



HIGH-PRECISION GPS SURVEY OF VIA APPIA: ARCHAEOASTRONOMY-RELATED ASPECTS

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ABSTRACT

Via Appia was built by the Romans around 312 BCE to connect Rome with Capua during the Samnite wars. The road is an astonishing engineering masterpiece. In particular, the segment which runs from Colleparado to Terracina - 61 km long - is renowned for being virtually straight; however this "straightness" was never investigated quantitatively. As a consequence, the techniques used by the ancient surveyors and their scope - whether it was only practical, or also symbolic - remain obscure. We report here a high-precision GPS survey of the road, performed with a u-blox receiver and further checked with a dual frequency receiver. We give a detailed analysis of the methods used and of the errors, which are shown to be less than 6'. To our knowledge it is the first time that such a long ancient manufactured structure has been surveyed with such a high accuracy. The results lead us to conclude that astronomy was certainly used in the construction of the road and in that of the associated grid, oriented to the setting of the star Castor and to the cardinal points respectively.

KEYWORDS: GPS, azimuth estimation, satellite image georectification, archaeoastronomy, *Via Appia*, centuriation.

1. INTRODUCTION

The issue of the accuracy required in archaeoastronomical analyses is a delicate one. There are, indeed, times when the accuracy required for obtaining sound results is relatively low and/or the quantity of data calls for quick methods of relief; for instance, for the collection of hundreds of pieces of data about many scattered dolmens, a combined compass-clinometer certainly suffices (Hoskin 2001). However, in other cases accuracy must be very good. This is the case when ancient architectures were oriented with astonishing precision, for instance, the pyramids of Giza (Magli 2009, Nell and Ruggles 2014), and/or when they exhibit perfectly conserved and clearly measurable features, as in architectural projects of ancient Greece (Belmonte & Hoskin 2002) and ancient India (Malville 2000).

Another context in which high-accuracy methods of modern survey are always needed is clearly the study of ancient high-accuracy surveys. Among these, as is well known, are many of the land-forming works carried out by the Roman *mensores*. These works, called centuriations, were regular divisions of huge territories according to orthogonal grids of lines. These divisions had multiple objectives: assigning the lands of new colonies, establishing the Roman rule and cadastral control, regularizing the hydrology of the area by tracing canals along the grid, and finally renovating or creating *ex novo* a system of roads.

Roman land-forming through centuriation is a very old system, as it traces back to the early fourth century BC (Settis 1983), and there exist famous examples which show the accuracy of the Roman surveyors and their ability to maintain it over vast territories. Perhaps the most astonishing centuriation is the one carried out in the territories of modern Tunisia by the 3rd Augusta Legion (Caillemer and Chevallier, 1957).

The orientation of the centuriation grids was in many cases dictated by topograph-

ical and/or hydrographical considerations; there exist, however, clear and documented cases (Troussset, 1997) in which the orientation was clearly astronomical (to the solstices or to the cardinal points), and an astonishingly accurate case of astronomical orientation of grid and roads will be presented in this paper. The centuriation in question, although already discovered in the 1970s (Cancellieri, 1990), is poorly known, while the road is the most famous among the Roman roads. It is *Regina Viarum*, 'the queen of the long roads', or as the Romans called it, *Via Appia*.

This road, constructed by the Roman consul Appius Claudius around the year 312 BC to connect Rome with Capua, is an astonishing work of engineering (Quilici, 1990). In particular, the first section of the road, leading from Rome to Terracina, is composed of two straight segments connected by a short zigzag section aimed to cross the Alban hills at Colle Pardo. The first of these segments runs for 26 km. The second crosses the Pontine Marshes, going straight for as far as 61 km.

To our knowledge, no one has ever tackled seriously the problem of the project of this road. Further, although it is well known –and actually obvious to anyone even today– that the path proceeds with impressive straightness, the accuracy associated with this "impression" was never analyzed quantitatively. For instance, it is usually taken for granted in the literature that the segment crossing the Pontine marshes runs with azimuth 135°; that is, along the northwest/southeast direction. Such a feature – if true – would have been of great help in the project of the road. Indeed, astronomy could be used to determine the north celestial pole, and then the *groma* (the instrument of the Roman surveyors) could be used first to find the meridian and then to bisect it two times to obtain the northwest/southeast direction. However, as we shall see, although the Romans did survey all the associated territory with a cardinaly oriented grid, they

did *not* choose the intercardinal azimuth for the road.

The aim of the present paper is to present the first high-precision GPS survey of the Colle Pardo – Terracina segment and of the associated Roman grid, while the complete historical and architectural analysis is provided in a companion paper (Magli et al., 2013). Many technical difficulties had to be solved and, to our knowledge, this is the first time that an ancient artifact stretched for so many tens of kilometers is analyzed with such a high accuracy.

2. THE GPS SURVEY OF VIA APPIA FROM ROME TO TERRACINA

The first section of *Via Appia*, starting from Rome, runs straight for about 26 km, then the road crosses the Albani hills. The second straight section, which is the main focus of the present work, crosses the Pontine marshes and proceeds to Torre Elena, near Terracina, for as far as 61 km. A very long section of this path, about 41 km, from Cisterna di Latina to Torre Elena, is covered by the modern road, which has been traced along the ancient one. A few visible remains, such as Clesippo's mausoleum in Mesa, survive here and there along the modern street, as do scattered blocks of the ancient crepidines (platforms) on the west side.

The survey of this segment of the *Via Appia* was performed with a u-blox AEK-4T GPS receiver processing data with goGPS software (Realini and Reguzzoni, 2013, <http://www.gogps-project.org>), and further checked with a dual-frequency Leica 1200 system GPS receiver processing data with LGO software (Leica Geosystems, 2006). Note that the present research, apart from the analysis of the Roman project of the *Via Appia*, had also the practical scope of investigating the possibility of using relatively low-cost GPS receivers, like the u-blox receiver, instead of the more expensive dual-frequency receivers, for the purpose of high-precision topographical and archaeoastronomical surveys.

Specifically, the u-blox antenna was positioned on the rooftop of a car (see figure 1) driven at an almost constant velocity of 60 km/hour from Cisterna di Latina to Torre Elena (round trip), with the receiver recording observations at the frequency of 1 Hz.



Figure 1. The u-blox antenna positioned on the rooftop of the car.

The Latina permanent GPS station was used as the master station in a double-difference GPS positioning, and a Kalman filter was applied in order to reduce the measurement noise (for details on the GPS processing with goGPS, see Realini and Reguzzoni 2013).

In this way the geocentric Cartesian coordinates and the corresponding geodetic coordinates, i.e., latitude, longitude and ellipsoidal height, respectively, of more than 5000 points, with an expected accuracy better than 1 m, were retrieved. The two coordinate systems are related by the relations:

$$\begin{cases} X = (N + h) \cos \varphi \cos \lambda \\ Y = (N + h) \cos \varphi \sin \lambda \\ Z = [N(1 - 2f + f^2) + h] \sin \varphi \end{cases} \quad (1)$$

where $N = \frac{a}{\sqrt{1 - (2f - f^2) \sin^2 \varphi}}$ is the radius of curvature of the prime vertical, i.e. the right, and 2.54cm top and bottom. The distance from the surface to the Z-axis along the ellipsoid normal, a and f the semi-major axis and the flattening of the ellipsoid respectively. In order to estimate the azimuthal direction of *Via Appia*, the

coordinates of these points have been expressed in a local east, north, up (e, n, u) reference system centered in the middle of the survey, close to Borgo Faiti. This can be done by the following equation (see Sansò 2006):

$$\begin{bmatrix} e \\ n \\ u \end{bmatrix} = R \begin{bmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{bmatrix}; \quad (2)$$

with

$$R = \begin{bmatrix} -\sin \lambda_o & \cos \lambda_o & 0 \\ -\sin \varphi_o \cos \lambda_o & -\sin \varphi_o \sin \lambda_o & \cos \varphi_o \\ \cos \varphi_o \cos \lambda_o & \cos \varphi_o \sin \lambda_o & \sin \varphi_o \end{bmatrix},$$

where (X_o, Y_o, Z_o) and $(\varphi_o, \lambda_o, h_o)$ are the Cartesian and geodetic coordinates of the centre of the local system (see figure 2).

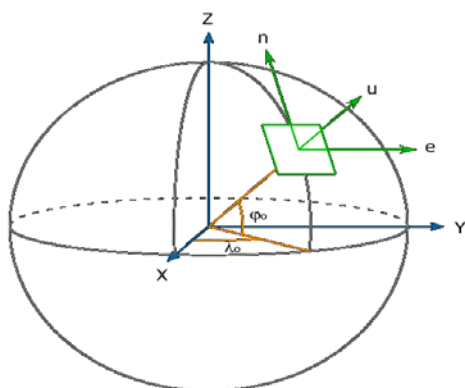


Figure 2. Reference systems used in order to estimate the azimuthal direction of *Via Appia*.

It should be observed that the above equations allow one to define a local reference system with the n -axis pointing toward the exact north direction only for points on the meridian passing through (X_o, Y_o, Z_o) , while in order to get the actual azimuth for all the other points, a rotation, defined by eq. 3, should in principle be applied. However it is simple to prove that in the case of the *Via Appia* survey, if the origin of the local system is fixed in the centre of the measured segment, the devia-

tion from the meridian is smaller than 17 km (i.e. $\delta\lambda \leq 0.15^\circ$), corresponding to a maximum error in the north definition smaller than 6 arcminutes. In fact, the rotation to be applied on a point of coordinates $(\varphi_o, \lambda_o + \delta\lambda_o)$ to get the correct north direction from the one obtained by centering the reference system in (φ_o, λ_o) is simply given by:

$$\delta R = R(\varphi_o, \lambda_o + \delta\lambda_o) R^{-1}(\varphi_o, \lambda_o). \quad (3)$$

Considering that in the *Via Appia* survey $\delta\lambda \leq 0.15^\circ$, $\varphi_o \cong 41^\circ 30' N$ and $\lambda_o \cong 13^\circ E$, the above equation can be approximated to the first order in $\delta\lambda_o$ as follows:

$$\delta R \leq I + \begin{bmatrix} 0 & 5.9' & -6.6' \\ -5.9' & 0 & 0 \\ 6.6' & 0 & 0 \end{bmatrix} \quad (5)$$

That is, the approximation in the estimate of the north direction due to the considered local reference system is not greater than 5.9 arcminutes (this approximation is well known in geodetic literature as meridian convergence; see for instance Soler and Fury 2000). Note that the rotation of 6.6 arcminutes around the north axis does not affect the azimuthal direction.

Keeping in mind this approximation, one can estimate the *Via Appia* azimuth by applying a least squares regression to the set of observed points; in particular, the observation equation can be formalized as:

$$(n_{oi} - \bar{n}) = \alpha(e_{oi} - \bar{e}) + v_i \quad (6)$$

where (e_{oi}, n_{oi}) are the GPS-derived coordinates of the i -th point, (\bar{e}, \bar{n}) are the coordinates of an arbitrary point lying on the interpolating straight line, α is the unknown azimuth, and v_i is the error. The corresponding (linearized) stochastic model is:

$$\sigma_{v_i}^2 = \sigma_n^2 + \tilde{\alpha}^2 \sigma_e^2 \quad (7)$$

where $\tilde{\alpha} = \frac{1}{m} \sum_{i=1}^m \frac{n_{oi} - \tilde{n}}{e_{oi} - \tilde{e}}$ with $\tilde{n} = \frac{1}{m} \sum_{i=1}^m n_{oi}$,

$\tilde{e} = \frac{1}{m} \sum_{i=1}^m e_{oi}$, m is the number of observations, σ_n^2 and σ_e^2 are the error variances of the north and east coordinates obtained from the GPS data processing. Choosing:

$$\tilde{e} = \frac{\sum_{i=1}^m \frac{e_{oi}}{\sigma_{v_i}^2}}{\sum_{i=1}^m \frac{1}{\sigma_{v_i}^2}}, \quad (8)$$

the least squares estimate of the azimuth results:

$$\hat{\alpha} = \frac{\sum_{i=1}^m \frac{n_{oi}(e_{oi} - \tilde{e})}{\sigma_{v_i}^2}}{\sum_{i=1}^m \frac{(e_{oi} - \tilde{e})^2}{\sigma_{v_i}^2}}. \quad (9)$$

In order to validate the result, a second survey was performed with a dual-frequency receiver, which was used to estimate the coordinates of three points (at the ends and in the centre of the path).

The coordinates were estimated by static positioning (lasting about 15 minutes), and in this case the observations were also elaborated by double differences using the permanent station of Latina, thus obtaining accuracy on the order of a few centimeters (Hofmann-Wellenhof et al. 2001). The dual-frequency GPS receiver could not be employed over the complete road segment because of the dense foliage that covers most of it (e.g. figure 3), which does not allow for centimeter-level positioning. However, the u-blox AEK-4T receiver could be employed, since it is a high-sensitivity receiver, with its lower positioning accuracy partly compensated for by the goGPS Kalman filter algorithm.



Figure 3. *Via Appia* at Clesippo's mausoleum in Mesa and the dual frequency GPS receiver (as discussed in the text, the setup did not work properly under dense trees, so the image is only explicative of the working scenario).

Our final result is the following: the azimuth is $135^\circ 57'$, with a maximum error of $\pm 6'$. This error is the sum of two terms: the GPS observation error propagated to the azimuth estimate, on the order of a few arcseconds actually, and the effect of the meridian convergence mentioned above. The latter is dominant, and, as demonstrated earlier, it is of about 5.9 arcminutes for the study case. We stress again that this 5.9 arcminutes error in estimating the north direction is not due to the observations (an intrinsic error of 5 cm would be reflected in an error of some 2 arcseconds) but to the use of the specific local Cartesian reference frame. This is basically due to the fact that for very extensive surveys the approximation of the actual shape of the earth's surface with the local tangent plane starts to be less effective, and therefore even the availability of more GPS observations will not result in a significantly better solution.

Using satellite images, this result can also be validated (with a slightly lower accuracy) for the remaining part of the road. Therefore, we conclude that the azimuth of the whole straight segment of *Via Appia* between Colle Pardo and Terracina is $135^\circ 57' \pm 6'$.

There is, therefore, no possible doubt to the fact that - contrary to what is written in many papers and textbooks - the Romans

did *not* align the road along the intercardinal direction. Further, the measures do not reveal any appreciable joint between segments of slightly different azimuths, which is what would be expected (even taking for granted the very high precision of the builders) if the road had been constructed using several different docks (building sites) working simultaneously on the plain. Therefore, the road was very likely built by a single, moving dock. Why? And how was the chosen direction maintained with such a high accuracy? The answer to the latter question will lie in a companion high-accuracy survey work, most probably carried out by the same planners, together with the road.

3. THE REDISCOVERY OF THE CENTURIATION OF THE PONTINE MARSHES

In the 1990s, a few traces of a regular division of the Pontine marshes were discovered using aerial photographs (Cancellieri, 1990). This centuriation, based on squared blocks of 10 actus (355 m), appeared to be oriented to the cardinal points. The centuriation was tentatively dated ca. 340 BCE, therefore before the construction of *Via Appia*; however, the issue of its chronological relationship with Appia remained unexplored, and even its existence was overlooked in many subsequent works.

Of course, the pre-existence of a regular grid would have facilitated the tracing of the road, so we became interested in studying the layout of this centuriation. To facilitate the identification of the original traces found by Cancellieri on currently available satellite images, we carried out a georectification of the available figures and maps. The process of georectification consists in associating geographical coordinates to points in a non-georeferenced image (in

our case, digital scans); the coordinates are generally surveyed or extracted from a georeferenced source (in our case, Google Earth satellite imagery). These points are usually referred to as Ground Control Points (GCPs). A transformation is then applied to rotate, scale and warp the original image, aiming at minimizing the introduced error according to a least squares principle. Different transformation models can be used; in this work, first or third order polynomials were applied, depending on the number of available GCPs and their distribution on the image. In fact, to apply the third order model at least 10 GCPs are needed.

The open source geographic information system (GIS) software GRASS (Neteler *et al.* 2012, <http://grass.osgeo.org>), and in particular its "Georectification Tool", was used to identify and select the GCPs, apply the polynomial transformations, and produce georeferenced image files. These files were then processed by means of the open source software MapTiler (<http://www.maptiler.org>), in order to produce KML files to overlay the newly georeferenced image on Google Earth.

Four images were georectified: two aerial photos with visible centuriation traces and two maps based on the Italian Military Geographic Institute (Istituto Geografico Militare (IGM)) cartography, with the traces and an extrapolated grid representing the centuriation. One of the two aerial photos had to be rectified by first order polynomials due to the poor distribution of the available GCPs, while for the other three images third order polynomials were used. All the final KML files are freely available for download at the website:

http://geomatica.como.polimi.it/elab/via_appia/.



Figure 4. One of the georectified images overlaid on Google Earth, representing an aerial photo (after Cancellieri, 1990) with centuriation traces indicated by triangles; the 13 GCPs used for the georectification (third order polynomials) are also shown; a section of *Via Appia* extends from the upper left to the lower edges of the figure (crossing GCPs 2 and 7).

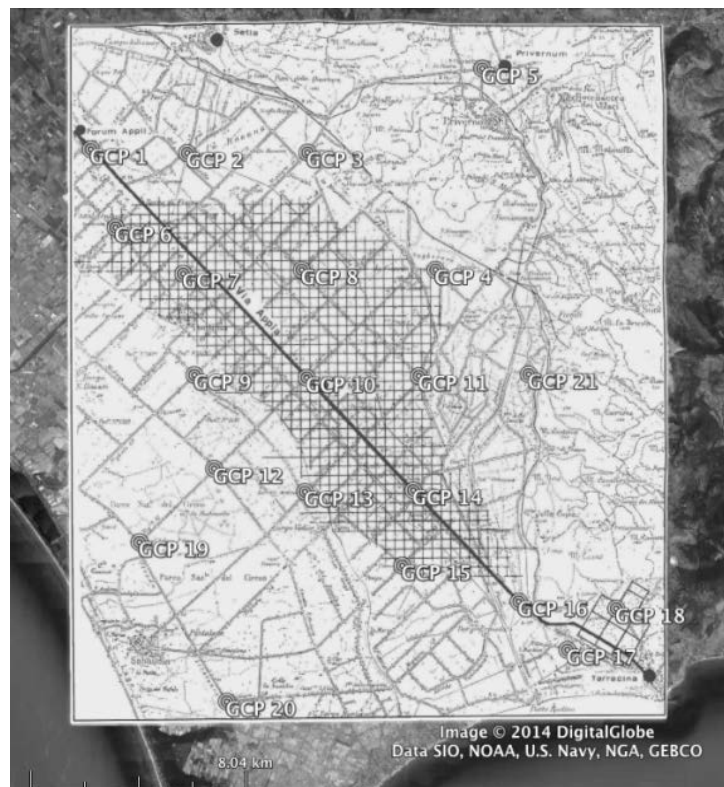


Figure 5. One of the georectified images overlaid on Google Earth, representing an IGM map (after Cancellieri, 1990) with centuriation traces indicated by horizontal and vertical lines; the 21 GCPs used for the georectification (third order polynomials) are also shown; the final section of *Via Appia*, ending at Terracina, is visible from the upper left to the lower right corners of the figure.



Figure 6. An example of the inconsistencies in the centuriation grids proposed by Cancellieri (1990), as shown by our computer-reconstructed grid (thin grid lines, with regular spacing of 10 actus, or 355 m) overlaid on Cancellieri's georectified grid (thick grid lines), using Google Earth. While the two grids agree quite well near GCP 8, the hand-drawn grid exhibits an increasing error along both the horizontal and vertical directions; it should be noted that the hand-drawn grid becomes inconsistent also with respect to traces that were actually first reported by Cancellieri (e.g. vertical trace near GCP 7 and horizontal trace near GCP 11).

Figures 4 and 5 show examples of georectified figures overlaid on Google Earth, respectively representing an aerial photo (after Cancellieri, 1990) and an IGM map, both with centuriation traces. A warning must be stated here: *In general, bad topographic correction of oblique images or non-compensation of perspective effects in aerial views may render Google Earth not a truly reliable GIS.* Actually the georectified Cancellieri's photo has been used to facilitate the identification of the original traces.

By utilizing the georectified figures, it was possible to confirm some, although not all, of the traces reported in the previous analyses. Some traces might have been destroyed by recent modifications of the environment or might not be visible on the available satellite imagery.

This procedure also highlighted some inconsistencies in the centuriation grid proposed by Cancellieri, probably due to the limited precision achievable by hand drawing on the IGM maps, further enhanced by the extrapolation of a few visible traces to produce full sections of the centuriation grid (see figure 6).

On the other hand, we were able to identify several new traces; in particular, we

have found three sides of a square of the original centuriation, located at Codarda (Latina). The square, whose "authenticity" is beyond any doubt since the side length is precisely 10 actus, breaks the regularity of the much later 19th-century grid and probably had been privately drained before the modern reclaim of the Pontine marshes.

At the end of the process, we obtained a computer reconstruction of the full centuriation grid and a computerized viewshed analysis of the corresponding inter-visibility areas, which allowed us to investigate the relationship with the *via Appia* in a quantitative way.

First of all, the centuriation was very precise and very well oriented to the cardinal points. There was no topographical reason whatsoever to orient it in this way; therefore, the grid cannot postdate the road (if this were the case, then every – admittedly not crazy – surveyor would have traced one of the two main axes along the existing road). Further, the possibility that the grid predates the road is very unlikely. Indeed, in this case every surveyor would have traced the road along the diagonal of the existing grid, that is, along the inter-cardinal direction. The most likely conclusion is thus that the construction of *Via Appia* also triggered a regular division of the surrounding land. Centuriation responded to the practical reasons of control of the territory and allowance of fertile lands to veterans, and also to the aim of establishing the Roman control and authority via a "terraforming" of the landscape. The accuracy of the grid is very good and comparable to that of the road. In fact, using a priori (before interpolation) single lines measured on satellite images, the grid turns out to be oriented about 10' east of north. Such accuracy is hardly established with a solar method, and therefore a stellar method (most probably based on circum-polar stars) was likely used.

To have a final proof that the road and the grid are indeed contemporary, and thus belong to a global project aimed at modelling the landscape of the Pontine Marshes

in Appius' times, we searched for intersections at grid nodes. To our surprise, we discovered that they intersect at a node very close to the beginning of the straight segment at Torre Elena (figure 7).

It is, therefore, very likely – if not certain – that the road was traced from the south-east only, starting from this node used as the main survey point and, therefore, with the key help furnished by the contextual tracing of the centuriation grid.

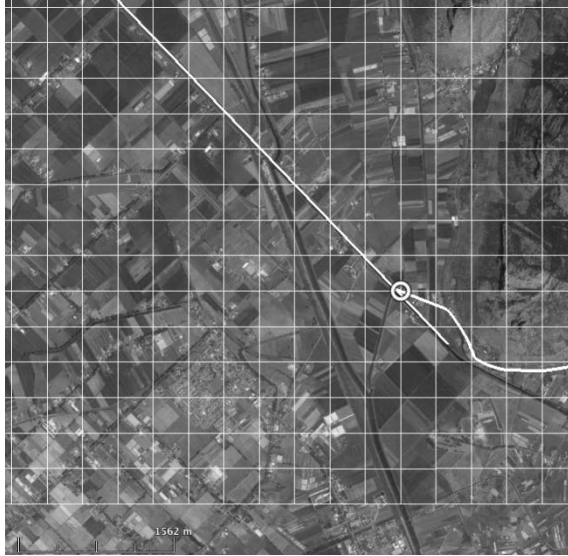


Figure 7. The intersection between the computer-reconstructed grid (thin grid lines) and the GPS-surveyed Via Appia (thick white line), overlaid on Google Earth satellite imagery.

4. DISCUSSION

Many ancient cultures devised and adopted suitable, probably astronomical methods allowing them to trace straight roads. Among them, one can mention the Hopewell (Lepper 1995, 2006), the Ancestral Pueblos (Sofaer, Marshall and Sinclair 1989, Malville 2008, Malville & Malville 2001) and the Maya (Mathews 1999).

It is pretty clear that the Romans also used astronomy – in many cases combined with a clever application of simple geometry – to trace their long, straight roads. As discussed in details in a companion paper (Magli et al 2013), in the present case the well-known “practical” mentality of the Roman builders (*Via Appia* was first of all a military road) seems to have been com-

bined with symbolic aspects related to the sky, as occurs, for example, in many Roman towns that are astronomically oriented (Magli 2008, Gonzalez Garcia & Magli 2012). *Via Appia* indeed points with impressive precision to the setting of the star Castor (taking the 1M star at 1° degree of altitude, it occurred at 315° 59' in 312 BC), and as is well known, the Dioscures (Castor and Pollux) were protectors of the Roman army (see e.g. Rüpke 2007) and were identified with the two brightest stars of the Gemini constellation as early as the fifth century BC (Castagnoli 1983).

Interestingly enough, a quite explicit link between the Appia and the Dioscures is documented in the historical sources, and such a link was fixed precisely at the times of the construction of the road (McDonnell 2006). It is the parade of the Roman *equites* (knights), which occurred annually at the Ides of July (15 July) and was called *transvectio equitum*. According to the ancient sources, the ceremony was instituted in 304 BCE, and its route started from a Temple of Mars located on the Appia outside Porta Capena, proceeded along the road up to the Temple of the Dioscures in the forum, where a sacrifice was offered, and then up to the Temple of Iuppiter Optimus Maximus on the Capitolium. The date of the ceremony might have been related to that of the Lake Regillo battle (which is unknown), but it is at least interesting to note that the Heliacal rising of Castor and Pollux occurred around the 26th of June and the 6th of July (*Julian*) respectively. The ancient ceremony later went into disuse and was revived in imperial times by Augustus (Humm 2005).

All in all, the main objective of the present paper was to show that, to study ancient high-accuracy works, high-accuracy modern measurement techniques can be applied. In this respect, satellite positioning is a particularly useful tool in archaeoastronomy, since it offers the means to carry out very precise measurements of archaeological remains all over the globe (if unobstructed view of the sky is available),

providing coordinates of the measured objects according to global reference systems that are inherently aligned to the cardinal directions. However, it is crucial to take into account approximations and errors that might be introduced when one moves from global to local reference systems (or, similarly, from geographic to projected coordinates) for estimating precise directions, in particular in the case of artefacts stretching over long distances, as is the case for *Via Appia*. By all means, the accuracy that its builders managed to obtain – probably

with repeated, accurate sighting of the star at the horizon, combined with a rigorous alignment of the direction of the road segments with the use of the *groma* – which we were able to grasp only with a seemingly accurate survey, can only be glimpsed by riding along the road, but not fully appreciated. Therefore, it was clearly not needed for practical purposes; rather, it seems to have been of vital importance to “build it in” as a ritual act of foundation for such an important artifact.

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