Colin Davis had a display of postcards and cigarette cards together with his *Old Colin's Sundial Almanac* computer programme in QBASIC. This gives the angles for the hour and half hour lines for a variety of dials, given the latitude. It also computes the equation of time. Members who wish to obtain a copy should write to him at 23, Vernon Walk, Northampton NN1 5ST.

Technology was also on display by Patrick Powers, our Registrar, who showed many members the records on his lap top computer. John Moir demonstrated some models of sundials featuring the Italic and Babylonic hours by J.M.Bores of Madrid. He also had an excellent selection of sundials including his origami one that featured in a recent Bulletin. Also impressive was Colin McVean's wooden lady who held a polar dial and can wear a variety of head-dresses to give gnomonic or meteorological information.

David Pawley brought along the large polar dial he designed for the Solent Business Park, and complemented this with smaller models of different types of dials. We owe him our sincere thanks for organising the conference and refreshments as well as laying out two fantastic displays. Not knowing who is going to turn up and give talks or exhibit material must make it quite a headache, but David took this all in his stride. He remained cool and confident

Fig. 4. Onwards and upwards (to Polaris) with David Pawley.

throughout, despite the photographic evidence which should not be misinterpreted. He assures us that his finger points to celestial north, for which we are all grateful. Many thanks David!

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ANALYSIS OF THE SUNDIALS ON THE TOWER OF THE WINDS, ATHENS:
POSSIBLE PARAMETERS USED IN CONSTRUCTION

MANFRED HÜTTIG

The Tower of the Winds in Athens, built by Andronikos Kyrrhestes, is one of the best preserved monuments from ancient times. In the past the sundials on the tower have been analysed by Delambre,[1] Drecker,[2] Antonacopolous & Fragakis[3], and Bromley & Wright,[4] based on the measurements made in 1762 by Stuart & Revett.[5] Only Palaskas[6] performed his own measurements. The data in all these cases, as is now apparent from new measurements, are not as accurate as they seem; despite this, all authors draw favourable conclusions about the accuracy of the construction. Gibbs[7] seems to be the first to have recognised the few remains on the cyclinder annex as part of another sundial. This fragment is also mentioned by Noble & de Solla Price[8].

Vitruvius, (writer of 'De Architectura' a 10-book work , in late 1st century B.C.) mentions the Tower of the Winds and its designer (Book 1) only in the context of finding the cardinal directions for town planning, not in connection with horology. Again later (Book 9) when he deals with sundials in particular, no mention is made of this outstanding time-standard. This aroused a discussion about whether the sundials were added later. Palaskas objected to this, and if it is not already clear from the overall architectural concept, the design of the cyclindical dial would be proof enough.

The current analysis of the sundials is part of a Greek-German Project to investigate thoroughly the whole building.(See Kienast[9]) The data acquisition was performed with the Leica System TC 1610, (a high-precision geodetic data-acquisition system) resulting in absolute coordinates with an uncertainty of less than 3mm. The position and orientation of the coordinate system is also known with high precision.

Taking into account contemporary achievements in mathematics, astronomy and geography, the analysis
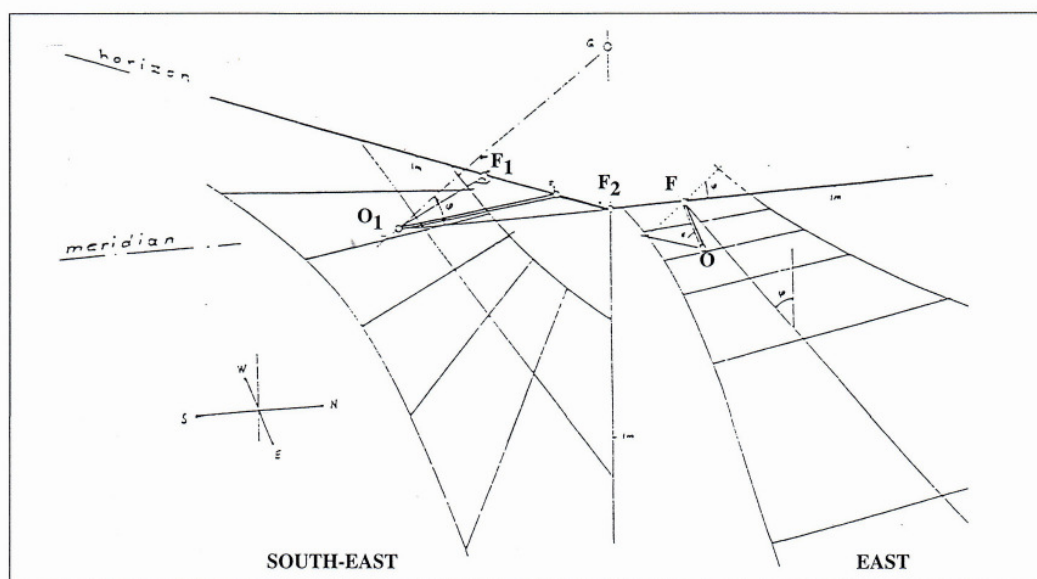
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Fig.1 Partial View of the Sundials on the South-east and East faces, showing different cardinal parameters

reveals the cardinal design parameters used in the construction of the sundials. These are:

(a) geographic latitude and orientation of the wall

(b) angle of the ecliptic

(c) length of the gnomon, in ancient units.

It should be pointed out that the engineers of that time faced a similar problem of measurement to that which must still be solved today in national laboratories: namely that when setting up a primary standard of time (atomic clock nowadays) there is no simple standard of comparison available. The duration of one day, when the shadow of the sundial arrives at the very same position, (which is observable with an uncertainty of only a few seconds) could have been used for calibrating the water-clock.

Since the objective of this analysis is to find parameters used in the construction of given sundials, not to construct a sundial according to given parameters, one is faced with an 'inverse problem,' with the intrinsic difficulty of possible deficiencies in the available data. The 'inverse problem' must be solved by knowledge-guided trial-and-error. A set of parameters is selected in order to calculate a model which will be compared with the reality presented. The consequences of the deficiencies will be that two or more models are equivalent, according to certain error-criteria. Fortunately the range of parameters is limited by the nature of the problem and by practical considerations of the design. A final selection will take advantage of special points on the day-line at equinox and the hour line at noon, together with *a priori* knowledge of the parameters.

There are four main reasons for the defects of the data:

deficiency of the basic concept; deficiencies during construction of the dials; changes by external impact such as earthquakes; uncertainties of data acquisition. The high-precision measurements showed that in any case the walls to the South, South-east and East are still very well in place after the long period, and therefore add no problems to the analysis. Doubts about the basic concept were listed merely for completeness; thus, the analysis for the three sundials mentioned above will have to deal only with the imperfections of the realization.

The first parameters - position of the wall and its orientation with respect to the cardinal points-- have been verified. The position of the Tower was found with respect to two trigonometric points as: 37° 58' 21.6" N and 23° 43' 28.8" E. The orientation of the Tower has been determined by observation of the sun and by utilising information from the global positioning system (GPS). A coodinate system was defined for the Tower based on the best fit of a regular octagon to the inner walls at floor level. The cardinal axis of this octagon nearest to the North-South direction has an azimuth of 5'30". Palaskas, who determined the orientation of several outer faces, obtained a mean value of 17', which shows the imperfections of his measurements; not, as he claims, those of Andronikos, who probably used the method now known as 'Indian Circles', as described by Vitruvius, obviously to great perfection.

The angle of the ecliptic was known in ancient times with limited accuracy: $\in = 23° 51'$ (Eratosthenes.) For practical reasons of geometric construction the value $\in =$

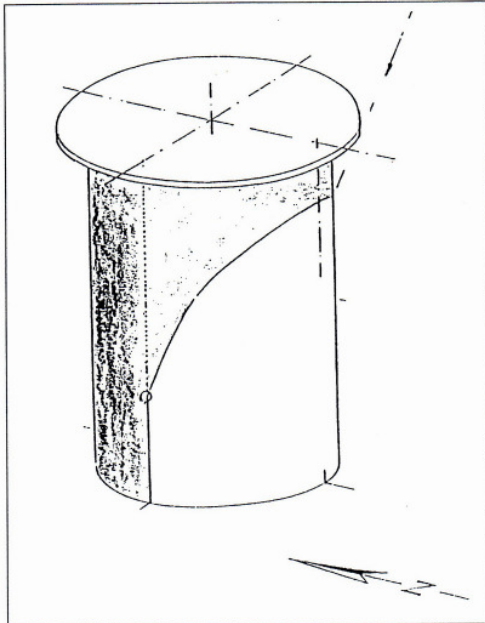*Fig. 2a Drawing to show possible functional principle of the sundial on the cylindrical annex*

Fig. 2b Drawing to show position of annex against south wall of Tower. Dotted lines show stone-work no longer in existence

24°(Vitruvius) might have been used. The value actually changes slowly with time so as to be 23° 42' 20" in 100 B.C. (23° 26' 21" in 2000 A.D.) These differences have only a small effect on the shape of the sundials and one can certainly not hope to date the building this way, as Palaskas suggested.

The geographic latitude, $\emptyset$, had been determined as the ratio of the shadow length at equinox noon to the gnomon height, expressed with small integer numbers. The following values were reported in the case of Athens (with modern writing):

Latitude $\emptyset$ = arctan 3/4 = 36° 52' 12" (Vitruvius, Book 9)

Latitude $\emptyset$ = arctan 16/21 = 37° 18 '14" (Plinius, Book 6)

With the East and West Sundials, the angle made by the day line at equinox with the vertical directly represents the latitude. It is found here close to:

$\emptyset$ = arctan 16/20 = 38° 39'36"

Finally the length of the gnomon is the free parameter to be chosen by the designer for determining the overall size of the sundial. One could reasonably expect 'nice' values in terms of the ancient unit of length. As a hypothesis supported by several dimensions of the Tower itself, it may be assumed that the construction is based on the roman foot: 1 pes monetalis = 16 digits = 12 unciae = 296.17 mm. This implies that the Tower was built after this length
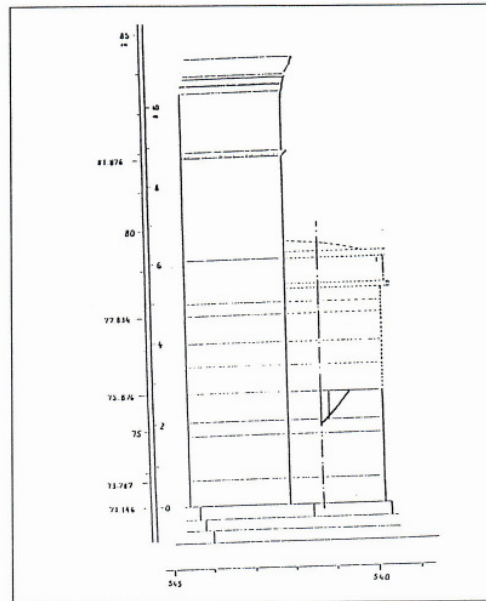
standard had been established in Athens by the Romans. If this result can be confirmed this investigation would also help to answer the question as to when the Tower was built, (Freeden,[10]). In contrast to modern sundials having a stylus mounted parallel to the axis of the earth, only the shadow of the gnomon *tip* is essential for ancient sundials; this gives freedom for the mounting of the gnomon onto the wall. In fact the gnomons were mounted here above the horizontal. The length is to be measured normal to the wall, (OF in Fig.1) in the case of S-, N-, E-, and W- dials, whereas for the others there is an angle of 30° ($F_1 O_1 F_2$) to the normal.

It is difficult to decide the question of whether the sundials were constructed according to theory with certain specific parameters, as most authors suppose; or simply by marking the shadow, using another 'horologion', maybe the water-clock inside, as a standard, (Palaskas): though the use of a water-clock for calibration has an inherent inaccuracy because of the large temperature effect on the viscosity of water. It is remarkable in particular that various different values of the latitude seem to have been used. From this it appears plausible that the combination $\emptyset$ = arctan 4/5, $\in$ = 24° is to be interpreted as geometrical construction, whereas the actual values (37°58'22", 23° 42'20") give a hint of the empirical method. Table 1 summarises the values of the parameters for the sundials on the eight sides of the Tower, according to the current working hypothesis.

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Dial	Gnomon length		Latitude, Ø			Ecliptic, ∈		
	unciae	mm	o	'	"	o	'	"
S	11	271.5	37	58	15	23	42	20
SE	30*	740.4*	37	58	15	23	42	20
E	20	493.6	38	39	35	24	00	00
NE	9*	222.1*	37	58	15	23	42	20
N	11	271.5	37	58	15	23	42	20
NW	9*	222.1*	37	38	15	23	42	20
W	20	493.6	38	39	35	24	00	00
SW	30*	740.4*	37	58	15	23	42	20

Table 1: Summary of cardinal elements of the sundials

*Angle against normal to wall, 30°

As to the cylinder dial, Bromley & Wright have already pointed out that the remaining lines on the cylinder cannot be explained with gnomons, and call for another solution. The following proposal has convincing aspects. Fig 2a shows how the combination of the shadow cast by the cornice like the 'brim' of a 'hat', together with the 'eigen'

Fig. 3 South wall of Tower of the Winds, showing ruin of cylindical annex near the base (Photo: C.K. Aked)

shadow of the cylinder body, forms a corner-point the position of which is unique for the day and the seasons. Traces on the south face lead to the reconstruction of a cornice 8 unciae in depth. With the values $\emptyset$ = arctan 4/5, $\in$ = 24°, this is consistent with the position of the lower end of the noon line on the cylinder at summer solstice.

Unfortunately the theory demands that the day line crosses at a right angle with the hour line at noon. The apparent 'day line' might also be interpreted as the shape of the shadow at noon, reducing the sundial to a noon indicator. In this case the theory would call for a much smaller angle towards the vertical. Since there is no other functional requirement for the cornice in the architecture of the annex, the basic idea - the corner point of two shadows - is plausible.

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