Addressing global challenges in conservation and digital recording of UNESCO sites with VHR radar space technology

D. Tapete & F. Cigna
The challenge

Examples of archaeological looting around the World

[the map is not exhaustive]
Archaeological looting in Syria

Location and severity of looting as documented by imagery-based analysis, over areas of factional control (early 2015).

Image courtesy: J. CASANA (2016)
Archaeological looting

Definition:
‘Unauthorised excavations without any scientific purpose to rob goods of historical or cultural value to sell on illicit markets’

Crisis and war can favour its spread

Key question:
Rate of occurrence?

Satellite data requirements:
1. Very High Resolution (VHR)
2. Regular acquisitions
3. Consistent acquisition geometry
4. Iterative methodology
Synthetic Aperture Radar (SAR) imagery

RADAR: RAdio Detection And Ranging
Sensor type: Active
Frequency: 0.3-300 GHz
Wavelength: 0.001-1 m
Resolution: up to < 1 m
Platforms: satellite, airborne, UAV, ground-based
Repeat cycle: daily-monthly
Satellite SAR missions

Acquisition strategies: routine, on demand, emergency
Satellite SAR in archaeology

Dry rivers revealed thanks to the radar penetration capability

Landsat MSS

Darfur, Sudan

SIR-A data (1981)
Satellite SAR in archaeology

The Open Initiative

Open Initiative on the use of space technologies to support the World Heritage Convention (2003)
… a growing scientific literature

Scopus publications on SAR for archaeological landscapes, archaeological prospection and condition assessment of cultural heritage

Publications co-authored by archaeologists

Tapete & Cigna (2016), *J Archaeological Science: Reports*
Archaeological site of Apamea, Syria

- Situated on the right bank of the Orontes, at the top of a high relief overlooking the Ghab plain
- Its strategic position was exploited to control the trade routes by Seleucus Nicator (~300 BC)
- 7 km-long ramparts refortified by the emperor Justinian (~500-600 AD) enclose the site
Cardo Maximus and colonnade at Apamea
Cardo Maximus and colonnade at Apamea
Industrial scale looting

- Evidence of looting starting from mid 2012
- “Satellite imagery shows that archaeological sites in Syria are dotted by thousands of illegal excavations ... that show there is looting on an industrial scale”
  
  (Irina Bokova, UNESCO, 2015)

- Use of excavators and bulldozers
- Very distinctive planimetric shape
- Holes up to a few metre-wide
- Excavations depths from < 1 m to a few metres (looters’ opportunistic rationale)
A look from space

Mar 2011  July 2011
A look from space
A look from space
A look from space

Evidence from Google Earth imagery

April 2012
- 0.93 km\(^2\) (~38%) looted, of which ~75% in excavated sectors, plus ~12% in unexcavated areas

September 2012
- New looting 0.015 km\(^2\) NW

March 2014
- Expansion NW up to 0.105 km\(^2\)

OPEN QUESTIONS
- Looting rates?
- Repeated looting?

TAPETE et al. (2016), Remote Sensing of Environment
VHR satellite radar experimental campaign

DLR grant LAN2377: TerraSAR-X Staring Spotlight mode for damage assessment, looting monitoring and prospection of archaeological features in semi-arid environment (PI: D. Tapete)

Marie Curie research grant; EU COFUND/Durham Junior Research Fellowship [EU grant agreement no.267209]

- Bespoke time series of **TSX Staring Spotlight**, bimonthly sampling, **24 cm azimuth resolution**
- Consistent geometry and acquisition parameters: ascending orbits, 39.7° θ
TerraSAR-X Staring Spotlight imagery

TAPETE et al. (2016), Remote Sensing of Environment
Conceptual model

TAPETE et al. (2016), Remote Sensing of Environment
Conceptual model

Set A
- $h = 1\,\text{m}$
- $\alpha = 0^\circ$
- $l = 0.5\,\text{m}$, $l = 1\,\text{m}$, $l = 1.5\,\text{m}$, $l = 2\,\text{m}$, $l = 2.5\,\text{m}$, $l = 3\,\text{m}$, $l = 3.5\,\text{m}$

Set B
- $l = 2\,\text{m}$
- $\alpha = 0^\circ$
- $h = 0.25\,\text{m}$, $h = 0.5\,\text{m}$, $h = 0.75\,\text{m}$, $h = 1.25\,\text{m}$, $h = 1.5\,\text{m}$, $h = 1.75\,\text{m}$, $h = 2.0\,\text{m}$

Set C
- $l = 2\,\text{m}$
- $h = 1\,\text{m}$
- $\alpha = 12.5^\circ$, $\alpha = 25^\circ$, $\alpha = 37.5^\circ$, $\alpha = 50^\circ$, $\alpha = 62.5^\circ$, $\alpha = 75^\circ$

Set D
- $l_1 = 2\,\text{m}$
- $l_2 = 3.5\,\text{m}$
- $\alpha = 0^\circ$
- $h = 1\,\text{m}$
- $\alpha = 0^\circ$, $\alpha = 30^\circ$, $\alpha = 60^\circ$, $\alpha = 90^\circ$, $\alpha = 120^\circ$, $\alpha = 150^\circ$

Set E
- Various
- $d = 1\,\text{m}$, $d = 2\,\text{m}$
- $h = 0.5\,\text{m}$, $h = 1\,\text{m}$
- $h = 1\,\text{m}$

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TAPETE et al. (2016), Remote Sensing of Environment
Texture analysis and feature extraction

TAPETE et al. (2016), Remote Sensing of Environment
Texture analysis and feature extraction

22\textsuperscript{nd} October 2014

27\textsuperscript{th} December 2014

20\textsuperscript{th} February 2015

\textbf{TAPETE et al.} (2016), Remote Sensing of Environment
Interpretation key matrix

<table>
<thead>
<tr>
<th>Un-looted ground</th>
<th>New looting</th>
<th>Hole filling</th>
<th>Unchanged hole</th>
<th>Looting cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="a" alt="Image" /></td>
<td><img src="b" alt="Image" /></td>
<td><img src="c" alt="Image" /></td>
<td><img src="d" alt="Image" /></td>
<td><img src="e" alt="Image" /></td>
</tr>
</tbody>
</table>

**Google Earth**

<table>
<thead>
<tr>
<th>(\sigma_{\text{t_s}}^0(i))</th>
<th>(\sigma_{\text{t_z}}^0(i))</th>
<th>(R_{t_s/t_z}(i))</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="a" alt="Image" /></td>
<td><img src="a" alt="Image" /></td>
<td><img src="a" alt="Image" /></td>
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<td><img src="b" alt="Image" /></td>
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</tr>
</tbody>
</table>

**SAR backscattering [dB]**

- High
- Low

**Ratio [dB]**

- +
- 0
- -

**TAPETE et al. (2016), Remote Sensing of Environment**
Dynamic assessment of looting rates

(a) Oct 2014 / Dec 2014

- 132 looting marks/month (Type 1)
- 82 filling marks/month (Type 2)
- Tot.: 214 marks/month

(b) Dec 2014 / Feb 2015

- 420 looting marks/month (Type 1)
- 235 filling marks/month (Type 2)
- Tot.: 655 marks/month

TAPETE et al. (2016), Remote Sensing of Environment
Dynamic assessment of looting rates

(c) Apr 2015 / Feb 2015

432 looting marks/month (Type 1)
255 filling marks/month (Type 2)

Tot.: **687 marks/month**

(d) Jun 2015 / Apr 2015

535 looting marks/month (Type 1)
245 filling marks/month (Type 2)

Tot.: **780 marks/month**

TAPETE et al. (2016), Remote Sensing of Environment
Looting in 2015 vs. 2016

Optical perspective

End 2015

Radar perspective

Texture

High: 6.01
Low: 0.001

Modern road

Cardo Maximus

Modern road

Cardo Maximus

Mid 2016

Looting intensification
Dura Europos
Dura Europos

Archaeological ruins

Icons in the Jewis Synagogue (~244 A.D.)

© Marsyas 2008

© umbrella.it

© heorthodoxlife.wordpress.com
Dura Europos

TerraSAR-X Staring Spotlight
Radar image 2016
Dura Europos

TerraSAR-X Staring Spotlight
Image texture 2016
Conclusions and future perspectives

Current scenario in satellite SAR science for archaeology

- SAR is not affected by weather conditions, hence monitoring campaigns are largely weather-independent in both arid and humid regions, overcoming limitations of optical imagery (occasionally cloud covered)

- TerraSAR-X Starting Spotlight (< 1 m) brings radar to resolution levels close to those of optical imagery (e.g. QuickBird, GeoEye)

Non-invasive analysis of VHR satellite radar imagery offers novel opportunities

- Digital recording and prospection (feature detection, delineation and mapping; discovery of semi-buried structures; palaeo-environmental studies)

- Conservation and preservation (looting monitoring and damage assessment; condition assessment; safeguarding from natural and anthropogenic geohazards; environmental landscape evolution)
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