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Археология и геоинформатика. Выпуск 7

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Integrated geophysical prospection by high-resolution optical satellite images, Synthetic Aperture Radar and magnetometry at the example of the UNESCO World Heritage Site of Palmyra (Syria)

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Introduction

In the last decades integrated geophysical prospection became a very important tool in archaeology [Scollar et als., 1990; Neubauer et als., 2002; Gaffney, Gator, 2003; Fassbinder, 2007]. Without a previous geophysical prospection modern excavations can hardly be performed because the survey results give strong hints for promising areas as expensive large scale excavations cannot be made anymore today. Furthermore geophysical prospection delivers a non-destructive tool for the understanding of an archaeological site in its context. Therefore in 1997-1998 a cooperation between the Bavarian State Department of Monuments and Sites (BLfD) in Munich and the Institute of Classical Archaeology of the University Vienna was established for geophysical surveys by magnetometry and resistivity prospection in the proposed area of the Hellenistic part of Palmyra (Syria) in advance of archaeological investigations. As a result of the huge size of more than 10 km² [Bounni, al-As'ad, 1990] and the fact that several parts of the Roman Palmyra are still preserved at the surface, we focused the prospection on the Hellenistic part of the city. So since 2011 another cooperation of the BLfD and the German Aerospace Centre (DLR) in Oberpfaffenhofen has the goal to investigate the whole site of Palmyra by remote sensing with optical and radar satellites. The advantages of satellite surveys over ground-based ones are manifold. First of all an area of several square kilometres can be surveyed in a short time (e.g. the used TerraSAR-X image was acquired in approximately one minute), whereas even for magnetometry only a few hectares per day can be achieved by using a motorised vehicle. Furthermore because of the possible size of satellite images not only the site itself is covered, but also the surrounding cultural environment can be studied and historic living landscapes can be seen in context. Another important topic is that several regions in the world, e.g. Syria itself at the moment, are not easily accessible for ground-based studies because of political reasons. In these cases only remote sensing can be performed. An advantage of radar over optical images is the use of an active sensor in the microwave spectrum. Therefore the data takes can be performed independently of daylight and weather conditions because the radio waves penetrate through clouds. In the last few years the resolution of satellite sensors increased rapidly. So with optical images of the new high-resolution satellites QuickBird and WorldView-2 a point spacing of 0,6 m is possible. In Synthetic Aperture Radar (SAR) the improvement is even more serious. So until the launch of the German radar satellite TerraSAR-X in 2007 the best resolution of SAR images has been 25 m, whereas now 1-2 m is possible. But even with the increased resolution, a ground truthing in selected areas should be performed to eliminate methodically errors of the satellite prospection.

Historical background

Palmyra is situated 230 km northeast of Damascus in a fertile oasis in the Syrian Desert (fig. 1). Hence the area has been settled since Palaeolithic times (75,000 BP) [Browning, 1979; Bounni, al-As'ad, 1990]. The first written evidence can be dated to the 2nd millennium BC, when Palmyra is mentioned in the Assyrian and Babylonian cuneiform plates of Kültepe (Cappadocia) and Mari (Syria) [Michałowski, 1968; Degeorge, 2002; al-As'ad, Schmidt-Colinet, 2005b]. So already then, Palmyra must have been a bigger settlement. Else it would not have been known in such a distance. The next secured findings can be found of Hellenistic times in the area south of the Wadi el Kubur which is running through the ancient city. Already in Hellenistic times, when in the 3rd Cent. BC Palmyra got part of the Diadochian Empire of Seleukos, there was an increase in prosperity as the Palmyrenes managed to set up the only safe caravan route in the region. In this time Palmyra only had few contacts to western cities like Pergamum and Rome. In fact the citizens oriented themselves and their culture towards the east, especially to the Seleucid cities of Seleucia and Dura Europos or the Parthian cities like Hatra. The contact to the western civilizations started in the 1st Cent. BC when there was a peace treatment between Rome and the Parthians [Schmidt-Colinet, 1997; al-As'ad, Schmidt-Colinet, 2005a]. Therefore the Palmyrene architecture shows a unique example of the intercultural connection between the East and the West in ancient times. In the 1st Cent. AD Palmyra got part of the Roman province Syria [Hartmann, 2001]. It was not until the following centuries when Palmyra got a Hellenistic-Roman town as a result of the steady Romanisation. The most prosperous time of Palmyra came in the 2nd Cent. AD, when the Nabatean Empire, which was the biggest enemy in caravan trade, was conquered by the Roman emperor Trajan [Degeorge, 2002]. This can be evidenced in the monumental architecture of this century, when the well known monuments like e.g. the Bel-sanctuary, the Great Column Road and the tower tombs were erected. In this time the Palmyrene trade network reached from Spain in the west to China in the east. But already at the end of the same century the decline began as a consequence of the Parthian wars and the associated shift of the trading route towards the north [Degeorge, 2002]. After the famous usurpation of Queen Zenobia in 262 AD, Palmyra was conquered by the Roman emperor Aurelian and afterwards it only served as a military post at the Roman Limes Arabicus. So around 300 AD Diocletian built a new city wall and a huge fortress in the western part of the city [Hartmann, 2001; Degeorge, 2002; al-As'ad, Schmidt-Colinet, 2005b; Gawlikowski, 2005]. In 634 AD it was conquered by the Arabs under their general Khalid ibn al-Walid [Degeorge, 2002; al-As'ad, Schmidt-Colinet, 2005a]. But after the Abbasids moved their capital from Damascus to Bagdad, Palmyra totally lost its importance and it declined to a small village [al-As'ad, 1987; 1993; al-As'ad et als., 2005; al-As'ad, Schmidt-Colinet, 2005b]. In Ottoman times (16th-19th Cents.) Palmyra was a negligible settlement, left open for the raid of the Bedouins [al-As'ad, 1993].

The ancient ruins were rediscovered by western explorers in the 17th Cent. and in the next century there were published the first books by Wood & Dawkins [1753] and Cassas [1799]. In the 19th and the beginning of the 20th Cent. several expeditions went to Palmyra, e.g. by the Russian Archaeological Institute under F.S. Uspienski, B.W. Farmakowski and P.K. Kokowzow (1900), O. Puchstein (1902), T. Wiegand (1917). After the World War I Syria got part of the French protectorate who resettled the remaining people to a new town north of the ancient ruins to be able to start the first systematic excavations in the 1920/30s under H. Seyrig, J. Cantineau, R. Amy, J. Starckey, D. Schlumberger and W. Will [al-As'ad, Schmidt-Colinet, 2005b]. Since this time there are continuously excavations by archaeologists from all over the world.

As Palmyra today is the most important ruin site of the Hellenistic-Roman times in Syria, it got a UNESCO World Heritage Site in 1980. Today the modern Palmyra has 40,000 inhabitants [Gerster, Wartke, 2003].

The ancient ruins of Palmyra provide an excellent test site for geophysical methods and Remote Sensing, because huge parts of the city still remain unexcavated and the whole city had never been overbuilt in post-ancient times. Another important factor is that the archaeological findings are only covered by a thin layer of sand and therefore provide good contrast to the surrounding material.

Geology and Climate

Geologically the region of Palmyra is characterized through two main units. In the north and west of the city there are the mountain ranges of the Palmyra Chains which run from Lebanon to the Euphrates. These depict geologically young mountains formed of disrupted folds by the subduction of the Arabian plate under the Eurasian and they are characterized by a uniform strike from southwest to northeast [Jux, Omara, 1960; Schachinger, 1987; Gerster, Wartke, 2003]. The mountains consist of Cretaceous sandstones, limestones and dolomites; the centre is underlain by basaltic rocks. Whereas these mountains can reach a height of nearly 1000 m, e.g. Djebel Hayān with 941 m above see level (a.s.l.) or Djebel al-Mazār with 808 m a.s.l., Palmyra is situated in a depression at the foot of these mountains at 395 m a.s.l. [Jux, Omara, 1960; Schachinger, 1987; Bounni, al-As'ad, 1990]. This depression was formed by lacustrine Quaternary sediments. South of Palmyra begins the Shamiya, the Syrian Desert, which reaches until Mesopotamia [Jux, Omara, 1960; Schachinger, 1987; Sanlaville, Traboulsi, 1996]. These hammadas consist of Pliocene lime- and sandstone and Quaternary conglomerates, debris and sands. Near Palmyra the depression is filled by a Sebkha with an area of 330 km² whose salt flats are exploited since ancient times and therefore depicts one reason of the prosperity of the Roman town [Sanlaville, Traboulsi, 1996].

Palmyra is characterized by an annual temperature average of 19° C and an average monthly precipitation of 11 mm (fig. 2). So climatically the region of Palmyra belongs to the Saharan Desert Climate [Combier, 1933; Schachinger, 1987]. Palmyra is the second driest area in Syria and worldwide only 178 regions are drier (while 4034 are wetter) [NCDC, 1998]. Whereas in winter there is a moderate amount of precipitation of 22 mm in monthly average, between June and September there is a strong dry season with hardly any rain. This very arid climate is a result of the Anti-Lebanon mountain chain which is prohibiting that in summer rain from the Mediterranean Sea arrives at Palmyra. In contrast in winter small amounts of rain reach Palmyra when humid air is brought by the wind from northwest [Higuchi, Izumi, 1994]. However in former time the climate must have been considerably wetter because the Sebkha has developed in Palaeolithic times. Radiocarbon dating gives evidence that even in Roman times there could has been a slightly more humid climate which favoured settlement in the region [Sanlaville, Traboulsi, 1996].

The used TerraSAR-X image has been taken on 28 February 2011. Although this date is still in the period of precipitation (fig. 2), there are excellent results. Partly this can be due to the fact that the February 2011 has been much drier than the monthly average, as there has been 6 mm lower precipitation (Internet: Monthly Climatic Data for the World). The resistivity measurements also were taken in March 1997 and 1998 because in this season there is a high enough amount of water in the subsoil that provides a good conductivity contrast between conduction soil and non-conducting walls.

The Missions TerraSAR-X and TanDEM-X

Synthetic Aperture Radar (SAR) provides a powerful tool for archaeological prospection from space. This method is based on a satellite sensor in the microwave frequency range which is illuminating the earth surface with short pulses. Therefore SAR is an active survey method and measurements are possible independently of daylight and weather conditions [Lee, Pottier, 2009]. As a result of the specific reflection conditions in the microwave spectrum, the SAR image show even structures which are smaller than the actual resolution of the sensor [Albertz, 2009]. This is a very important fact for the satellite based prospection of archaeological sites like Palmyra.

To get the highest possible resolution from space a technical trick, the aperture synthesis, has to be applied. The targets are illuminated several times in one measurement cycle and the returned signals are correlated by their amplitude and phase. Afterwards the data points are treated as if they were gathered by one long antenna [Bamler, 1999; Albertz, 2009; Lee, Pottier, 2009]. This is called the aperture synthesis and the method is named Synthetic Aperture Radar. SAR is the only possibility to get high-resolution radar data from space because of the huge distance between sensor and targets otherwise an antenna length of 15 km would be needed for a resolution of 1 m. By SAR this length is reduced to 5 m.

For the following SAR-survey in Palmyra the TerraSAR-X satellite was used. TerraSAR-X is a new German radar satellite that was launched in June 15, 2007 (fig. 3). It carries a high frequency X-band SAR sensor that can be operated in three different modes and various polarizations. The Spotlight-, Stripmap- and ScanSAR-modes provide high resolution images for detailed analysis as well as wide swath data whenever a larger coverage is required. These high geometric and radiometric resolutions together with the single, dual and quad-polarization capability are innovative and unique features with respect to space borne systems. Additionally several incidence angle combinations are possible and double side access can be realized by satellite roll manoeuvres. The satellite is positioned in a sun-synchronous 11 days repeat orbit [Werninghaus, Buckreuss, 2010]. For the main parameters of the TerraSAR-X-Mission see Table 1.

TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) opens a new era in spaceborne radar remote sensing. A single-pass SAR interferometer with adjustable baselines in across- and in along-track directions is formed by adding a second (TDX), almost identical spacecraft to TerraSAR-X (TSX) (fig. 4). With typical across-track baselines of 200-400 m a global Digital Elevation Model (DEM) with 2 m relative height accuracy at a 12 m posting will be generated [Moreira et als., 2004].

The TDX satellite is a rebuild of TSX with only minor modifications. This offers the possibility for a flexible share of operational functions for both the TerraSAR-X and TanDEM-X missions among the two satellites. The TDX satellite is designed for a nominal lifetime of 5 years. Predictions for TSX based the current status of system resources indicate at least one extra year (until the end of 2013) of lifetime, providing the required three years of joint operation.

The missions TerraSAR-X and TanDEM-X jointly share the same space segment consisting of the TSX and TDX satellites orbiting in close formation and are operated using a common ground segment, that was originally developed for TerraSAR-X and that has been extended for the TanDEM-X mission. A key issue in operating both missions jointly is the different acquisition scenarios: whereas TerraSAR-X requests are typically single scenes for individual scientific and commercial customers, the global DEM requires a global mapping strategy. The two satellites will downlink their data to a global network of ground stations: Kiruna in Sweden, Inuvik in Canada and O'Higgins in the Antarctic. The entire processing chain is a new TanDEM-X specific development. However, it consists of individual modules which strongly benefit from the TerraSAR-X and the Shuttle Radar Topography Mission (SRTM) heritage. Major design drivers result from the acquisition strategy which requires the combination of several (global) coverages and application of multi-baseline processing techniques based on supporting intermediate products.

The TDX satellite was launched on 21st of June 2010. The first three months of the commissioning phase were dedicated to calibration and performance verification and revealed calibration accuracies and overall performance of the TDX SAR system and its products as good as for TSX. Comprehensive testing of the various safety measures has been performed in parallel to check-out activities on the new ground segment elements. In a Formation Flight Review early October "green light" was given for entering the close formation, which was achieved on October 14th, 2010. Bistatic DEMs are being acquired since then.

Table 1.
Main TerraSAR-X System Parameters.

Height	4,88 m
Width	2,4 m
Launch Mass	1,230 kg (including payload mass 400 kg)
Orbit height	514 km

Inclination	97,4°, sun-synchronous
Orbit tube	250 m radius
Orbit maintenance frequency	between 1/week and 1/day (depending on solar activity)
Orbit determination accuracy	better than 20 cm (with 2-frequency GPS)
Imaging capability	up to 300 sec/orbit
Launcher	Dnepr-1 (former SS-18)
Launch TerraSAR-X	15 June 2007, 4:14 h (CEST) From Baikonur, Kazakhstan
Life time	5 years (consumables up to 7 years)
Radar frequency	9,65 GHz
Transmit bandwidth	5 ... 150 MHz nominal 300 MHz experimental
Polarization	HH / VV / HV / VH
StripMap Mode [Range × Azimuth]	Resolution: 3 m × 3 m Scene Size: 30 km × 50 km
Spotlight Mode [Range × Azimuth]	Resolution: 1 m × 1.5 m ... 3,5 m Scene Size: 10 km × 5 km ... 10 km
ScanSAR Mode [Range × Azimuth]	Resolution: 16 m × 16 m Scene Size: 100 km × 150 km

Back

Geophysical prospection

For the prospection of archaeological sites several geophysical methods can be used. These are mainly magnetometry, resistivity prospection and radar. Whereas the last two methods are very time consuming, but provide high resolution images of buried stone structures, magnetometer prospection is suitable for most types of archaeological remains. Magnetometry is a successful and cost-effective tool for the detailed mapping of large areas in a reasonable time [English Heritage, 2008]. For our purpose and in order to reach the highest possible sensitivity combined with a maximum speed of prospection, the so-called "duo-sensor" configuration [Becker, 1999] was chosen. The probes are therefore mounted on a wooden frame and are carried in a zigzag-mode 30 cm above the ground. The profiles are oriented approximately east-west in order to minimize technical disturbance of the magnetometer probes. The used Scintrex Smartmag SM4G Special magnetometer provides a measurement of the geomagnetic field with a sensitivity of ± 10 pT; for comparison: the value of the geomagnetic field in Palmyra in March 1997 has been 45,440 ± 30 nT. During 1997 and 1998 solar activity and the diurnal variation induced by the solar wind were very low. These linear changes in the daily variation of the geomagnetic field were reduced to the mean value of the 40 m sampling profile or alternatively to the mean value of all data of a 40 × 40 m grid [Fassbinder, Gorka, 2009]. Here it is assumed that the variation of the Earth's magnetic field during one profile length of 40 m follows a linear increase or a linear decrease in intensity. If so, it is possible to eliminate this variation for each traverse line by a reduction to the mean line value. This filters apparent linear structures parallel to the profile. Alternatively in magnetically quiet areas it is also useful to calculate the mean value of the whole 40 × 40 m square and use this value as described above. Additionally by using this procedure the difference between the measurement of both magnetometer probes and the theoretically calculated mean value of the Earth's magnetic field was obtained. This intensity difference gave the apparent magnetic anomaly, which was caused by the magnetic properties of the archaeological structure, the soil magnetism and the geology. To cancel the natural micro-pulsations of the Earth's magnetic field, a band pass filter in the hardware of the magnetometer processor was used. Usually more than 90 % of the magnetometer data in a 40 m grid on archaeological sites vary in the range of ± 10 nT from the corrected mean value of the geomagnetic field. Stronger anomalies can be ascribed to burned structures or to pieces of iron containing slag or iron rubbish. In situ burning, pieces of iron and the traces of hypocausts are easily distinguishable by their different direction of magnetic dipole anomalies but also by their high intensities (> ± 50 nT).

The geophysical prospection of intensively used ancient archaeological sites is very promising. This is proved by a huge amount of successful measurements [Benech, 2007; Fassbinder, 2011; Erkul et als., 2011]. While the majority of such sites show magnetic anomalies of more than ± 30 nT, in Palmyra comparatively weak anomalies occurred.

Almost all of the Roman buildings are stone constructions. Stone in the adjacent soil however provides a high contrast in the electric conductivity. So similar structures can be mapped very clearly by resistivity and radar prospection. The first method is based on the apparent differences in the conductivity of the soil. Clays and marls for example have specific values of resistivity of 3-100 Ohm m. In contrary sands, lime stones and sandstones provide resistivity values of 100-5000 Ohm m. Hence especially in a very well conducting wet soil the resistivity of stone constructions is several degrees higher than in the surrounding soil.

For the measurements we used the commercial Geoscan RM15 instrument (Geoscan Research, Bradford, UK) in a so called dual-pole configuration. In this configuration one current and one potential probe are positioned in "infinity" (i.e. in a distance of around 50 m away from the measurement grid). The survey is then conducted with two electrodes mounted at a frame in a fixed distance of 50 cm.

The visualization is carried out with a greyscale image like in the magnetometer prospection. High resistivity values of the walls appear in black, undisturbed soil in lighter grey. By the application of a high-pass filter it is possible to further highlight the differences between soil and stone constructions by the elimination of the differences in the natural water content of the soil.

Results

Geophysics

The magnetometry and resistivity prospection were conducted in March 1997 and 1998. Whereas the first one covered ca. 20 ha in the area of the supposed Hellenistic town (fig. 5), the second one comprised only two small grids (fig. 6), where the magnetogram showed a dense layout of stone walls which could be resolved by electric measurements in more detail. The results prove that the Hellenistic Palmyra was subdivided by three main streets oriented to the east and meeting in a V-shaped conjunction (fig. 5). This conjunction astonishingly appears nearly empty and is only flanked by some kilns and grave monuments [Becker, Fassbinder, 1999]. The northern main street runs parallel to the wadi in a distance of 70-100 m to it and depicts an elongation of the trade road from Emesa/Homs. The two parallel southern roads that are linked with a dense net of small roads have the direction of the trade route to Damascus [Schmidt-Colinet, al-As'ad, 2000]. The northern one is underlain by a water pipeline, which can be identified by a higher magnetization in the magnetogram and which has been proved by subsequent excavations.

North of this road the so called "Northern Quarter" is located (fig. 5). It is characterized by a loose arrangement of huge palaces with inner courtyards. One of the most striking buildings, the so called "Khan", afterwards has been surveyed by resistivity prospection (fig. 6, a) and archaeological excavations. In the geophysical results it shows up with a negative magnetization and a high electric resistivity. Therefore it has been constructed of limestone. The building consists of several distinct rooms and apparently has been erected in a building pit filled with burnt debris [Schmidt-Colinet, al-As'ad, 2000]. Near the wadi the magnetogram shows comparatively obscured but nevertheless monumental floor plans. This could probably be explained by an extensive destruction of the buildings by periodic flooding and sedimentation by the wadi. Perhaps this is the reason why the Hellenistic town has been abandoned in Roman times and a new one has been constructed north of Wadi el Kubur.

The "Southern Quarter" in contrary is built with dense arranged small scale houses (fig. 5; 6, b). They are not limited to the parallel main roads, but extend to the minor roads, too. So this quarter gets a nearly radial structure [Becker, Fassbinder, 1999]. Small scale excavations in selected parts of the magnetogram proved this interpretation and showed that the majority of the houses is constructed of weak magnetized limestone. In contrary some of the fundaments show up as positive anomalies and therefore eventually are built by burnt mud bricks which have a higher magnetization than the surrounding soil. Unfortunately the southern limit of the quarter could not be reached with the geophysical prospection because of a highly frequented modern road which limited the survey area.

West of the Khan a nearly empty space is visible in the magnetogram (fig. 5). Schmidt-Colinet and al-As'ad [2000] supposed that this place could have been used as temporary storage yard for camel caravans or a place for nomad tents which do not leave many traces in the soil. This assumption cannot be verified by geophysics, but it is very obvious if one compares the results with those intensively used parts in the rest of the magnetogram. Some faint structures which are oriented towards the rest of the town support this thesis.

In the western most part of the survey area a city wall can be identified in the elongation of a hill ridge which serves as a natural barrier (fig. 7) and limits the town to the west. Outside of the wall a dense layout of extensively burnt structures can be seen that reach until the wall and is an evidence of an extreme fire. Archaeological structures cannot be distinguished in this part.

Remote Sensing
For the analysis of optical satellite data, an image of QuickBird of 29.11.2010 and one of WorldView-2 of 11.04.2011 were used. Both provide a resolution of 0,6 m and therefore even faint and small-scale anomalies at the surface can de identified. The cloud cover of both data takes is 0%, so no disturbance and invisibility by cloud occurs. As a result of the high resolution first of all the modern town of Palmyra with distinct buildings and the infrastructure is visible in the northern part of the image (fig. 7). Even some vehicles and people can be identified by their shadows. In the south and east of the ruin site the palm groves of the oasis become visible as dark areas. As the two data takes originate

from two different seasons, an analysis of a CMYK-composite of them offers a colour shaded view of the temporarily changing structures like vegetation (fig. 8, a) or land use (fig. 8, b).

The area of the ancient city is disturbed by several modern tracks and a row of regularly arranged holes of a quanate, a special water supply system in arid regions. But nevertheless a perfect view on the upstanding ancient Palmyra can be achieved (fig. 7). Especially in the Roman town several monuments have been preserved. First of all the Diocletian city wall surrounding the settlement can be clearly identified in huge parts, even an amount of watch towers and bastions is visible. Only in the western part around the late Roman military camp and along the wadi the wall is only preserved as a debris wall. In the interior of the city the good state of preservation of the official buildings is remarkable. In the eastern corner the huge Bel-sanctuary can be seen. Still today the 200 × 200 m court with the surrounding wall and the temple in the interior are striking. Further to the west the Nabu-sanctuary, the agora and the theatre are flanking the famous Great Column road which runs through Palmyra from southeast to northwest. These monuments have been excavated in detail and are reconstructed in their original layout. The western most part of the city is occupied by the late Roman military camp whose layout is still visible today. In the living quarters some of the roads and the adjacent buildings appear because of small sand accumulations at these shallow buried structures. It is remarkable that only the southwest to northeast running roads can be detected. Eventually the sand accumulation by the wind is only possible in this direction, so the orthogonal linking roads remain unseen by optical images in the subsurface. Around the Bel-sanctuary the remains of the Arab settlement broken down in the 1930s by the French protectorate are located. The layout of this settlement can still be observed in the aerial photos of this time. South of the wadi the earlier Hellenistic town detected by magnetometry is visible. There only the Khan which has been excavated by a German-Austrian-Syrian mission is remarkable by the first look. But a detailed analysis of this area offers several other buried structures. So some of the palaces in the "North Quarter" and the main roads detected in the magnetogram, appear as slight sand accumulations in the satellite image. Some of these walls were already reported as soil marks in the spring aerial photos of the 1930s [Dentzer, Saupin, 1996]. In the west, the Hellenistic Palmyra is limited by a city wall which already was identified in the magnetogram and which is an elongation of the natural boundary of a nearby hill. The whole ancient settlement of Palmyra is surrounded by a huge amount of burials. Remains of the graves which were sometimes constructed as tower tombs can be seen everywhere outside the city walls.

Even with a resolution of 0,6 m only structures that create a visible mark at the surface can be identified. The other ones buried in the ground can only be visualized by satellite radar. Therefore a radargram of the German satellite TerraSAR-X of 28.02.2011 was used (fig. 9). The resolution of 1-2 m ensures that at least the larger archaeological structures can be resolved. But it must be kept in mind that even features smaller than the resolution of the sensor can be detected as a result of the special reflection characteristics in the microwave spectrum [Albertz, 2009]. Like in the optical images, the radargram shows very well the geological structures like the hills in the west of the ancient city. The modern town appears in white because the regular buildings with rectangular corners provide good reflectors for the radar waves. In contrary the fallow acres, the sebkha and the dessert soil appear darker because the even surface acts as a mirror and the radar waves are reflected away from the sensor.

The same effect than for the modern buildings can be found for the upstanding ancient remains. Therefore the important monuments known from the optical images like the Diocletian city wall, the Bel-sanctuary, the Column Road, the agora and the theatre appear very clearly [Linck, Fassbinder, 2011; Linck et als., 2011]. The city wall with its bastions and watch towers depicts a very strong reflector as it is 2,8 m thick [Wiegand, 1932] and therefore is even bigger than the resolution of the sensor. In the area of the military camp the reflections of the wall are hidden by imaging effects of the SAR theory. For the same reason the remains of the camp itself are obscured. The Nabu-sanctuary west of the huge Bel-santuary appears more detailed in the radar image than in the optical one, because the preserved columns depict good corner reflectors for radar waves but are small for optical views. That is why also the Column Road with its partitioning gates is better visible. The Bel-sanctuary itself acts as one of the strongest reflectors at all, as it is one of the best preserved monuments. The buried archaeological structures appear mainly on the sub pixel-level. So a time consuming detailed analysis is necessary to map them. Thus in the Roman town finally the layout of the whole rectangular grid of the roads can be drawn and for the first time it is possible to get an impression of the city layout [Linck, Fassbinder, 2011; Linck et als., 2011] (fig. 9; 10). Furthermore because of the special reflection characteristics of radar waves even some of the ancient buildings are detectable. Among these archaeological features there is a considerable amount of so far unknown structures that are not mapped in the most recent map of the site by Schnädelbach [2010].

The most striking object in the Hellenistic part is the excavated Khan (fig. 9). Furthermore the radargram shows several structures already known from the magnetic survey, e.g. the main roads which are visible very clearly because of their size, some minor roads, the city wall in the west and some walls of buildings. However it is not possible to get the whole density of buildings like in the magnetogram, as the resolution is limited. Again like in the Roman part, several until now unknown archaeological objects become visible, especially in parts outside the magnetogram and in areas where the differentiation of distinct anomalies is difficult because of physical reasons.

Conclusion

The geophysical surveys are of great importance for the archaeological research in ancient Palmyra. It enables us to locate the Hellenistic part of the town and to create a detailed map of its radial layout. Even several quarters can be discriminated: in the north, the Palmyrene elite has had its palaces, whereas in the south there is a dense building development with small irregular houses. In the western part a nearly empty area could possibly be identified with a temporary deposit yard for caravans. The relative weak magnetic anomalies in huge parts of the measurement do not prove the hypothesis that the Hellenistic part was abandoned after a huge destruction by fire. In fact it is much more probable that the city was moved to the north of the wadi after several catastrophic flooding. This would be consistent with the fact, that the archaeological remains near the wadi are heavily destroyed and overlain by sediments.

The remote sensing approach by optical images and Synthetic Aperture Radar provides the verification of already known parts of the city map of Palmyra, but also several new features can be identified. As in the TerraSAR-X data not only upstanding monuments, but rather also buried archaeology can be traced, the X-band radar waves can penetrate into the ground. This fact has hardly ever been observed before and therefore it offers totally new horizons for the use of high-resolution satellite radar in the archaeological prospection. Although remote sensing cannot substitute ground-based geophysical measurements, it can provide a perfect overview of the expected features and the more time consuming geophysical surveys can be done in previously selected areas.

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Fig. 1. Topographic map of Syria showing the location of Palmyra in central Syria, 230 km northeast of the capital Damascus

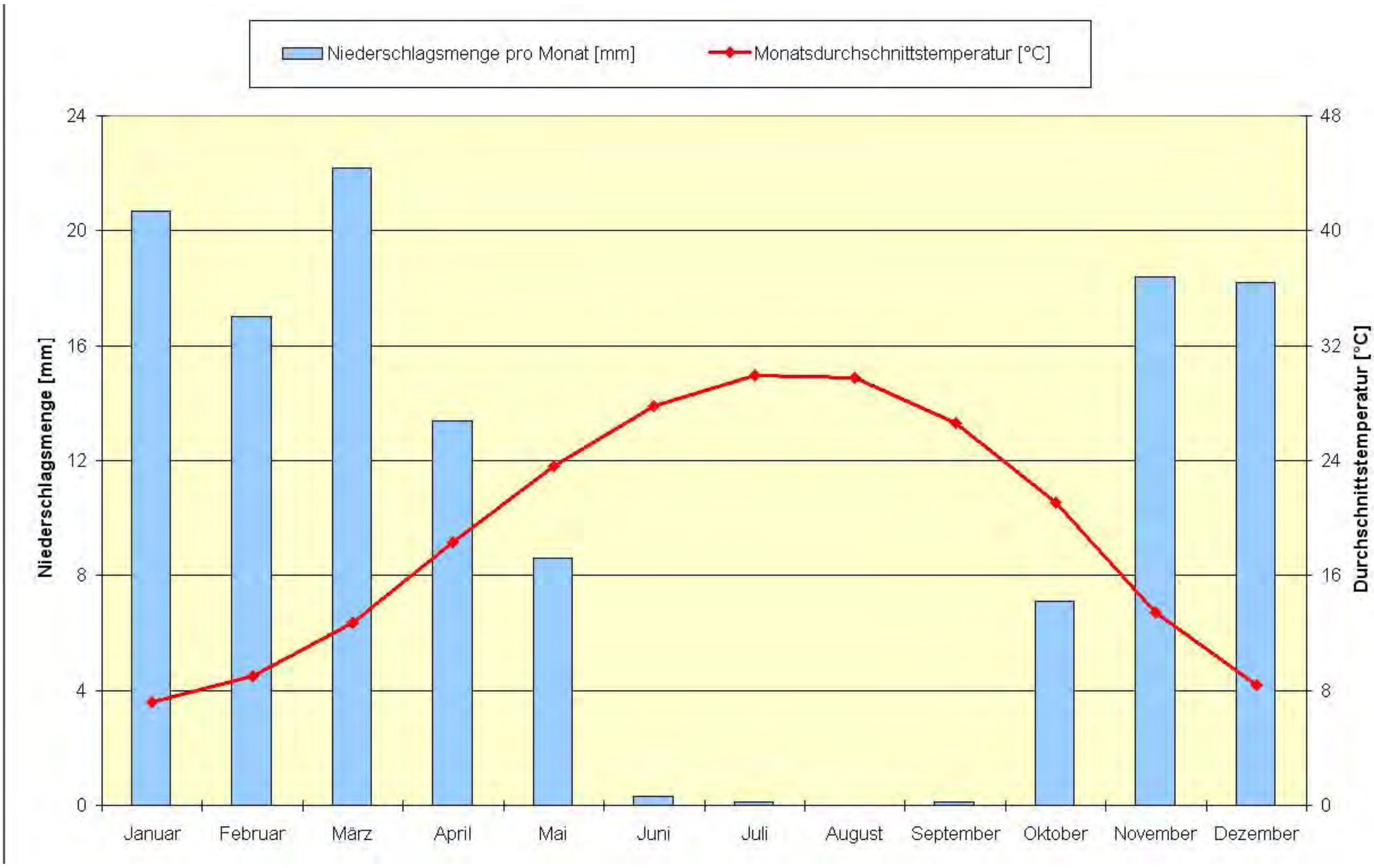

Fig. 2. Schematic diagram of the annual distribution of temperature and precipitation in the region of Palmyra. Data source: [Monthly Climatic Data for the World]

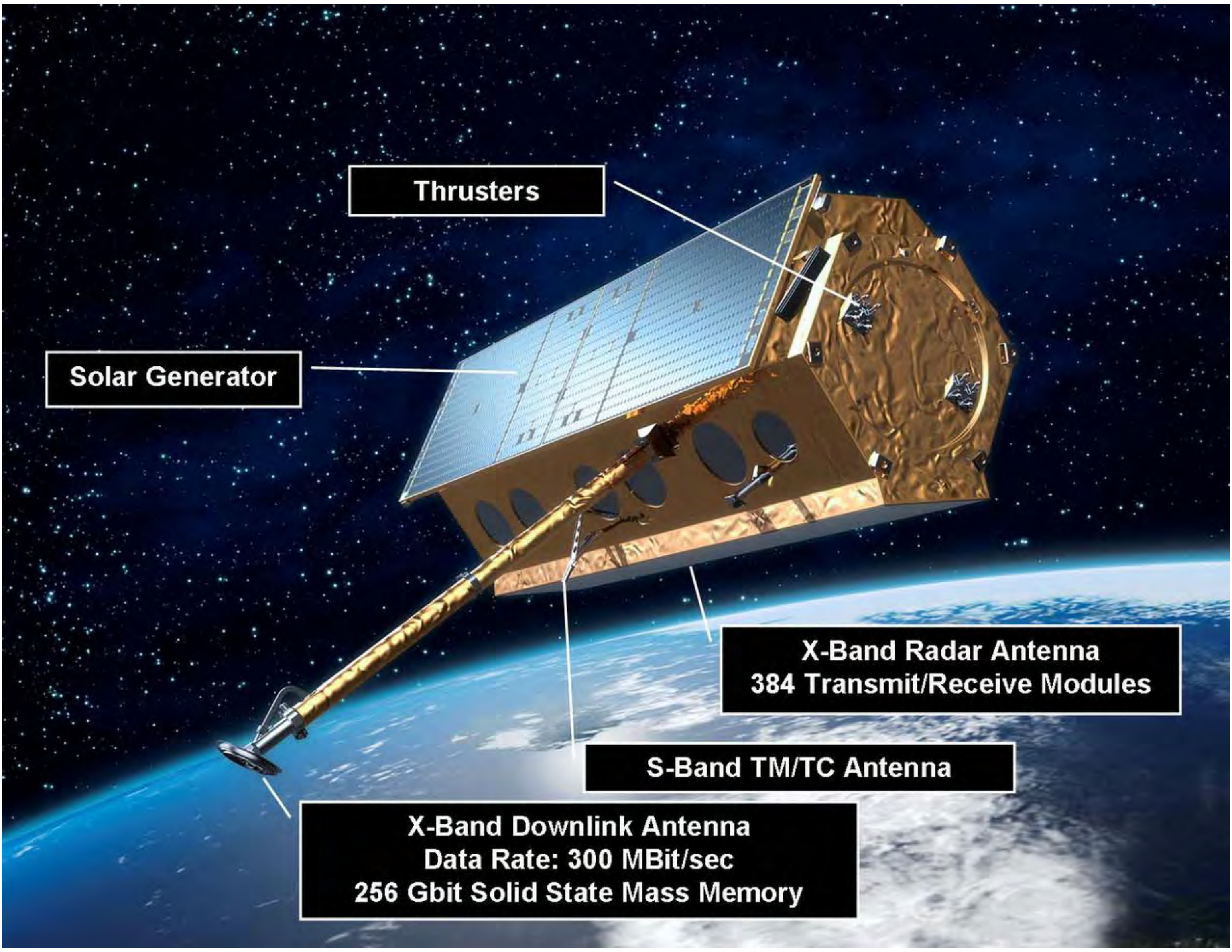

Fig. 3. Artist view of the TerraSAR-X satellite. Note the solar generator (upper left), the boom with the X-Band downlink antenna (lower left) and the X-band radar antenna (lower right). Data source: DLR (2012)

Fig. 4. Artist view of the TerraSAR-X and TanDEM-X satellites flying in close formation. Main goal of the TanDEM-X mission will be the acquisition of a global, high-quality Digital Elevation Model with high resolution. Data source: DLR (2012)

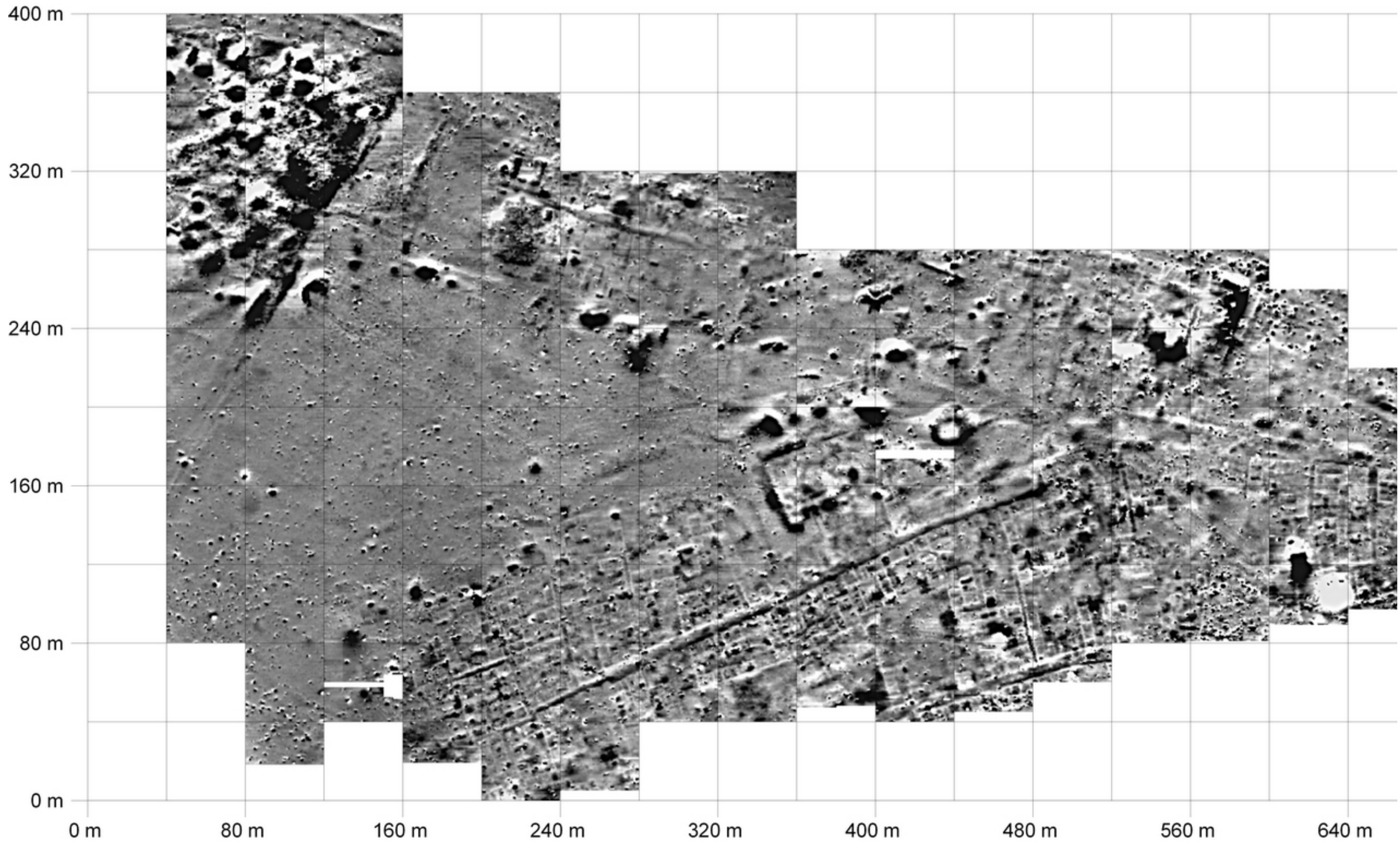

Fig. 5. Magnetogram of the Hellenistic town of Palmyra. Overlay with the high-pass filter to visualize the stone walls in more detail. Caesium Smartmag SM4G-Special, Duo-Sensor-configuration, Dynamics: clipped to ± 3 nT in 256 greyscales, Sensitivity: ±10 pT, Point density: 50 × 25 cm, interpolated to 25 × 25 cm, 40-m-grids

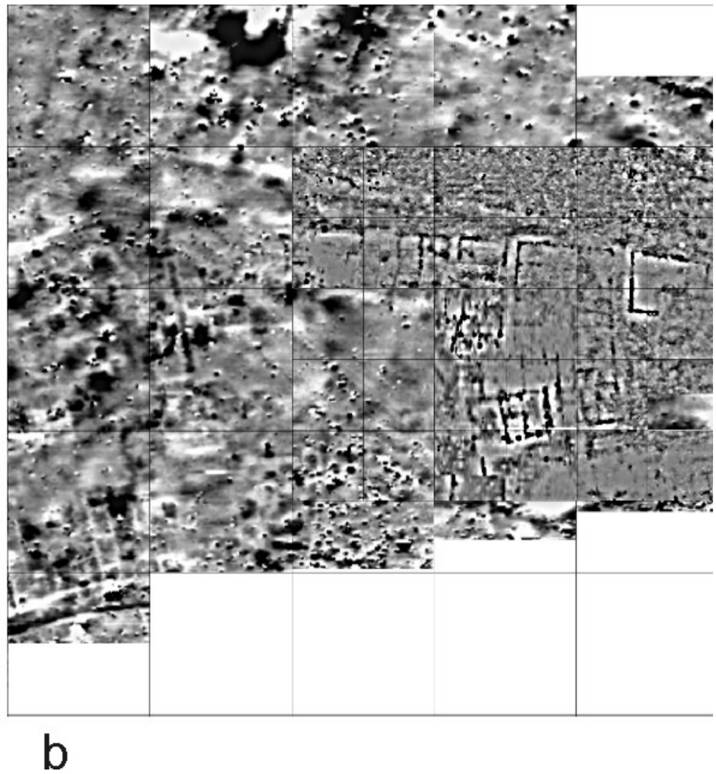

Fig. 6. Resistogram of: a) one of the palaces of the Palmyrene elite; b) an area with dense irregular houses in the east of the town. Plotted over the corresponding part of the magnetogram. Geoscan RM15, Dualpol-configuration, Dynamics: ± 10 Δ Ohm m, Point density: 50 × 50 cm, interpolated to 25 × 25 cm

Fig. 7. Optical image of the U.S. remote sensing satellite WorldView-2 in the area of the ancient caravan city Palmyra. Clearly visible are the upstanding remains, but because of small sand accumulations at shallow buried walls even subsurface structures are visible because of the high. Data take on: 11 April 2011; Resolution: 0.6 m. DigitalGlobe. Image provided by: European Space Imaging (2011)

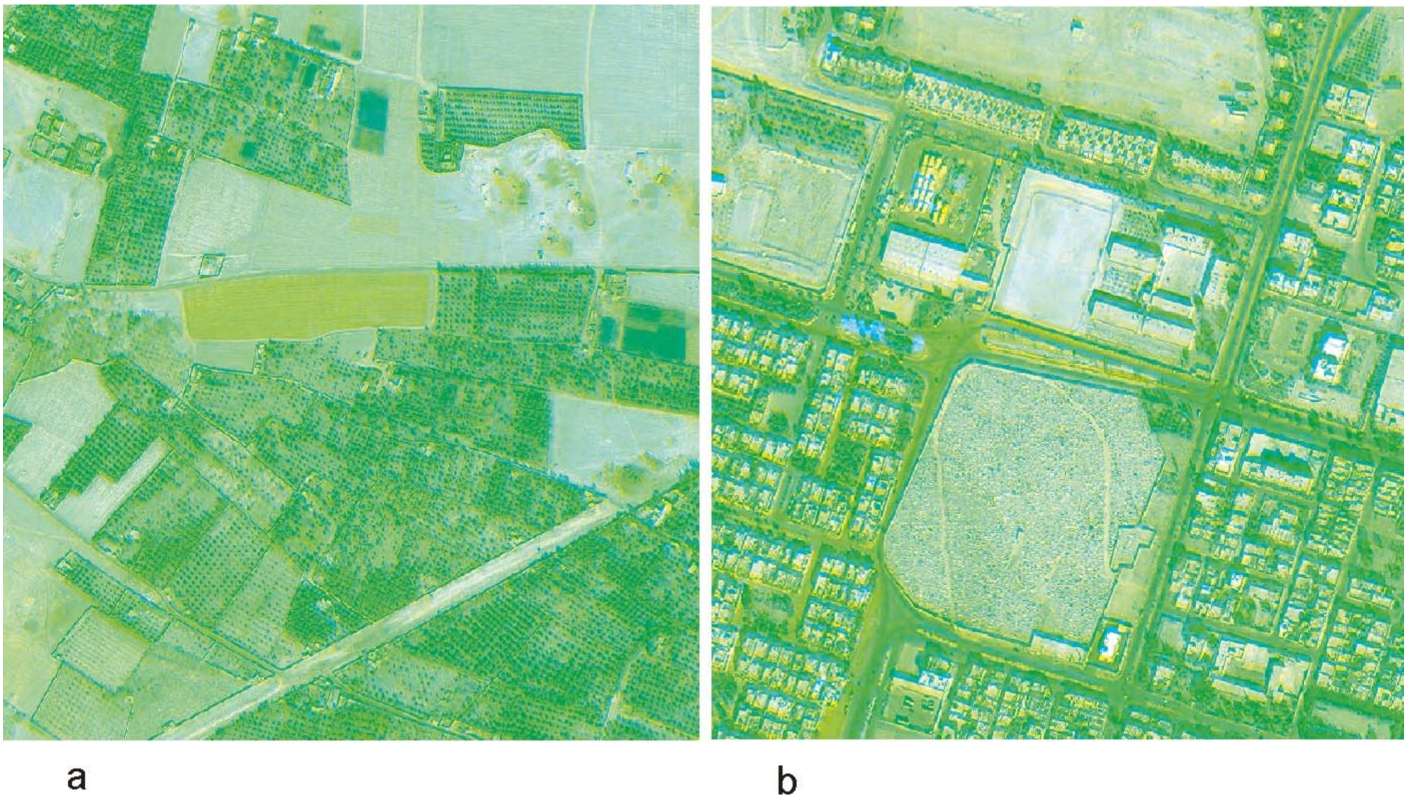

Fig. 8. CMYK-overlay of the QuickBird and WorldView-2 images to visualize temporal changes in the modern environment: a) the vegetation changes on an acre comes up in yellow because between autumn 2010 and spring 2011 the plants have grown higher; b) in an industrial site in the modern town some more containers have been placed which appear in yellow. Copyright of optical images: DigitalGlobe. Image provided by: European Space Imaging (2011)

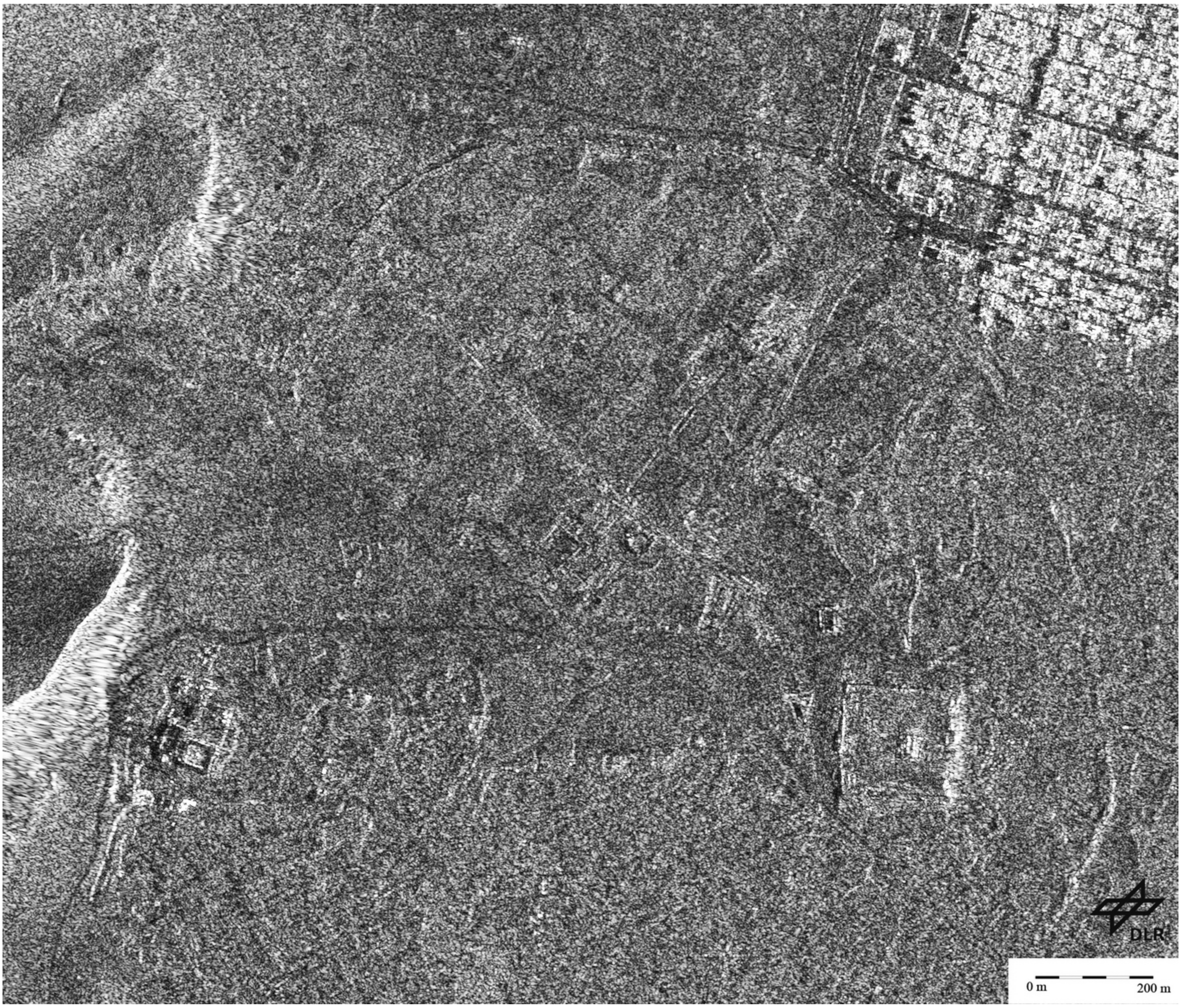

Fig. 9. Radargram of TerraSAR-X in the area of the ancient Palmyra. Especially upstanding structures can be distinguished very well, but even several buried archaeology is visible. Data take on: 28 February 2011; horizontal polarisation and spatially enhanced mode. Data source: German Aerospace Centre (2011)

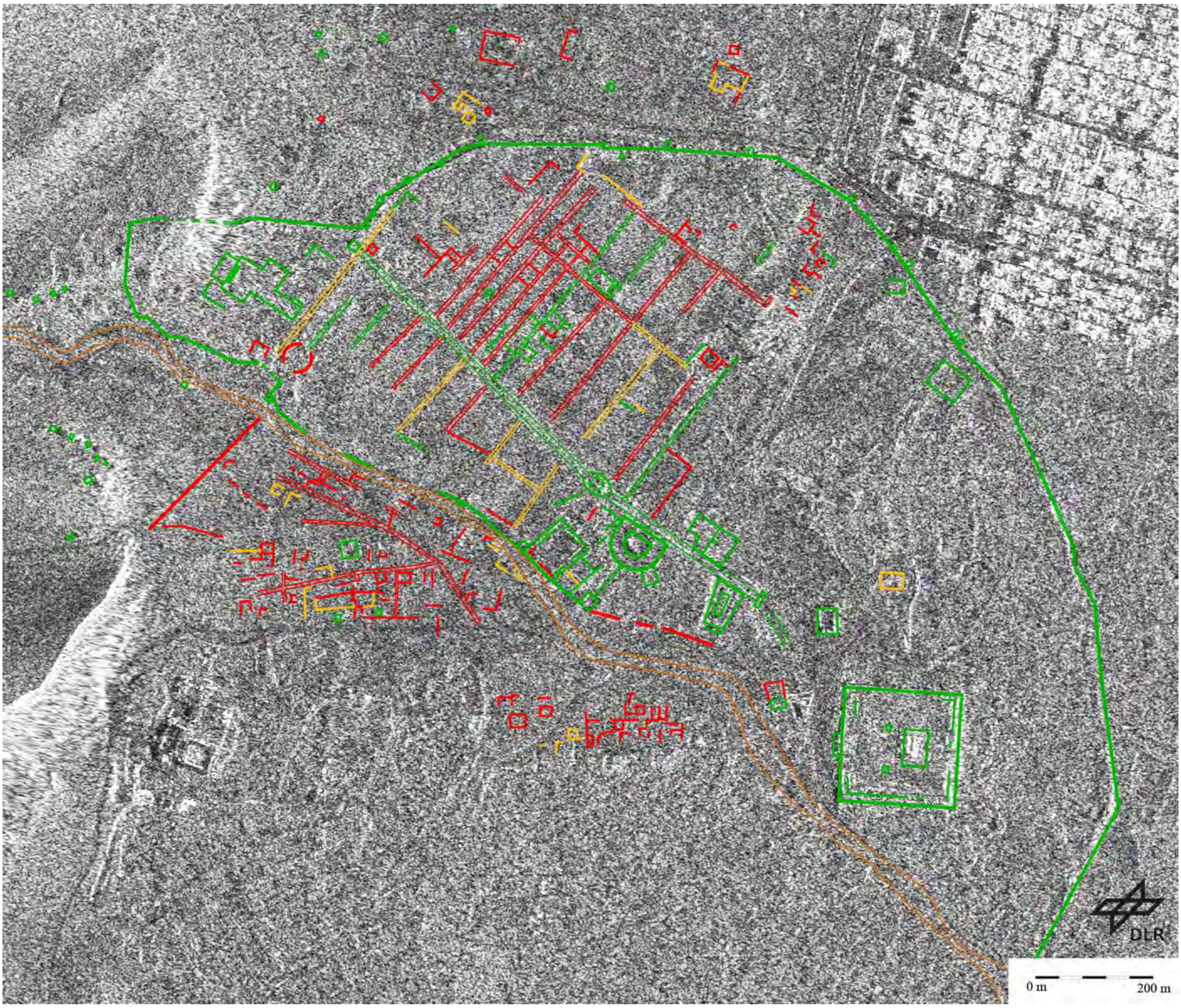

Fig. 10. Overlay of the TerraSAR-X image with the interpretation plan of the visual structures. Colour coding: green = upstanding monuments; brown = Wadi el Kubur; red = buried monuments already known from other sources; yellow = buried monuments detected by TerraSAR-X. TerraSAR-X-radargram by German Aerospace Centre (2011)