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High-accuracy azimuth measurements: The ENEA solar compass in its instrumental and smart version

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Summary. — The accurate assessment of the azimuth of a given direction as, *e.g.*, the geographic North, is of utmost importance in many fields. The electronic solar compass patented by ENEA achieves an accuracy of 0.01°, it is up to 100 times cheaper than instruments having similar accuracy (GPS, gyros, . . .), and it is also very fast in answering (few seconds). It is based on a simple but effective optical system to capture the Sun direction, and on an analytical algorithm to provide the Sun position. The ENEA solar compass has been tested and used in many circumstances, *e.g.*, for mapping surveys, to align concentrating solar mirrors, and for orientation measurements of structures in archaeological sites. We obtained notable results, together with INGV, in magnetic declination measurements in Antarctica. Finally, we moved the ENEA solar compass algorithm to smartphones, enabling their use as orienteering devices.

1. – The ENEA solar compass

In order to determine the azimuth of a given direction, it is necessary both to measure the orientation of the Sun with respect to a reference plane of the solar compass (SC) (fig. 1, left) and, at the same time, to know the Sun azimuth (with respect to the geographic North) when and where the measure is performed.

The first objective is attained by letting the Sun rays pass through a narrow slit, generating a line of light on an electronic sensor. The reference plane Π is the vertical one containing the slit (see fig. 1, right), whose width minimises the width of the light line on the sensor, taking into account the diffraction broadening. The sensor was a

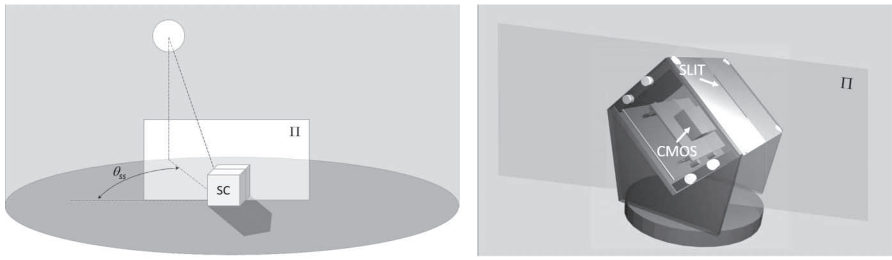

Fig. 1. – Angle θ_{ss} between the Sun and the solar compass (SC) reference plane Π (left). Sketch of the SC, with the slit, the optical sensor (CMOS) and the reference plane Π position (right).

serial transmission CMOS camera with VGA resolution (640×480, pixel dimension 5.6 μm). Given the pixel dimension and slit-to-CMOS distance, this translates into a $2 \cdot 10^{-3}$ degrees accuracy on the measured angle θ_{ss} between the Sun rays and the SC reference plane. All the details on the construction parameters of the ENEA SC can be found in [1-4]. The device has also been patented [5].

The second aim is achieved by using an original algorithm we developed [6] to determine the expected position of the Sun at a given place and time on Earth, relying on an approximate analytical solution of the Kepler equations. The Sun azimuth values obtained with our algorithm agree within $3.3 \cdot 10^{-3}$ degrees with those given by the Solar Position Algorithm [7].

A microprocessor combines then the measured value of θ_{ss} with the calculated Sun azimuth, allowing to obtain in few seconds the azimuth of the SC reference plane with respect to the geographic North. The SC must be kept strictly horizontal.

By coupling the SC with high-accuracy direction pointer and goniometer, it is possible to assign an azimuth value to a desired pointed direction, based on the previously determined SC reference plane azimuth. We joined the SC to a theodolite (Tecnix, model FET402K-L), which guarantees about 10^{-3} degrees of accuracy in pointing, and horizontality adjusting within $8 \cdot 10^{-3}$ degrees.

In a succeeding version of the SC we substituted the 2-D CMOS camera with a linear sensor (Hamamatsu S9226-03), in order to reduce the response time and the memory space, as well as to increase the horizontal acceptance angle of the sensor and the dynamic range of the acquired data.

In both cases, a careful calibration procedure on a dedicated optical bench was needed in order to achieve a high accuracy in azimuth measurements, due to unavoidable internal misalignments among the different components. By means of this procedure, we assessed a set of mechanical parameters and used them to adjust the azimuth calculation [1, 2, 4].

2. – ENEA Solar Compass achievements

During the development of the SC, many surveys have been carried out, mainly by pointing targets from the ENEA Research Centre in Frascati, which lies on a hill south-east of Rome. From there it is possible to see structures up to more than 20 km distance, a very good condition in order to increase the accuracy in pointing the desired direction. The obtained azimuth results have been compared with the theoretical values derived by averaging several satellite maps and considering the Earth ellipsoidal shape. The azimuth values obtained with both sensor types (averaged on at least 5 measurements for each considered direction) coincided with the theoretical ones within errors ranging from $0.6 \cdot 10^{-3}$ degrees to 10^{-2} degrees. These SC performances are comparable with those of the most advanced (and expensive) orientation measuring devices.

We exploited the high accuracy of the SC in several surveys: in measuring the orientation of the main axis of concentrating solar mirrors [8]; in mapping the relative position of a group of wells (belonging to a public company); in making precision measurements of the orientation of ancient ruins [9]; and, finally, in providing a reference direction for magnetic declination measurements [10].

In the latter case, during the 2017–2018 Antarctic campaign, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) exploited the ENEA SC at the Concordia Station to check the azimuth of the reference direction (RD, identified by two poles), used for their periodic magnetic declination measurements. The RD was set up in 2003 and its azimuth was determined with astronomical methods. In the next years, the RD azimuth was assessed by differential GPS measurements and a steady unexpected variation was observed. The value obtained with the SC in December 2017 fully confirmed the original data. The result is reported in table I together with the previous ones. The GPS measurements were affected by an increasing systematic error, probably due to the ice growth around the reference poles [11].

3. – The app Sunpass

Smartphones' rich instrumental apparatus (camera, GPS, inclinometer, microprocessor) pushed us to exploit their equipment for developing an app, named Sunpass, able to transform these popular devices in solar compasses. The software developed for the SC, both for Sun position calculation and data elaboration, has been written for Android, using input data given by the smartphone instruments. The expected accuracy is lower than the SC one, mainly due to camera aberrations and inclinometer imprecision, but it is anyway far better than that provided by magnetic compasses.

In the case of a smartphone, Π (see fig. 1) is the vertical plane parallel to its long side and the Sun direction with respect to it can be determined in several ways. The first (the less accurate, $\simeq 1°$ error) allows the user to trace on the display the Sun direction with respect to the plane Π. Secondly, one can frame with the camera the shadow of a vertical pole (second method) or a shadow edge (third method). Finally, the fourth

TABLE I. – *Azimuth of the reference direction (RD) for magnetic declination measurement at Concordia Station, Antarctica, measured with different techniques in past years (see text). The two poles defining RD are about 26 m far and, in the case of GPS measurements, were localised with an error ranging from 10 to 34 mm* [11]. *The ENEA SC result almost perfectly reproduces the original one obtained with astronomical methods.*

Year	2003	2005	2007	2009	2013	2017
Method	Astronomical	GPS	GPS	GPS	GPS	ENEA SC
Azimuth (253°+)	$56' \, 52''$	$54' \, 24.4''$	$56' \, 01''$	$1° \, 02' \, 04.5''$	$1° \, 12' \, 34''$	$56' \, 48'' \pm 11''$

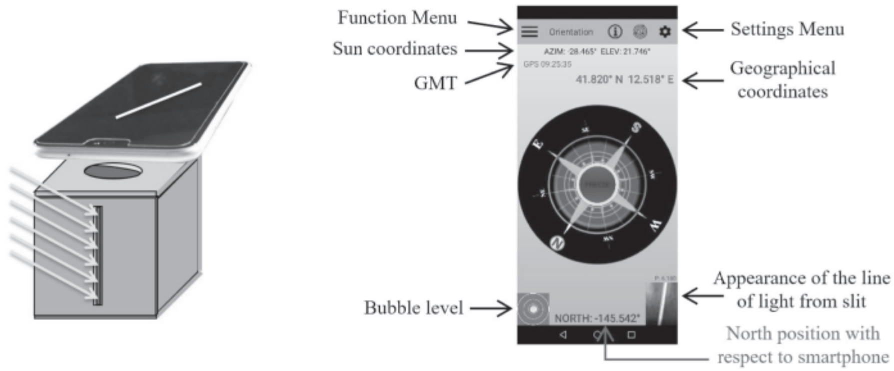

Fig. 2. – Sunpass slit method: example of a box to be put below the smartphone camera for Sun direction determination (left); screenshot of the Sunpass Orientation function (right).

method consists in framing with the camera the line of light generated by an added simple device like a box (see fig. 2, left) put below and in contact with the smartphone, having an upper hole and a vertical slit. In this way the camera can frame the line of light which appears on the internal floor of the box. The last method allows to reach accuracies of $\simeq 0.1°$ [4]. In fig. 2, right, the appearance of the main screen of the Orientation function of Sunpass is shown, in the case the slit method is used.

Sunpass is now at beta version; it should be available in the Play Store shortly.

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