Testing the Functionality and Applicability of Smart Devices for a Handheld Celestial Navigation System

Testiranje funkcionalnosti i primjenjivosti pametnih uređaja za ručni sustav astronomske navigacije

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DOI 10.17818/NM/2021/3.3
UDK 520/524:656.61
Preliminary communication / *Prethodno priopćenje*
Paper accepted / *Rukopis primljen:* 4. 2. 2021.

Summary

In this paper, the functionality and applicability of smart devices for the purpose of handheld celestial navigation systems is investigated. The main instrument used to determine observer position (altitude measurements) in celestial navigation is the sextant. The use of a sextant and almanac or computer is a classical approach to determining the observer's celestial position. This approach has two significant limitations, firstly the time window for the measurements is short, and secondly, the view of the ocean horizon must be clear. With the use of smart devices, we can overcome these two obstacles and create a so-called handheld celestial navigation system. Currently, smart devices have very accurate sensors to measure various physical quantities such as acceleration, angular velocity, orientation, etc. We are particularly interested in validating the orientation sensor for measuring the altitude and azimuth of the celestial body. The altitude of the celestial body is the primary parameter in determining the celestial position using a sextant. The idea is to replace the sextant with a smart device to measure the altitude and possibly the azimuth of the celestial body. To test this idea, two types of experiments are designed. In the first, a system on a tripod to obtain the most accurate measurements possible is set. Such tests will provide detailed information about the accuracy of the smart device's sensors and its applicability in measuring altitude and azimuth. The test system will essentially resemble a theodolite device. In the second experiment, a hands-free measurement experiment that resembles a sextant to test the idea for practical use and functionality in the process of celestial positioning is set. The observed data show that the results of the measurements under controlled conditions are promising and within reasonable bounds for the accuracy of celestial positioning. Estimates of the position error by the graphical method are in the range of 10 Nm to 30 Nm. In order to obtain a fully functional stand-alone celestial positioning system, the proposed assembly needs to be improved through several unchallenging upgrades. A fully functional system can be considered as a cheap off-the-shelf handheld Celestial Navigational System (CNS).

KEY WORDS
smart devices
smart phone
celestial navigation
hand-held CNS

Sažetak

U ovome radu istražuje se funkcionalnost i primjenjivost pametnih uređaja za ručni sustav astronomske navigacije. Osnovni instrument koji se koristio za utvrđivanje pozicije promatrača (mjerenja visine) u astronomskoj navigaciji je sekstant. Uporaba sekstanta i almanaha ili računala predstavlja klasičan pristup određivanju astronomske pozicije promatrača. Ovaj pristup ima dvije značajne prepreke, prvo vremenski okvir za mjerenje je kratak, a drugo, pogled na obzor oceana mora biti jasan. Uporabom pametnih uređaja možemo prevladati ove dvije prepreke i stvoriti takozvani ručni sustav astronomske navigacije. Trenutno pametni uređaji imaju vrlo precizne senzore kojima se mjere različite fizičke vrijednosti poput ubrzanja, kutne brzine, orijentacije, itd. Nas posebno zanima validacija orijentacijskog senzora za mjerenje visine i azimuta nebeskog tijela. Visina nebeskog tijela je primarni parametar u određivanju astronomske pozicije uporabom sekstanta. Ideja je zamijeniti sekstant pametnim uređajem za mjerenje visine i po mogućnosti azimuta nebeskog tijela. Da bismo testirali ovu ideju, dizajnirana su dva tipa eksperimenata. U prvome, ispitat će se sustav na tripodu da bi se dobilo najpreciznije moguće mjerenje. Ovi testovi dat će detaljnu informaciju o preciznosti senzora pametnog uređaja i njegovoj primjenjivosti u mjerenjima visine i azimuta. Sustav za testiranje će biti jako sličan teodolit uređaju. U drugome eksperimentu, ispitat će se oprema za mjerenje eksperimenta hands-free koja nalikuje sekstantu za testiranje ideje za praktičnu uporabu i funkcionalnost u procesu određivanja pozicije. Podatci pokazuju da su rezultati mjerenja u kontroliranim uvjetima obećavajući i u okviru razumnih granica preciznosti određivanja pozicije. Pogreške u procjenama pozicije grafičkom metodom kreću se od 10 Nm do 30 Nm. Da bi se dobio sustav astronomske navigacije koji je potpuno samostalno funkcionalan, predloženi sklop treba pobljšati uz pomoć nekoliko jednostavnih nadogradnji. Potpuno funkcionalan sustav može se smatrati jeftinim i lako dostupnim ručnim sustavom astronomske navigacije (CNS).

KLJUČNE RIJEČI
pametni uređaji
pametni telefon
astronomska navigacija
ručni sustav astronomske navigacije (CNS)

1. INTRODUCTION / *Uvod*

The classical methods of celestial navigation [21] are slowly becoming obsolete. Many practitioners of celestial navigation are not found among ship's officers but mainly among recreational sailors who use it for fun navigation during long voyages on the open seas. While the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) [5] still requires that all officers in charge of a navigational watch be able to determine the altitude of a celestial body, a line of position (LOP) and finally the final position, the convention also states that the use of appropriate celestial navigation calculation software and an electronic almanac is permitted. This legal requirement is probably the main reason that the sextant is still found on board many ships today; but this state of affairs is not expected to last forever. Also, the SOLAS convention [16] in Chapter V, Regulation 19, does not require ships to carry a sextant onboard.

Unfortunately as times and technique change, cyber-attacks are part of the new model. In the Electronic Chart Display and Information System (ECDIS), the primary navigation parameters are taken exclusively from a Global Navigation Satellite Systems (GNSS) device. The position, navigation and timing (PNT) data obtained from the GNSS device can be hacked. This fact has been proven in many cases and studied in many recent works [1,9,20].

The stages of hacking are different but can be omitted. One way is to use classical navigation methods without a GNSS device to obtain PNT data. This is the motivation for reusing celestial navigation methods with smart devices to have a fast, accurate, general, and fun method [6]. As Kaplan points out in his recent debates [7], there is a need for new approaches. On the website of the US SBIR and STTR programs [19], there is a US Department of Defence solicitation with the topic "*The objective of this topic is to develop innovative approaches to celestial navigation in order to provide non-GPS (Global Positioning System) navigation capabilities to Soldiers on the ground*". The specification seeks solutions that produce new technologies and systems similar to those discussed in this paper. There are similar approaches as in [15], where the use of mobile devices is used for positioning with the sun as the celestial body. The error shown in this study is significant and not applicable to CNS. In Cam-Sextant Project [13], a camera and star identification method is used to determine the altitude of the celestial body, but only in a way that leads to a very inaccurate positioning approach. A similar approach, but using a very advanced camera system and software, is described in [2]. Based on difficult image recognition algorithms, they are able to reconstruct the sky image as seen from the observer position. The described system is very advanced and fully automatic, but currently, it cannot be used in commercial navigation.

The innovative element introduced in this work is the use of smart devices to measure the altitude and azimuth of a celestial body in a time-averaged manner with a method that does not require an assumed observer position. Compared to other reviewed methods, it is shown that the measurement inaccuracy in the celestial body orientations can be filtered and a relatively good estimate of the observer position can be obtained by celestial navigation. Filtering is used to define a hybrid method of time signal averaging and calculations of the centre of the position polygon. The results support the idea and make the system a good candidate for a low-cost, commercially available handheld Celestial Navigational System.

2. MATERIALS AND METHODS / *Materijali i metode*

In the Materials and Methods section, we give a complete description of the equipment used with sensor error analysis. This is followed by a description of the methods, where we explain in particular the method of equal altitudes used. Last, we explain how the circles of equal altitude are used to determine the observer position.

2.1. Smart device description / *Opis pametnog uređaja*

The material section is divided into the description of two smart devices. The first device is a smartphone mounted on a homemade platform that is firmly attached to a tripod mount (Figure 2a). This experiment provides the most accurate measurements of orientation angles possible, which form the basis for analysing the systematic error of the sensor. The description continues with the handheld experiment performed with the Samsung Galaxy TAB S5 tablet and the analysis of the systematic error of the sensor. The method of data collection is the same for both experiments and a detailed description follows.

(a)

(b)

Figure 1 (a) wooden support on a tripod with scope and smartphone; (b) scope view with zero level calibration
Slika 1. (a) drveni nosač na tripodu s teleskopom i pametnim telefonom; (b) pogled kroz teleskop s nultom kalibracijom

Source: Figures made by authors

(a) (b)

Figure 2 Tripod with a detailed view of carrier, scope, and smart device. The tripod allows for very accurate device positioning
Slika 2. Tripod s detaljnim pogledom na nosač, teleskop i pametni uređaj. Tripod omogućuje vrlo precizno pozicioniranje uređaja
Source: Figures made by authors

The first device is the Meizu 15 smartphone, a fairly advanced smartphone with several built-in sensors. The device is mounted on a homemade wooden carrier with the scope Kahles Helia 3 with illuminated crosshairs. The carrier is made of wood to avoid magnetic interference, as shown in Figures 1 and 2.

The scope is made of aluminium, also a non-magnetic material. The smartphone is placed on a central plate and fixed with wooden rods (Figure 2). For night observation it is very important to have an illuminated reticle. In our case it is a small red dot in the cross centre. The complete setup is based on a tripod, as shown in Figure 2. The grip under the support allows very accurate measurements needed for sensor error analysis. We refer to this setup as the tripod experiment and thus define the fixed experiment.

The Meizu 15 smartphone is equipped with classic orientation sensors. The accuracy of orientation sensors varies from device to device [8] and needs to be tested accordingly. The experiment with the smartphone is performed in several steps. In the first step, the zero level must be tested with the zero level experiment. The tripod setup is positioned at the same location and height for all measurements (Figure 2). To measure the accuracy of the zero level, the second point was placed at the same water level on the electric column on the opposite side with accurate zero level markers (Figure 3). The beginning of all measurements starts with the zero level measurement. This step is the instrument calibration step. Knowing the error of the zero level, one can proceed with the measurements of the altitude of the celestial body.

Altitude measurements, including zero altitude, must be taken over an extended period of time to obtain a mean value. In our case, the interval was about 30 seconds. A typical sensor output for the Meizu 15 can be seen in Figure 4 for the zero level measurement. The standard deviation of the signal is about 0.01°. It can be clearly seen in Figure 4 that using only single-shot data can lead to a more significant systematic error in orientation. Based on this result, all measurements must be averaged to obtain a mean value. We distinguish two types of mean values with respect to the tag for the time of measurement. In the tripod test, the measurement starts with the exact alignment to the point intended for the measurements (the point is set in the crosshair centre, as shown in Figure 1b). Data acquisition follows with the fixed position of the instrument in space and it takes about 30 seconds to complete the measurement. During this time interval, the device is not moved and always points to the initial point in space. The data set is stored and averaged to obtain its mean value.

Figure 3 The position and measure of a zero altitude level. Position of the cross is seen in Figure 1
Slika 3. Pozicija i mjerenje visine na nultoj razini. Pozicija križa vidi se na slici 1.
Source: Figures made by authors

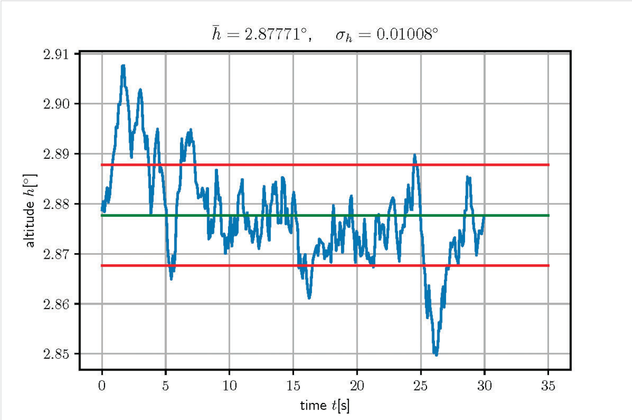
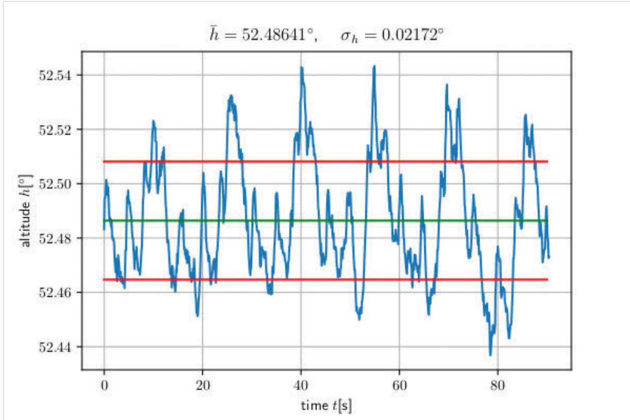


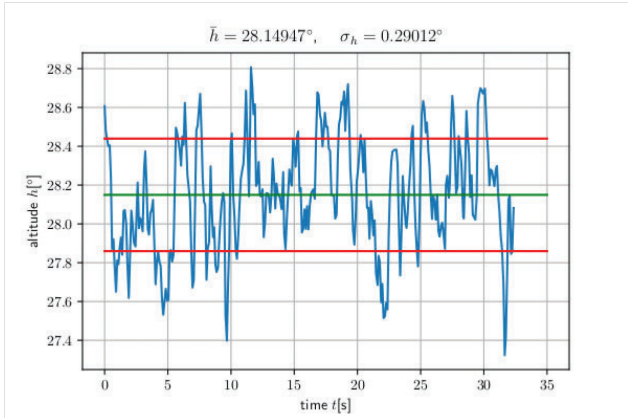
Figure 4 Signal of zero level altitude measurement. The average altitude is $\overline{h} = 2.87771^\circ$ (green line) with a standard deviation $\sigma_h = \pm 0.01008^\circ$ (red lines). Data represent a set of approximately 300 samples of altitude in the time interval of 30 seconds

Slika 4. Signal mjerenja visine na nultoj razini. Prosječna visina je $\overline{h} = 2.87771^\circ$ (zelena linija) sa standardnom devijacijom $\sigma_h = \pm 0.01008^\circ$ (crvene linije). Podatci predstavljaju niz od otprilike 300 uzoraka visine u vremenskom razmaku od 30 sekundi

Source: Figures made by authors



(a)



(b)

Figure 5 Processing of the altitude signal in two different devices showing the mean with a green line and the standard deviation with a red line. Both the mean and standard deviation of the height signal is shown in the above plots. (a) is the Meizu 15 signal; (b) is the Samsung TAB-S4 signal

Slika 5. Procesuriranje visinskog signala na dva različita uređaja gdje je srednja vrijednost prikazana zelenom linijom, a standardna devijacija crvenom linijom. Srednja vrijednost i standardna devijacija prikazane su na gornjim grafikonima. (a) je Meizu 15 signal; (b) je Samsung TAB-S4 signal

Source: Figures made by authors

The mean value is labelled with the start measurement time because it relates the correct time to the measured mean point in space. A typical sensor output for altitude measurement in the case of a fixed experiment is shown in Figure 5a. The standard deviation in this case is different from the standard deviation for zero level measurements. It has been observed that the standard deviation has a variation with respect to altitude, unless it is simply a systematic error of the sensor.

The second type of measurement is a handheld experiment. In the handheld experiment, data is collected over a period of approximately 30 seconds. The data is averaged to obtain the mean, as was done in the fixed experiment. Here, a different approach is taken to distinguish how the time marker is set to the mean. In this case, the time is set to the mean time of the measurement. The mean time must be set because the observer follows the celestial body over the entire measurement time interval. Following the celestial body means that the observer is actually following the celestial body at a variable altitude. This is exactly the opposite of the fixed experiment. In this case, the mean time marker is set to the averaged time, but the averaged time is the actual mean time. A typical sensor output is shown in Figure 5b. The change in altitude with time can be seen by the significant difference in standard deviation. In this case it is more than a magnitude of 10 with respect to Figure 5a.

The measurement data from the orientation sensor of the smart device is retrieved using a particular application for Android devices [4]. It samples the data from the orientation sensor and sends it over the network using the UDP protocol. The custom application ASL (Figure 6), written by the authors, listens on the UDP port, displays the data and saves it in a CSV formatted file. The sampling rate for all orientation sensors is approximately 10 Hz.

Each data entry stores the GNSS synchronized time. All the collected data from the smart device sensor can be seen in Figure 6. The stored data is ready for post-processing. In handheld mode, orientation measurements of the celestial body are made without the use of a spotting scope using only the built-in camera. In this case, the field of view is relatively large and the camera's light sensitivity is below the starlight threshold for most celestial bodies. The camera sensor can only see the brightest celestial objects. To enhance the light coming from the stars, we used another application [11] that can enhance the light coming from the stars and reduce the field of view with the zoom option. Even with this application, we could only scan the brightest stars in the sky. How to further improve the sensitivity of the camera sensor is discussed in the Discussion section.

Post-processing of the data is done entirely in the Python environment using modules for plotting and astronomy [3,12,14]. The Python environment provides a wide range of open source packages that can be used for almost all types of computation and plotting. The first step is to average all the data to obtain the mean altitude and mean azimuth of the celestial body. For each celestial body, the Astronomy module is used to calculate its geographic position (GP) based on the time of day of the mean values. With the module Plot it is possible to draw circles of equal height on a sphere and to project them onto a Mercator map. How to calculate the points of the circles is described in the next subsection Positioning method. In the zoomed region centred at the observer position (Figure 8c), contains the lines as approximations to the circles of equal height. Lines of equal altitude define the position polygon.

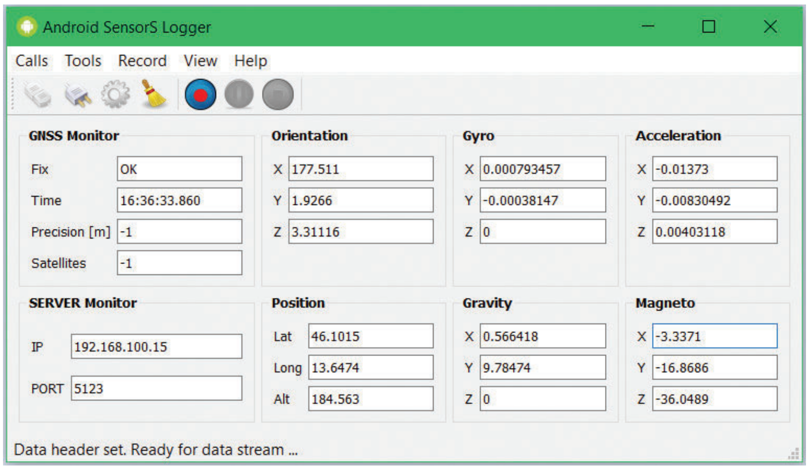


Figure 6 Android Sensor Logger (ASL) application written by authors. The application is developed under the Qt platform
Slika 6. Android Sensor Logger (ASL) aplikacija koju su sastavili autori. Aplikacija je napravljena na Qt platformi
Source: Figures made by authors

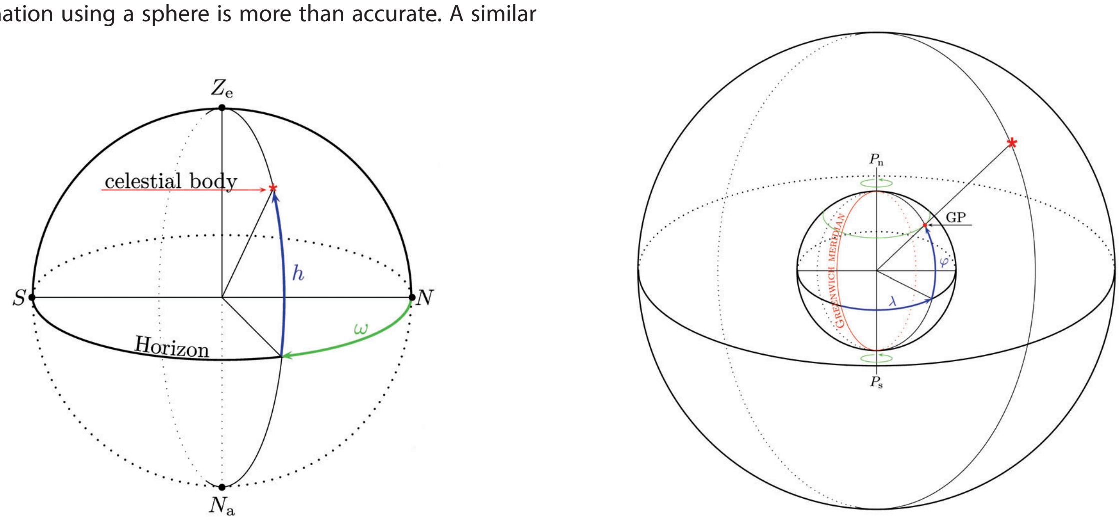
Figure 8 shows all three described steps leading to the construction of the position poygon.

2.2. Positioning method / *Metoda pozicioniranja*

The present method uses the classical celestial body altitude approach without an assumed position to find the observer position. The idea goes back very far and was also described in [17]. It is a hybrid method that uses the intersection of circles of equal altitude on the sphere centred in the GP. The method itself is not fully explained, since in this paper we only use the method already developed. For those interested, a complete description can be found in [17]. The method is very elegant, but requires the assistance of a computer or smart device to display the position circles and their intersection points. Calculating the intersection of two altitude circles is not a simple task, especially when the underlying Earth body is not a sphere but an ellipsoid [18]. Here we are concerned with the intersection of several 2D objects (circles) defined on a 3D manifold (sphere).

At this stage high accuracy is not so important, so the approximation using a sphere is more than accurate. A similar method, but using the azimuth approach, is described in [9]. Similar to our method, the accuracy of the measurements is very important. One way to overcome the accuracy problem is to increase the number of measurements and average the measured data over a certain time interval. In our work, both scenarios are measured and compared (altitude and azimuth).

The most important step in both positioning methods is to determine the GP of the celestial body, as shown in Figure 7b. If we know the altitude and/or azimuth of the celestial body (Figure 7a), we can identify it by name, or if the observer is skilled in astronomical observation, can immediately know which celestial body is under the measurement. In all methods of celestial navigation, accurate time is a must. With accurate measurement time and astronomy software, it is possible to calculate the GP of the celestial body. In this study, the program [14] is used to obtain the coordinates of the celestial body. How the coordinates of the celestial body are converted to GP will be explained later. All observers equidistant from GP measure the same body altitude.



(a) (b)

Figure 7 Coordinates of a celestial body in two different coordinate systems used in the process of a positioning method. (a) Observer horizontal coordinate system with height h and azimuth ω, (b) Projection of celestial body onto Earth with its geographic positions (GP)
Slika 7. Koordinate nebeskog tijela u dva različita sustava upotrebljena u procesu pozicioniranja. (a) Horizontalni sustav promatranja s visinom h i azimutom ω, (b) Projekcija nebeskog tijela na Zemlju s geografskim pozicijama (GP)
Source: Figures made by authors

The line of equal body altitude is a circle on the sphere with GP in the centre. A point on the circle of equal body altitude is calculated using the following algorithm. With the astronomy program [14] we can determine the coordinates of the celestial body

- declination - δ,
- Greenwich hour angle - Gha,

simply by entering the date/time. The coordinates of the celestial body's position can be converted to the Earth's position coordinates using the following transformation (Figure 7b)

$$\varphi_{GP} = \delta, \quad \lambda_{GP} = \begin{cases} -\text{Gha} & ,\text{if Gha} < 180^\circ \\ 360^\circ - \text{Gha} & ,\text{else} \end{cases} \tag{1}$$

In the calculation of the arbitrary point on the circle of equal altitude centred at GP (Equation (1)), altitude is replaced by the zenith distance

$$z = 90^\circ - h. \tag{2}$$

One of the several conditions is based on the absolute maximal latitude of the point on the circle and is defined as

$$\varphi_{max} := |\varphi_{GP}| + |z| \tag{3}$$

If the condition $\varphi_{max} > 90^\circ$ is fulfilled, then the circular path passes through the pole. In this case special care must be taken to ensure that the longitude λ_i of points following the path on the circle are in the range of a complete circle, that is $\lambda_i \in [0^\circ, 360^\circ]$. The coordinate (φ_i, λ_i) of the arbitrary point on the circle is calculated using the following relation

$$\sin\varphi_i = \sin\varphi_{GP}\cos z + \sin z \cos\varphi_{GP}\cos\alpha_i, \quad \lambda_i = \lambda_{GP} + \eta_i, \tag{4}$$

where parameters η_i, a_i, b_i and α_i in Equation (4) are defined as

$$\tan\eta_i = \frac{a_i}{b_i}, \quad a_i = \sin z \cos\alpha_i, \quad b_i = \cos z \cos\alpha_i - \sin z \sin\varphi_{GP}\sin\alpha_i, \quad \alpha_i \in [0^\circ, 360^\circ]. \tag{5}$$

Position (φ_i, λ_i) defined in Equation (4) and (5) uses free variable α_i defined as the angle of point (φ_i, λ_i) around the GP, where GP is the centre of rotation. In this case circle will be replaced by polygon with an arbitrary number of points (φ_i, λ_i). There are a couple of conditions to keep in mind when calculating η_i. The first is the condition for small b_i defined in Equation (5). We consider b_i to be small if $b_i < 10^{-15}$. This condition avoids division by zero. The following table provides the values of η_i for this case with various values of a_i and b_i:

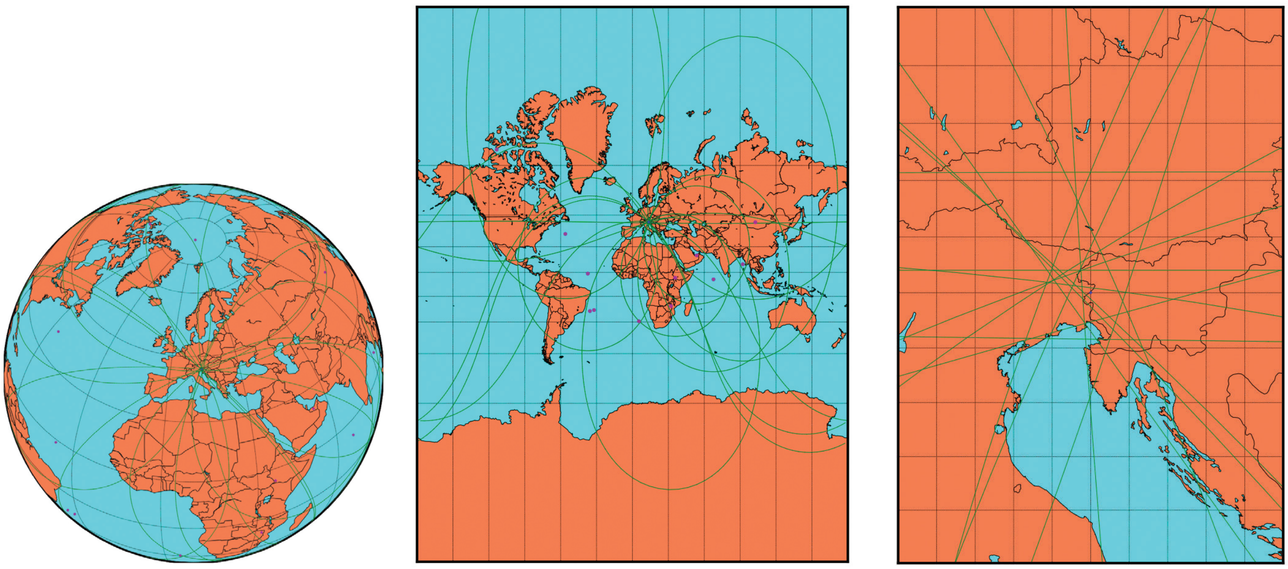
η_i	a_i	b_i
90°	>0	>0
-90°	>0	<0
270°	<0	<0
-270°	<0	>0

In the case of $b_i > 10^{-15}$, there is no preoccupation with a small denominator in Equation (5) for η_i. In this case, the denominator b_i in Equation (5) is finite and it can be calculated, but again there are a few conditions to be considered for various cases defined in the following table

η_i	a_i	b_i
$\eta_i = 180^\circ + \eta_i$	any	<0
if $\varphi_{max} > 90^\circ$ $\eta_i = 360^\circ + \eta_i$	<0	>0

The upper conditions take into account the possibility that the circular orbit lies beyond the pole if $\varphi_{max} > 90^\circ$ (Equation (3)). Finally, the calculated value of longitude λ_i needs be converted to correct longitude between E and W side by the following two conditions

$$\lambda_i = \text{mod}(\lambda_i, 360^\circ), \quad \text{if } \lambda_i > 180^\circ \rightarrow \lambda_i = \lambda_i - 360^\circ. \tag{6}$$



(a) (b) (c)

Figure 8 Orthographic (a) and Mercator projections (b) and (c), created with the module Matplotlib Basemap [3]. Graph (c) is the zoomed area of (b) near the observer position. Purple dots show the GP of the celestial body, green lines are the circles of equal measured average altitude of the celestial body

Slika 8. Ortografska (a) i Mercatorove projekcije (b) i (c), napravljene modulom Matplotlib Basemap [3]. Grafikon (c) u zumiranom području (b) u blizini pozicije promatrača. Ljubičaste točke pokazuju GP nebeskog tijela, zelene linije su krugovi jednako mjerene prosječne visine nebeskog tijela

Source: Figures made by authors

Now it is possible to construct an arbitrary point on the circle (φ_i, λ_i) defined by the equal altitude, based only on the centre location $(\varphi_{GP}, \lambda_{GP})$, h and α_i. Using an iterative procedure for the intersection of two circles, the intersection point can be computed numerically. The criterion for finding the intersection point is the minimum distance between two adjacent points belonging to two different GP circles. When mapping circles from the globe to the Mercator map, points on the circle with equal altitude are a pure representation of the geographic position (φ_i, λ_i) on a Mercator map. The circle is now seen as a disconnected S-curve or connected egg-shaped curve (Figure 8b). The estimated observer position is determined by a graphical procedure. A position polygon can be constructed from the intersection of the circles. The estimated observer position is actually at the centre of the position polygon. In our case, the centre of the polygon is found by a simple graphical procedure. The steps of the graphical approximation of the position polygon can be seen in Figure 8. Circles on the orthographic projection are mapped onto the Mercator map and then zoomed around the observer position to obtain an image of the position polygon shown in Figure 8c.

In the control step all measurement results are compared with calculated values for the altitude and azimuth of the celestial body. In the calculations, a very accurate GNSS position (φ, λ) of the observer is used to obtain accurate values for the altitude and azimuth of the celestial body. With the following set of equations [21] it is possible to calculate the altitude H and azimuth ω of the celestial body

$$\sin H = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos \mathrm{Lha},$$
$$\cos\omega = \frac{\sin\delta - \sin H \sin\varphi}{\cos H \cos\varphi}, \tag{7}$$

where Lha is local hour angle. Calculated azimuth must be corrected up to the condition set in Equation (8).

$$\omega = \begin{cases} \omega & ,\text{if } 180^\circ \le \mathrm{Lha} \le 360^\circ \\ 360^\circ - \omega & ,\text{if } 0^\circ < \mathrm{Lha} < 180^\circ \end{cases} \tag{8}$$

3. RESULTS AND DISCUSSION / *Rezultati i rasprava*

Two smart devices were used for testing purposes. For each device, the basic coordinate system is introduced based on the definitions of directions and orientations shown in Figure 9. The altitude of the celestial body is measured as the angle rotated about the "x" axis. The azimuth of the celestial body is measured as the magnetic angle. The magnetic angle is post-processed from the three magnetic directions and is already part of the output of the smart device's magnetic sensor. The time window for each measurement is about 30 seconds. The data is averaged and a mean value is calculated. Each average has an exact time associated with it as part of the measurement type and was described in detail in Section 2.1.

Table 1 shows the results obtained using the Meizu 15 smart device on a tripod mount. These are 13 measurements of celestial bodies. Each measurement has a time marker set as the start time of the measurement. For each body, we calculate the declination, Greenwich hour angle, altitude, and azimuth based on the accurate GNSS position of the observer. The last two columns contain the measured data of altitude (zero level is already subtracted) and azimuth. The overall comparison between the calculated data and the measured data shows an average difference between the measured and calculated altitude of 0.26 degrees. The error is high compared to the sextant altitude measurements, but was to be expected and is entirely due to the systematic error of the measurement method. However, the error is filtered out by the higher number of measurements. Using the method described (Section 2.2), it is possible to construct a position polygon, the centre of which is a very good estimate of the observer position, as shown in Figure 10. The graphically estimated observer position is only 3 Nm away from the true observer position obtained by the GNSS device. The measurement of azimuth has a large error. The error is in the range of 1 to 10 degrees. Azimuth data with such a large error cannot be used for positioning, but only for identification of the celestial body.

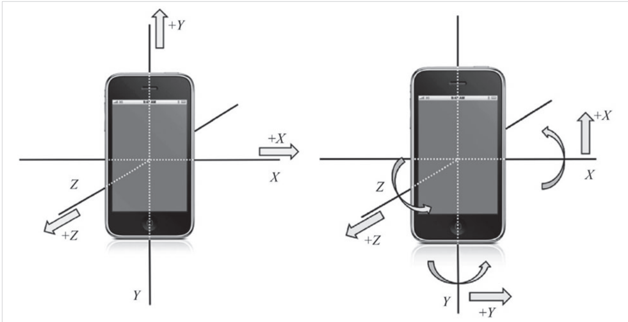
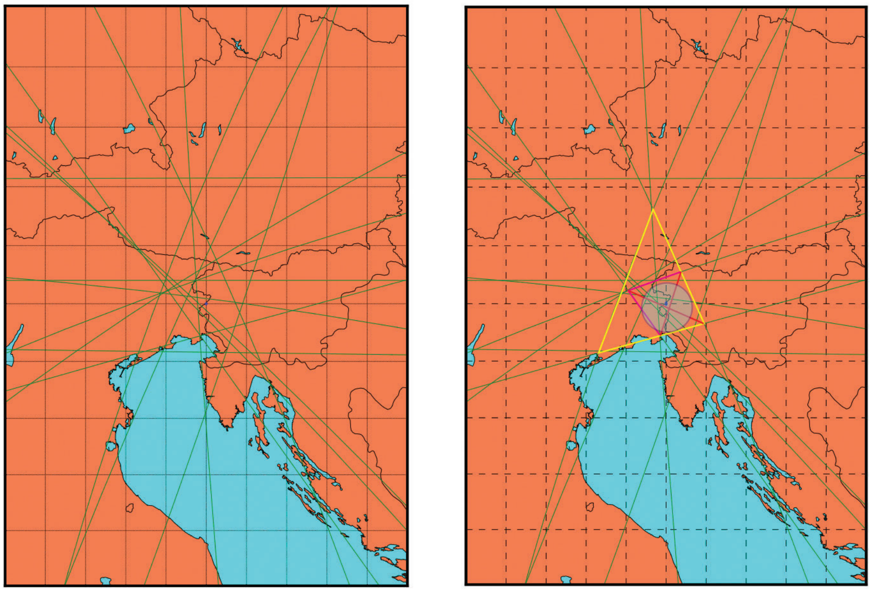


Figure 9 Coordinate system attached to the smart device [8]
Slika 9. Koordinatni sustav spojen na pametni uređaj

Table 2 shows the results obtained with the tablet in handheld mode. The structure of the table is the same as in the case of the mobile phone (Table 1). The average difference between the calculated and the measured altitude is 1.37 degrees. At first glance, one could argue that this is completely useless data. The difference arises from the fact that the handheld measurements were not calibrated to zero level. In the handheld experiment, it is not possible to measure the sensor error at zero level. However, when the data are transformed into a plot, as seen in Figure 11, the position polygon obtained has a centre very close to the observer position. The difference in zero level is constant and present in all measurements. Such an error does not affect the position of the polygon centre. The zero level error only increases or decreases the area of the position polygon, but its shape is not affected at all. This argument is considered to be a very strong assertion and forms the basis for the accuracy principle in the handheld experiment. As can be seen in Figure 11, the estimated observer position is only 10 Nm away from the true observer position.

In the handheld case, we have only six celestial bodies. The low number of observed celestial bodies is the result of only being able to scan the brightest celestial bodies, since the tablet does not have a spotting scope mounted in front of the camera. With special spotting scopes for smart devices, the sensitivity of the camera sensor can be greatly improved, and many fainter celestial bodies can be scanned.

Measuring the azimuth of celestial bodies in handheld mode with a tablet is a complete disaster. The cause is most likely the poor internal tablet calculation of azimuth. The overall results of azimuth measurement show that smart devices cannot currently be used with the positioning method that relies only on the azimuth (i.e., the method explained in [10]).



(a) (b)

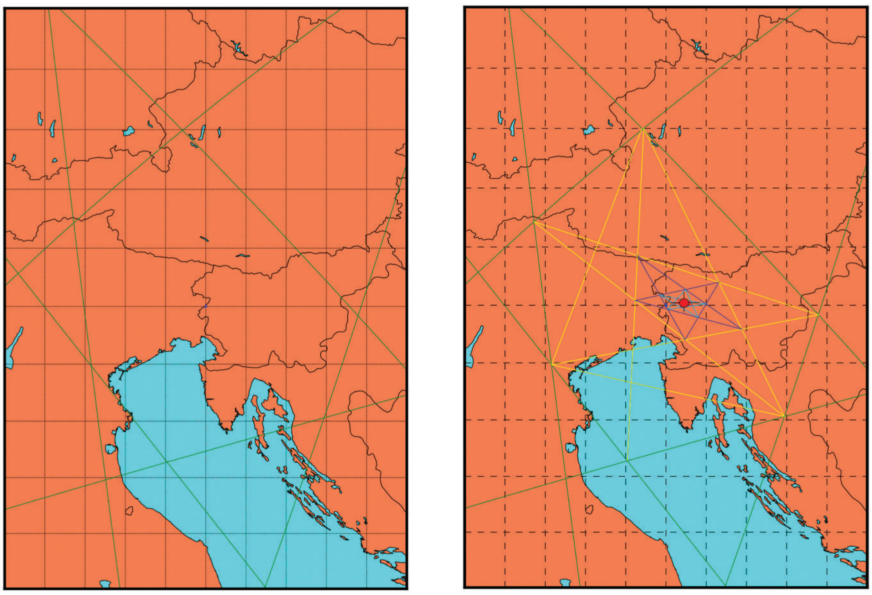
Figure 10 Tripod results on 18.11.2020 with 13 celestial bodies. Figure (b) shows the graphical construction of the observer position with measured altitude lines. The true observer position is the small blue dot in the centre of the plot; the red circle is the graphically obtained observer position. The error is about 3 Nm from the true position

Slika 10. Tripod rezultati dana 18. 11. 2020. s 13 nebeskih tijela. Slika (b) daje grafički prikaz pozicije promatrača s izmjerenim visinama. Stvarna pozicija promatrača je mala plava točka u središtu ucrtanoga; crveni krug je grafički dobivena pozicija promatrača. Greška je oko 3 Nm od stvarne pozicije

Source: Figures made by authors

4. CONCLUSIONS / *Zaključci*

Smart devices such as smartphones, tablets, pocket PCs, etc., have very powerful built-in sensors for orientation. It is possible to take orientation measurements in all three directions (pitch, roll, and yaw/azimuth). The question arises, "Can smart devices be used in celestial navigation as a measurement device to measure the orientation angles of celestial bodies?" This is our primary hypothesis. Our answer is "yes"; however, the number of celestial bodies measured must be as large as possible, and each measurement must be made at a specific time interval to obtain a good time average. Recently, the accuracy of orientation sensors for smart devices was analysed in [8]. The results of the research show that any smart device must be tested appropriately. The test must confirm or reject the applicability of the tested



(a) (b)

Figure 11 Freehand results on 18.11.2020 with 6 celestial bodies. Figure (b) shows the graphical construction of the observer position with measured altitude lines. The true observer position is the small blue dot in the centre of the plot, the red circle is the graphically obtained observer position. The error is about 10 Nm from the true position

Slika 11. Ručno dobiveni rezultati dana 18. 11. 2020. sa 6 nebeskih tijela. Slika (b) daje grafički prikaz pozicije promatrača s izmjerenim visinama. Stvarna pozicija promatrača je mala plava točka u središtu ucrtanoga, crveni krug je grafički dobivena pozicija promatrača. Greška je oko 10 Nm od stvarne pozicije

Source: Figures made by authors

device for use in CNS. To have a fully functional system, one also needs a good application or applications for the measurement process and post processing of the measurement data. In the acquisition process, the system must be able to handle a narrow field of view (FOV) and low light environment. A narrow FOV can be achieved with particular scopes for mobile devices. Low light conditions are handled with an application capable of amplifying the light sources hitting the camera sensor [11]. The averaging of the measured data and the calculation of the intersection points of the circles, the construction of the position polygon and the generation of the position and its error, have to be done by a dedicated application in the post-processing step. At the moment the post-processing part is done on a PC with specially developed software.

The proposed method uses orientation sensors from smart devices to determine the altitude and azimuth of a celestial body. The body altitude is used in the altitude method [17] to determine the position of the observer without the information of the assumed position. The orientation sensor of the smart device is capable of measuring all three angles. In our case, only the altitude is of some practical accuracy and we exploited its practical application to measure celestial bodies. Two different types of experiments have been designed. In the first experiment, the accuracy of the orientation sensor of the smart device is tested. It was found that the accuracy of the orientation sensor is good, but averaging the signal over time is essential to filter out sensor oscillations. The accuracy of the azimuth sensor is unpredictable and can only be used as a control mechanism or star identification system.

In the second experiment, we tested the idea of hands-free handling of altitude measurements. The authors were aware that such an approach would lead to a rather large systematic error. The idea was to control the error and use a processing algorithm that filters out most of the error in computing the observer position. The concept can be successful if we keep the number of celestial bodies as large as possible. This can easily be achieved since the method does not require a horizon or even an apparent position. In one night we can measure almost all navigable celestial bodies that are above the horizon. The number of celestial bodies that are above the horizon averages from 10 to 20 at the same time.

The handheld smart device must be upgraded with a mobile scope to reduce the field of view and use an application that enhances the light of the darker celestial bodies. In our case for the handheld experiment, we were only able to scan the brightest stars (only six compared to the first test when 13 celestial bodies were scanned using a telescope).

The post-processing step also needs to be improved by using a suitable algorithm to post-process the measurements. Currently, the graphical method can reliably reproduce the position of the observer within a radius of 10 to 30 Nm. This is a more than satisfactory result for celestial navigation in merchant shipping. In order to use this method in a stand-alone and fully automatic approach, an advanced smart device application must be developed.

For example, it is advisable to further develop the CamSextant [13] application by adding an averaging and position algorithm, as well as some additional tools such as light amplification and crosshairs. The new application would need to include all the steps we have described. To improve freehand measurements, it is advisable to use a mobile phone telescope and possibly a laser pointer to make it easier to point the instrument at the stars. Mobile phone telescopes are now available in many online stores for 10-20 EUR. The use of a mobile telescope extension and a specially designed position algorithm is already the subject of research.

In this study, we describe and analyse a system that could be a good candidate for a low-cost handheld device for the Celestial Navigational System. However, the described system and methods need additional extensions (mobile telescope and additional pre- and post-process software), which are described in detail in the paper. In any case, the perpetual bane of the seafarer - interference from piracy, which has never abated over millennia of commercial maritime trade, now having a branch in the advanced form of cyber attacks, requires means of eliminating their capabilities.

Table 1 Results for Tripod measurements on 18.11.2020. alt and az are calculated altitude and azimuth from known precise location, m_alt and m_az are measured altitude and azimuth.

Tablica 1. Rezultati tripod mjerenja dana 18. 11. 2020. Alt i az su izračunata visina i azimut s poznate precizne lokacije, m alt i m az su izmjerena visina i azimut

body_name	time	dec	Gha	alt	az	m_alt	m_az
Aldebaran	18:35:23	16.5501	267.824	19.72122	86.33681	19.59917	80.91345
Saturn	18:13:39	-21.0277	32.14398	11.11206	222.98885	11.18619	216.98934
Polaris	18:33:05	89.35176	291.60046	46.47285	0.76869	45.96664	359.30347
Kochab	18:31:24	74.07014	113.45875	35.31595	344.43974	35.01885	343.78812
Diphda	18:42:58	-17.87434	327.84723	23.86805	160.71173	23.59591	153.10356
Vega	18:28:55	38.80677	56.08091	39.70127	288.17558	39.37512	286.27647
Altair	18:27:57	8.92554	37.29845	32.91376	246.03976	32.66407	237.81776
Jupiter	18:12:24	-21.78005	35.51581	8.84022	225.31753	8.97105	220.13007
Capella	18:34:25	46.01637	257.30283	31.7667	54.7558	31.49668	50.79253
Menkar	18:39:34	4.17061	292.30948	27.28821	114.71344	27.05084	109.11398
Mars	18:41:35	5.46846	324.24422	45.08447	147.95323	44.7347	138.34816
Hamal	18:40:45	23.56086	306.36111	50.80255	111.23184	50.28912	100.99822
Fomalhaut	18:44:04	-29.51478	354.58475	14.01644	187.37878	13.96725	178.73042

Source: Data made by authors

Table 2 Results for free-hand measurements on 18.11.2020. alt and az are calculated altitude and azimuth from known precise location, m_alt and m_az are measured altitude and azimuth

Tablica 2. Rezultati ručnih mjerenja dana 18. 11. 2020. Alt i az su izračunata visina i azimut s poznate precizne lokacije, m alt i m az su izmjerena visina i azimut

body_name	time	dec	gha	alt	az	m_alt	m_az
Aldebaran	18:23:42	16.5501	264.89517	17.69732	84.28241	16.41159	136.04185
Kochab	18:21:15	74.07014	110.9143	35.79846	343.81926	34.34807	192.29677
Vega	18:19:07	38.80677	53.6242	41.32575	286.84317	39.82295	214.32563
Jupiter	18:15:39	-21.77998	36.33011	8.43658	225.9643	7.37687	192.84111
Capella	18:18:14	46.01636	253.24592	29.49713	52.81616	28.14947	128.06898
Mars	18:17:14	5.4672	318.14039	42.60084	140.25975	41.04597	155.29959

Source: Data made by authors

Funding: Aleksander Grm research was co-funded by ARRS grant number P2-0394.

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