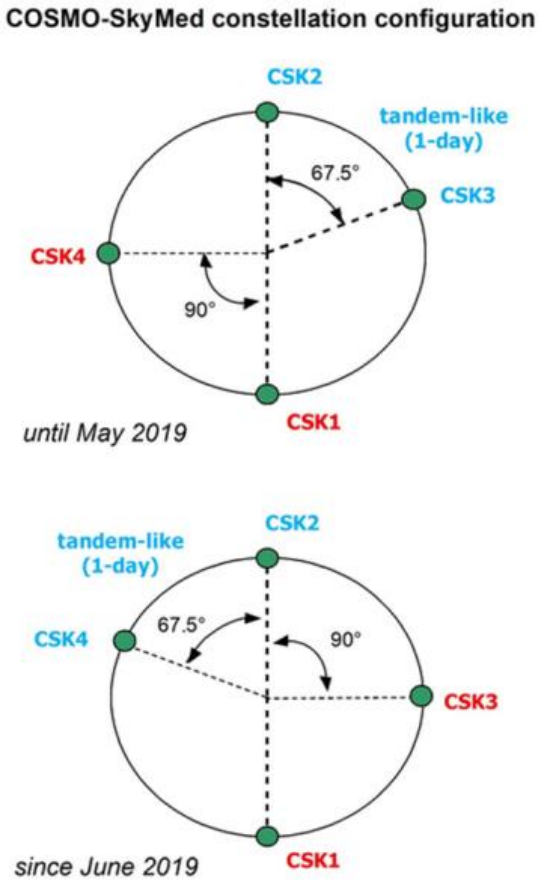
COSMO-SkyMed for cultural heritage (DEM-based surveying)



ALOS World 3D DEM

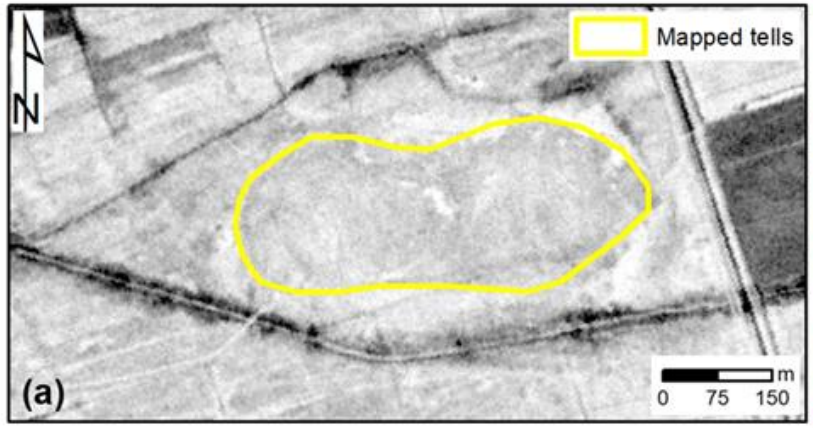


StripMap CSK DEM

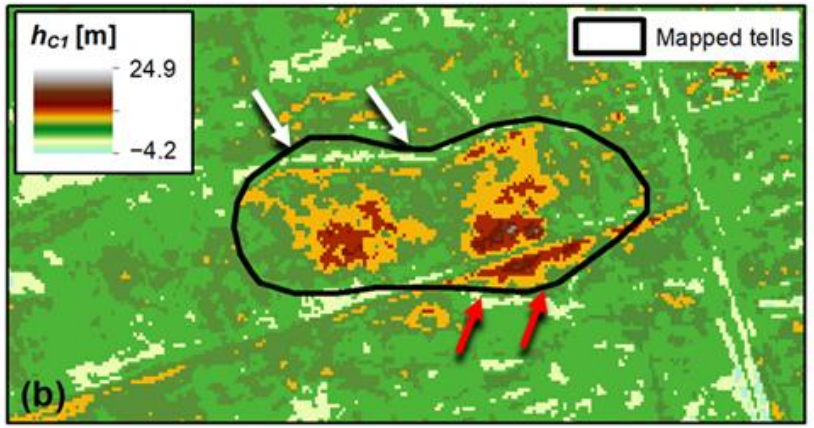


Tapete & Cigna (2019, 2021)

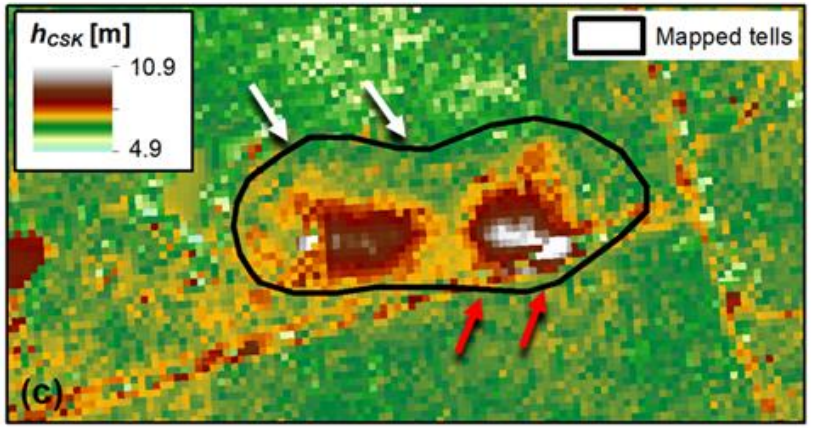
COSMO-SkyMed for cultural heritage (DEM-based monitoring)



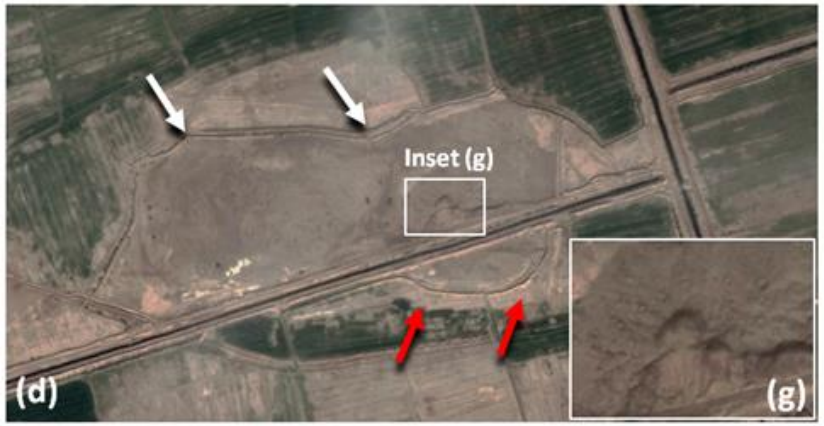
CORONA imagery



CartoSat-1 DSM ©GAF AG

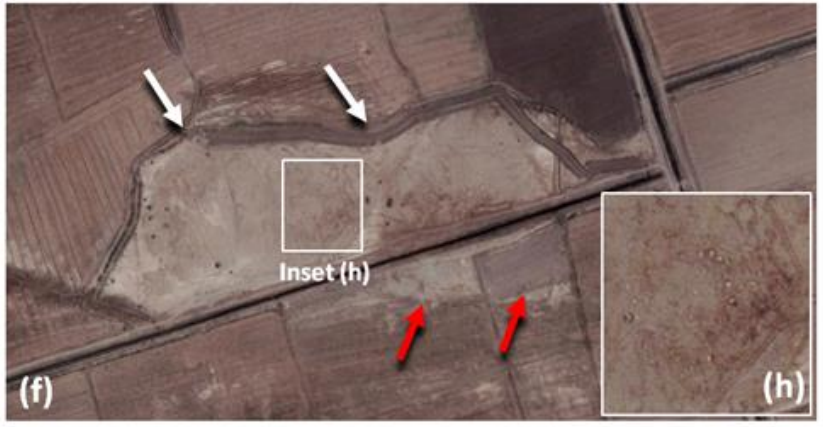


COSMO-SkyMed DEM ©ASI 2018



Google Earth 18/01/2015 ©Maxar Tech.

Google Earth 07/01/2018 ©Maxar Tech.



Google Earth 26/07/2018 ©Maxar Tech.

Tapete & Cigna (2022)

References list – 1

Anniballe R., Chini M., Pierdicca N., Bignami C., Stramondo S., Noto F., Scalia T., Martinelli A., Mannella A. (2015) Detecting earthquake damage in urban area: application to COSMO-SkyMed imagery of l'Aquila earthquake. In: *SAR Image Analysis, Modeling, and Techniques XV (September 21, 2015)*, vol. 9642, C. Notarnicola, S. Paloscia, and N. Pierdicca (Eds.), art. 96420C, 2015. doi: 10.1117/12.2195723

Cigna F., Tapete D., Lasaponara R., Masini N. (2013) Amplitude change detection with ENVISAT ASAR to image the cultural landscape of the Nasca region, Peru. *Archaeological Prospection*, 20(2), 117–131. doi: 10.1002/arp.1451

Cigna F., Tapete D. (2018) Tracking Human-Induced Landscape Disturbance at the Nasca Lines UNESCO World Heritage Site in Peru with COSMO-SkyMed InSAR. *Remote Sensing*, 10(4), 572. doi: 10.3390/rs10040572

Ferretti A., Fumagalli A., Novali F., Prati C., Rocca F., Rucci A. (2011) A new algorithm for processing interferometric data-stacks: SqueeSAR. *IEEE Transactions on Geoscience and Remote Sensing*, 49, 3460–3470. doi: 10.1109/36.898661

Lasaponara R., Masini N. (2013) Satellite Synthetic Aperture Radar in Archaeology and Cultural Landscape: An Overview. *Archaeological Prospection*, 20(2), 71-78. doi: 10.1002/arp.1452

Plank S. (2014) Rapid Damage Assessment by Means of Multi-Temporal SAR — A Comprehensive Review and Outlook to Sentinel-1. *Remote Sensing*, 6(6), 4870-4906. doi: 10.3390/rs6064870

Refice A., Capolongo, D., Lepera A., Pasquariello G., Pietranera L., Volpe F. (2014) SAR Amplitude and InSAR Coherence for Flood Monitoring: Examples with COSMO-SkyMed Data.

https://www.academia.edu/22647444/Sar_Amplitude_and_Insar_Coherence_for_Flood_Monitoring_Examples_With_Cosmo_Skymed_Data

Tapete D., Fanti R., Cecchi R., Petrangeli P., Casagli N. (2012) Satellite radar interferometry for monitoring and early-stage warning of structural instability in archaeological sites. *Journal of Geophysics and Engineering*, 9(4), S10–S25. doi: 10.1088/1742-2132/9/4/S10

References list – 2

Tapete D., Cigna F., Masini N., Lasaponara R. (2013) Prospection and monitoring of the archaeological heritage of Nasca, Peru, with ENVISAT ASAR. *Archaeological Prospection*, 20(2), 133–147. doi: 10.1002/arp.1449

Tapete D., Morelli S., Fanti R., Casagli N. (2015) Localising deformation along the elevation of linear structures: An experiment with space-borne InSAR and RTK GPS on the Roman Aqueducts in Rome, Italy. *Applied Geography*, 58, 65-83, doi: 10.1016/j.apgeog.2015.01.009

Tapete D., Cigna F. (2017) Trends and perspectives of space-borne SAR remote sensing for archaeological landscape and cultural heritage applications. *Journal of Archaeological Science Reports*, 14, 716–726. doi: 10.1016/j.jasrep.2016.07.017

Tapete D., Cigna F. (2019a) COSMO-SkyMed SAR for Detection and Monitoring of Archaeological and Cultural Heritage Sites. *Remote Sensing*, 11(11), 1326. doi: 10.3390/rs11111326

Tapete D., Cigna F. (2019b) Detection of Archaeological Looting from Space: Methods, Achievements and Challenges. *Remote Sensing*, 11(20), 2389. doi: 10.3390/rs11202389

Tapete D., Traviglia A., Delpozzo E., Cigna F. (2021) Regional-Scale Systematic Mapping of Archaeological Mounds and Detection of Looting Using COSMO-SkyMed High Resolution DEM and Satellite Imagery. *Remote Sensing*, 13(16), 3106. doi: 10.3390/rs13163106

Tapete D., Cigna F. (2022) Detection, Morphometric Analysis and Digital Surveying of Archaeological Mounds in Southern Iraq with CartoSat-1 and COSMO-SkyMed DEMs. *Land*, 11(9), 1406. doi: 10.3390/land11091406

Zaina F., Tapete D. (2022) Satellite-Based Methodology for Purposes of Rescue Archaeology of Cultural Heritage Threatened by Dam Construction. *Remote Sensing*, 14(4), 1009. doi: 10.3390/rs14041009

Interested in collaborating with ASI?

- Cultural heritage is a key application domain of Earth Observation technologies & data among ASI's R&D and downstream activities
- Opportunity to undertake joint scientific research with COSMO-SkyMed (& PRISMA hyperspectral) data

If interested, please get in touch:

deodato.tapete@asi.it

THANK YOU FOR YOUR ATTENTION!