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Smart physics to create kinematic data from GPS measurements

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Abstract

An experimental exercise is presented where students explore the principal concepts of kinematics with the GPS sensor of their smartphone. It enables our students to record and analyze a self-performed complex movement independently. Students learn how to transform geographical into Cartesian coordinates and how to investigate movements in everyday life.

Keywords: smart physics lab, kinematics, GPS-sensor, smartphone-based experiment, geographical koordiantes

Did you ever ask yourself how geotracking apps or navigation systems determine your current position and path on a map and how do they verify velocities? Nowadays satellite navigation systems such as GPS (USA) or Galileo (EU) are able to provide the geographical coordinates longitude $\lambda(t)$, latitude $\phi(t)$ and altitude $h(t)$ (height) above sea level [1]. These coordinates refer to the ECEF (earth centred, earth fixes) coordinate frame. Its origin is located at the centre of mass of the earth. It rotates with the Earth. Thus, navigation or geotracking apps on a smartphone or other mobile devices measure these three geographical coordinates via a suitable GPS sensor and locate you in the map electronically stored in there memories [2].

Generally, a map is a two-dimensional representation of the Earth's surface. Thus, one has to reduce the three-dimensional information of the geographical coordinates to a two-dimensional planar representation. Behind this complex mathematical procedure, there is a relatively simple idea. Assuming the earth as a sphere with the averaged radius R, the latitude $\phi(t)$ represents the position on the surface in South–North direction, which we will denotes $y(t)$. Correspondingly, the longitude $\lambda(t)$ identifies the position in West–East direction (see figure 1). The equation for the transformation of the latitude data is

$$y(t)-y(t=0)=[\phi(t)-\phi(t=0)]\cdot\frac{\pi}{180^\circ}\cdot R, \tag{1}$$

where $y(t=0)$ denotes the starting position in South-North direction. This equation is nothing else than the application of the mathematical

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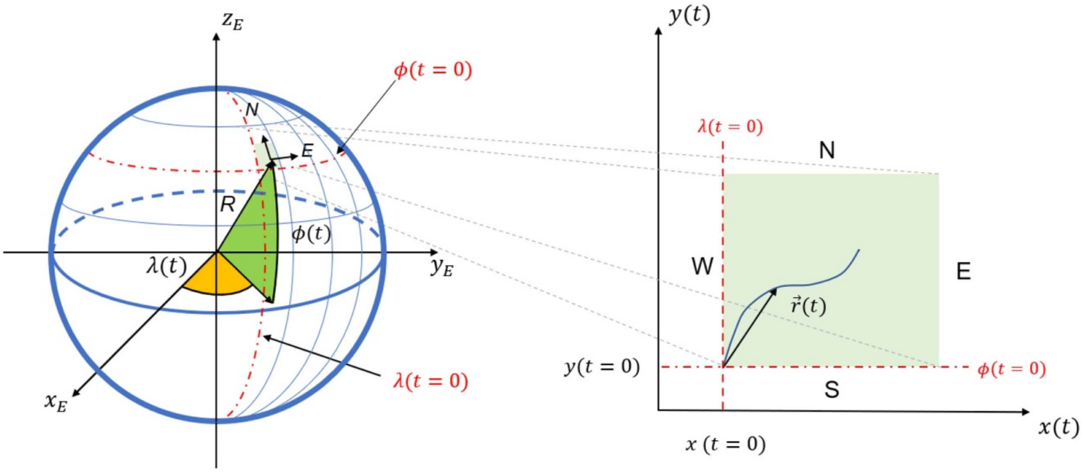
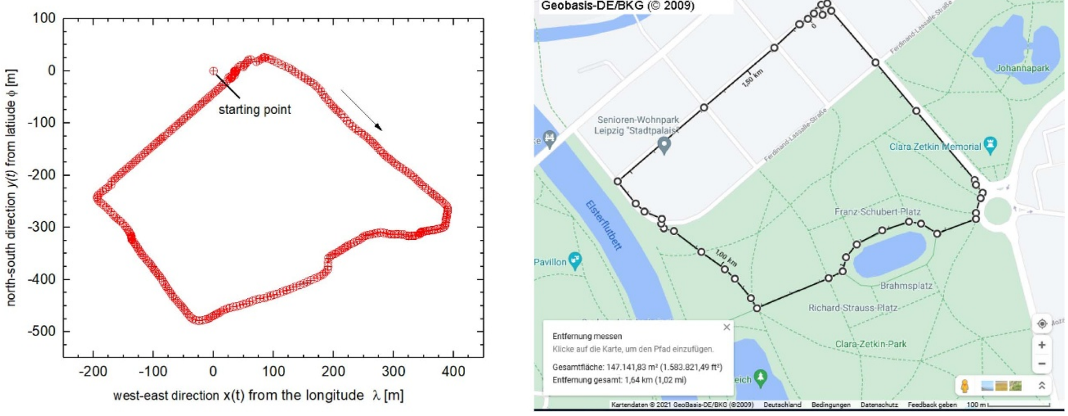


Figure 1. Transformation of the geographical coordinates into a two-dimensional map. The yellow angle represents the longitude $\lambda(t)$ and the green angle is the latitude $\phi(t)$.



Entfernung messen
Klicke auf die Karte, um den Pfad einzufügen.
Gesamtfläche: 147.141,83 m² (1.583.821,49 ft²)
Entfernung gesamt: 1,64 km (1,02 mi)

(a) (b)

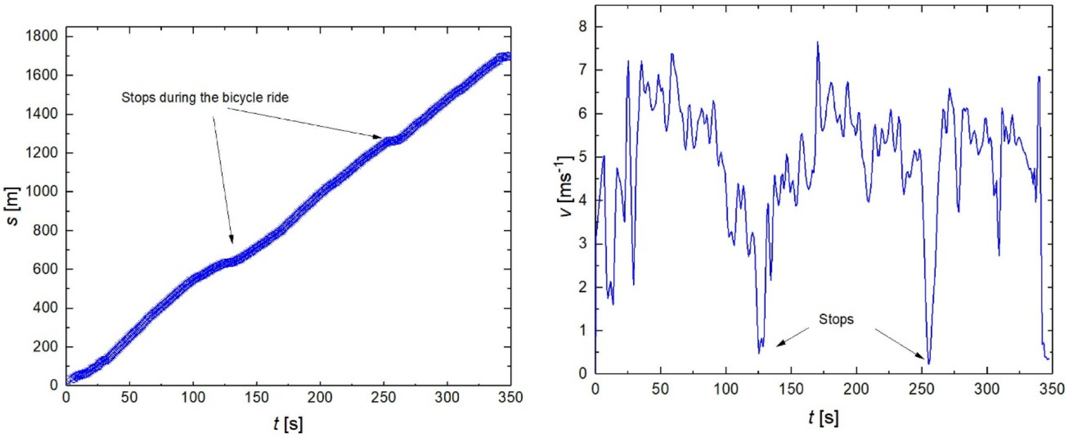
Figure 2. (a) The trajectory $\vec{r}(t)$ of our bicycle ride calculated via equations (1) and (2) from GPS-data and (b) comparison with a presentation of the same track in Google Maps [6].

definition of a planar angle as relation between the length of an circular arc segment to its radius. The description of the movement in the West–East direction is a little bit more complicated, because you have to consider the change of the latitude $\phi(t)$ meanwhile. The second equation to transform the coordinates is

$$x(t) - x(t=0) = [\lambda(t)\cos(\phi(t)) - \lambda(t=0) \times \cos(\phi(t=0))] \cdot \frac{\pi}{180^\circ} \cdot R, \quad (2)$$

where $x(t=0)$ is the starting position in West–East direction. These two transformations neglect the altitude $h(t)$ and its change during the motion. However, for motions along the earth surface, which we will consider for our simplified approach, changes in altitude are much smaller than R. Their relative influence on the x and y coordinates are proportional to $\frac{h}{R}$ and generally smaller than the GPS accuracy of ± 1 m [3].

As example, figure 2(a) shows the resulting two-dimensional trajectory $\vec{r}(t)$ of a bicycle ride in a public park in Leipzig (Germany). The GPS



(a)

(b)

Figure 3. (a) Path-time diagram $s(t)$ and (b) velocity-time diagram $v(t)$ of the bicycle ride.

data of the closed loop ride were recorded with a smartphone via the *phyphox* app (RWTH Aachen, Germany, [4, 5]). Obviously, our own calculation with the raw geographical coordinates via equations (1) and (2) yield a two-dimensional trajectory (parameter-free representation) which is in a very good accordance with the representation in Google Maps (see figure 2(b)).

With the individual time intervals Δt_n of the recorded geo coordinates, the distance travelled in each direction Δx_n and Δy_n during Δt_n may be calculated with the following recursive equations

$$\Delta t_n = t_n - t_{n-1} \quad \Delta x_n = x_n - x_{n-1}$$
$$\Delta y_n = y_n - y_{n-1} \quad n \in \mathbb{N}, n \geq 1 \,. \tag{3}$$

Using the Pythagorean theorem, the distance $\Delta s_n(t_n)$ in the considered time interval is [3]

$$\Delta s_n = \sqrt{\Delta x_n^2 + \Delta y_n^2} \,. \tag{4}$$

Successively summing up all Δs_n, the path–time diagram $s(t) = \sum_{i=1}^{n} \Delta s_n$ of the movement is obtained. For the example of the bicycle ride in Leipzig this is shown in figure 3(a). Obviously, the ride extended over 1.6 km for about 5 min. In order to finally obtain the velocity–time diagram $v(t)$, the definition of the velocity $v(t)$ as the first derivative of distance needs to be calculated. This is easily numerical done by $v(t) = \frac{\Delta s_n}{\Delta t_n}$. Figure 3(b) represents the velocity during our bicycle ride. As seen in figure (3(a)), there were two short interruptions (stops) which are also clearly visible in the velocity-time diagram $v(t)$ (see figure 3(b)). The maximum velocity during the movement is $v_{\max} = 7.5\,\mathrm{m\,s^{-1}}$, which is reasonable for a bicycle ride.

The presented experiment is part of our 1st semester mechanics course for physics teacher trainees since 2018/2019 [7]. The students record a freely chosen, self-performed movement with the GPS sensor of their smartphone. The measurement itself can be performed with e.g. the *phyphox* app, menu Sensors, Location (GPS) [4, 5] or with any other geotracking app that reads the GPS sensor data and provides them as raw data depending on time. With this experiment, the students should first of all understand the transformation between different coordinate systems by applying and reproducing it independently with an own example. In addition, they learn how to fully evaluate and interpret a complex motion graphically, which is a fundamental competence in mechanics. Our students are usually quickly able to use the smartphone for physical experiments to record and analyse physical data digitally. Since many students find it very difficult to derive equations (1)–(4), we address this within the associated lecture and recitations. The presented experiment offers students the opportunity to explore the physical concepts of kinematics independently by means of an authentic and context-oriented problem.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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