**Introduction**

In this paper, we present the results of Ground-Penetrating Radar (GPR) measurements performed in the church of the Jesuits in Valletta, Malta, during the International Training School on “Ground-Penetrating Radar for civil engineering and archaeology” organised by the COST (European COoperation in Science and Technology) Action TU1208 “Civil engineering applications of Ground Penetrating Radar” (Pajewski and Benedetto, 2013) and held in The University of Malta on January 25-29, 2016. For more information on the Training School, see www.gpradar.eu/activities/training-schools/malta2016.html.

The Jesuits' church (in Maltese Knisja tal-Ġiżwiti) is one of the oldest and largest churches in Valletta. It was re-built in the 17th century, after an explosion caused serious damage to the previous church and the adjacent college. Four streets bound the site. In Fig. 1(a), a map showing the location of the church is reported.

St Ignatius of Loyola, founder of the Society of Jesus in 1534, had considered founding a college in Malta in 1553. Ignatius hoped for Jesuit vocations from Malta: He had been informed that the Maltese spoke Arabic and thought they would make excellent missionaries in North Africa among Muslims. However, the idea of a college in Malta did not materialise in Ignatius’s lifetime: It was 1592 when Pope Clement VIII solicited the setting up of a Jesuit college and church in Malta; Grandmaster Martin Garzez laid the Foundation Stone of the Collegium Melitense on 4 September 1595.

The present church was built according to the plan and design of the architect and engineer Francesco Buonamici from Lucca: It was the first work on the island of Malta to be designed by an architect of international repute. The facade bears features of the Baroque style, whereas the interior is influenced by Doric architecture. The plan followed the Gesù church in Rome, with a four-bay nave (see Fig. 1(b)) and seven side chapels; there is an eighth chapel, the Onorati Congregation Chapel, opening from the nave and leading through a door onto Archbishop Street. The Jesuits lectured in the college until their expulsion from Malta by Grandmaster Manuel Pinto da Fonseca, in 1768. The Collegium Melitense then became the University of Malta, where our Training School was held.

The results of our measurements are of particular interest, as they show a technical feature worth outlining, namely the fact that the method of the diffraction hyperbolas (Persico et al., 2015) for the retrieving of the propagation velocity is tricky and potentially deceiving. This case study offers a very clear example of this fact. To overcome this difficulty, we did not have the possibility to employ a Common Mid-Point (CMP) or Time-Domain Reflectometry (TDR) technique (Persico, 2014). Hence, we made use of a sequential migration with progressively lower trial propagation velocities. This is an easy and intuitive method, but it presents some delicate aspects from the theoretical point of view, as explained in the following Section.

(a) (b)

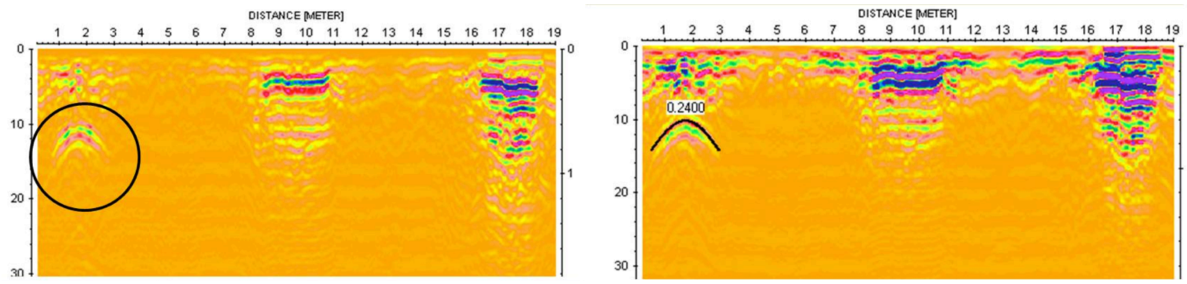
**Figure 1 (a)** *Map of Valletta (Malta), showing the location of the Jesuits’ church;* **(b)** *Photo of the nave of the Jesuit’s church, where our measurements were performed.*

**Ground-Penetrating Radar prospection and data processing**

The prospection was performed by using a prototypal reconfigurable stepped-frequency GPR system (Persico and Prisco, 2008), implemented within the Aitech research project (www.aitechnet.com). A description of the system was provided elsewhere (Persico et al., 2014) and so it will be avoided here. The radar prototype was recently improved and further tested within the COST Action TU1208 (Matera and Sala, 2015; Persico and Matera, 2015).

The survey regarded a rectangular area in the main nave of the church, 5.2 m large and about 19.2 m long. Data where gathered along 14 parallel lines, spaced 40 cm from each other.

Fig. 2 shows the first B-scan. As can be noticed in the (a) panel, a clear hyperbolic anomaly is evident. This anomaly is present also in several adjacent B-scans. At a first sight, this signature resembles that of a pipe. However, as can be appreciated in the (b) panel of Fig. 2, in order to match (and indeed quite well) that hyperbolic appearance a propagation velocity c = 0.24 cm/ns is needed. This value is too high for the soil that we surveyed.



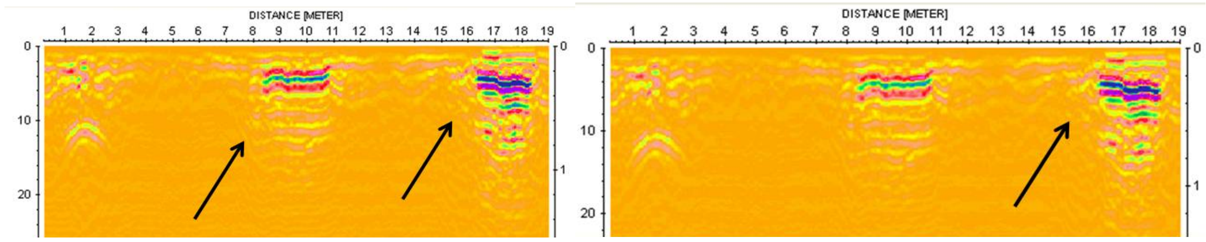

(a) (b)

**Figure 2 (a)** *Hyperbolic feature, evidenced with a circle;* **(b)** *The same feature, matched with a propagation velocity c = 0.24 m/ns.*

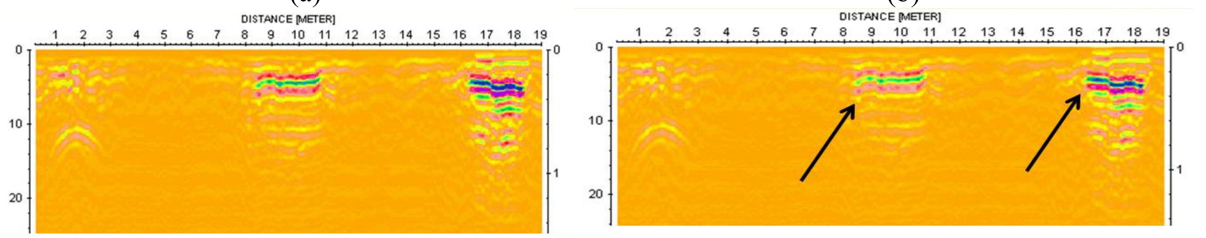
A more probable hypothesis is that the target at hand was not small in terms of wavelength, which made unreliable the classical diffraction-hyperbola approach. Consequently, the evaluation of the propagation velocity c was done by means of a sequential migration procedure, with several trial values of c. In Fig. 3, we show the results that we obtained with c = 0.12 (a), 0.10 (b), 0.09 (c) and 0.07 (d) m/ns. A "smile effect" can be noted for c = 0.12 m/ns, still weakly visible for c = 0.10 m/ns (see the arrows). This effect disappears for c = 0.09 m/ns and c = 0.07 m/ns. However, for c = 0.07 m/ns, the reconstruction of the main targets appears faded, which indicates that the migration algorithm is losing its focusing power. Therefore, a propagation velocity c = 0.09 m/ns was chosen.

The procedure is less straightforward than it might seem, because we don't have theorems that assure that the strongest focusing occurs when the exact value of propagation velocity is chosen. In particular, this is true for small targets (Soldovieri et al., 2008). But, for large scatterers, we cannot exclude more tricky effects, due e.g. to corner points, nonlinear interactions between different parts of the targets, concave shapes that focus the radiation in some unforeseeable way. However, a series of simulations had made us numerically sure that strange effects should not happen when the targets are sufficiently far from each other, do not show unusual shapes and are of the order of a few wavelengths. We deem that these hypotheses are reasonable in the case at hand.

After that, the processing included: zero timing (shift of the start time) at -8 ns, time cut at 80 ns, Kirchoff migration on 151 traces, application of a gain function vs. the depth with parameters 0.1 and 0.1 both for the linear and exponential gain and with saturation at 1000, and finally a Butterworth filter between 150 and 1000 MHz. This processing was performed with the commercial code Reflexw. Afterwards, 8 horisontal slices were achieved between 0 and 20 ns, with interpolation factors set equal to 0.4 m. These slices are shown in Figs. 4 and 5.




(a) (b)




(c) (d)

**Figure 3** *Sequential migration results. From the top to the bottom, the trial velocities are: c=0.12 m/ns* **(a)***, c=0.1 m/ns* **(b)***, c=0.09 m/ns* **(c)** *and c=0.07 m/ns* **(d)**.

Looking at the slices, several shallow anomalies can be seen, probably ascribable to tombs. This assumption is due to their shapes, dimensions and positions. As is well known, there was a common habit to bury corps under the naves of churches up to the 18th century. In particular, we circled an anomaly at 22 cm in Fig. 4, surrounding it with a circle, and a large but weaker anomaly at 45 cm, which is evidenced with a rectangle in Fig. 5. The anomaly in the rectangle refers to the hyperbolic feature evidenced in Fig. 1: It might be due to a mass grave with a cylindrically vaulted ceiling. This anomaly appears faded with respect to the other ones, because the ceiling is not flat and scatters the impinging energy in all directions. Moreover, the intrinsic procedure of the time depth slices should ideally show just two "linear cuts," given by the intersection of the vaulted ceiling with the considered depth level (indeed, this is not true because the slices are constructed by averaging a range). The anomaly circled at 22 cm might be ascribable to a sort of manhole entrance to this sepulchre.

## Conclusions

Results of Ground-Penetrating Radar (GPR) measurements performed in the church of the Jesuits in Valletta, Malta, were presented. This experimental activity was carried out during a Training School organised by COST Action TU1208 and hosted by the University of Malta. The case study is of particular interest, as it shows that the well-known method of the diffraction hyperbolas, for the estimation of the propagation velocity, is not always reliable. As an alternative, a sequential migration with progressively lower trial propagation velocities was proposed and successfully used. Several tombs in the subsurface of the main nave of the church were detected and located.

## Acknowledgement

The support of the COST Action TU1208 "Civil engineering applications of Ground Penetrating Radar" and the efforts of the University of Malta in organising the Training School on "Ground Penetrating Radar for civil engineering and archaeology" were essential for this work.

## References

Matera L., Sala J., 2015. Tests, comparison and improvement plans for an innovative reconfigurable stepped-frequency GPR. Short-Term Scientific Missions - Year 2. COST Action TU1208 series, Aracne Editrice, L. Pajewski, M. Marciniak, S. Lambot, Eds, Rome, Italy, ISBN 978-88-548-8488-5.

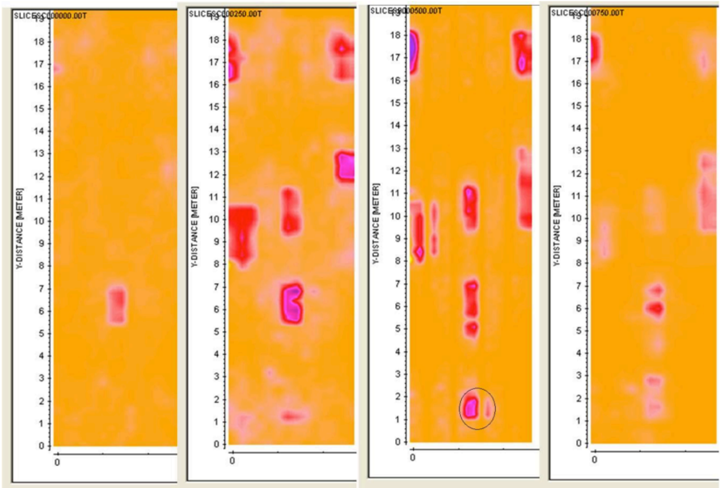


**Figure 4** *Depth slices. From left to right: 0, 11, 22 and 33 cm of apparent depth.*

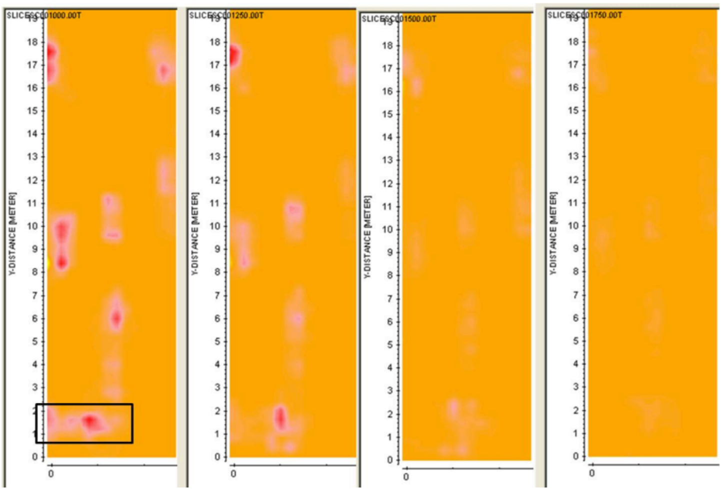


**Figure 5** *Depth slices. From left to right: 45, 56, 67 and 78 cm of apparent depth.*

Pajewski L., Benedetto A., 2013. Advanced Ground Penetrating Radar: open issues and new research opportunities in Europe. Proc. 10th European Radar Conference (EuRad), 9-11 October 2013, Nuremberg, Germany, pp. 1847-1850.

Persico R., Prisco G., 2008. A Reconfigurative Approach for SF-GPR Prospecting. IEEE Trans. on Antennas and Prop., vol. 56, n.8, pp. 2673-2680.

Persico R. 2014. Introduction to Ground Penetrating Radar: Inverse Scattering and data processing. Wiley.

Persico R., Leucci G., Matera L., De Giorgi L., Soldovieri F., Cataldo A., Cannazza G., De Benedetto E., 2015. Effect of the height of the observation line on the diffraction curve in GPR prospecting. Near Surface Geophysics, vol 13, n. 3, pp. 243-252.

Persico R., Ciminale M., Matera L., 2014. A new reconfigurable stepped frequency GPR system, possibilities and issues; applications to two different Cultural Heritage Resources. Near Surface Geophysics, vol. 12, n. 6, pp. 793-801.

Persico R., Matera L., 2015. Reconfigurability of integration times in a stepped-frequency GPR system: an example in urban area. Proc. Third General Meeting. COST Action TU1208 series, Aracne Editrice, L. Pajewski, A. Benedetto, A. Alani, A. Loizos, Eds, Rome, Italy, ISBN 978-88-548-8486-1.

Soldovieri F., Prisco G., Persico R., 2008. Application of Microwave Tomography in Hydrogeophysics: some examples, Vadose Zone Journal, vol. 7, n. 1 pp. 160-170.