How can one detect
the rotation of the Earth “around the Moon”?
Part 2: Ultra-slow fall

Bertrand M. Roehner\textsuperscript{1,2}

Abstract The paper proposes an alternative to the Foucault pendulum for detecting various movements of rotation of the Earth. Calculations suggest that if the duration of a “free” fall becomes longer the eastward deflection will be amplified in proportion with the increased duration. Instead of 20 micrometers for a one-meter fall, one can expect deflections more than 1,000 times larger when the fall lasts a few minutes. The method proposed in this paper consists in using the buoyancy of a (non viscous) liquid in order to work in reduced gravity. In a liquid of density $\rho$, the gravity $g$ is replaced by a virtual gravity $g' = g(1 - \rho/\rho_1)$ where $\rho_1$ is the density of the falling body.

Not surprisingly, as in many astronomical observations, the main challenge is to minimize the level of “noise”. Possible sources of noise are discussed and remedies are proposed.

In principle, the experiment should be done in superfluid helium. However, a preliminary experiment done in water gave encouraging results in spite of a fairly high level of noise. In forthcoming experiments the main objective will be to identify and eliminate the main sources of noise.

This experiment differs from the Foucault pendulum by its greater flexibility. By adequately selecting the major parameters, e.g. duration of the fall, viscosity of the fluid, size of the falling body, one can change the deflection target.

It is hoped that the present paper will encourage new experiments in this direction.

\textit{11 December 2011. Preliminary version, comments are welcome}

Key-words: Moon-Earth, Coriolis force, rotation, free fall, turbulence, buoyancy, gyrometer

\textsuperscript{1}: Department of Systems Science, Beijing Normal University, Beijing, China.
\textsuperscript{2}: Email address: roehner@lpthe.jussieu.fr. On leave of absence from the “Institute for Theoretical and High Energy Physics” of University Pierre and Marie Curie, Paris, France.
Introduction

In this paper we propose an alternative to the Foucault pendulum for the detection of movements of rotation of the Earth. This method is based on the well-known observation that instead of following a vertical trajectory, a falling body is in fact slightly deflected toward the East.

It can be noted that this deflection is the same in the northern and southern hemisphere. The reason is because this effect is due to the horizontal component of the vector of angular rotation (see Fig. 2a,b of Part 1), whereas the Foucault effect is due to the vertical component. The horizontal component is directed toward the north in both hemispheres.

Free fall in the air

Various experiments performed in the past (Table B1) show that in air or in vacuum the eastward deflection is small. The theoretical formula discussed in more detail in the appendix shows that for a fall from a height of one meter one should expect a deflection of only 22 micrometers. Clearly, for such a short deflection it is almost impossible to get a good accuracy. One major problem is the exact determination of the bottom point which is on the vertical of the starting point. If one wishes an accuracy of 1%, this point must be determined with an accuracy of 0.2 micrometer. Consequently, to improve the accuracy of this experiment one needs to increase the size of the deflection. So the question becomes: “How can the eastward deflection be amplified?”

Free fall in a fluid

The theoretical formula for the deflection may give us a possible hint. This formula can be written in different ways. There are basically 4 variables.

- The horizontal angular velocity of the earth \( \Omega_h = \Omega \cos \lambda \), where \( \lambda \) is the latitude.
- The acceleration of gravity \( g \)
- The height of the fall \( h \)
- The duration of the fall \( t \)

The standard free fall formula \( h = \frac{1}{2}gt^2 \) allows us to write the deflection in two alternative forms:

\[
d = \frac{2}{3} \Omega_h t \quad \text{(1a)}
\]
\[ d = \frac{2\sqrt{2}}{3} \Omega h^{3/2} g^{1/2} \]  

Expression (1a) suggests that, for a given height, \( d \) can be amplified by increasing the duration of the fall.

At first sight this condition may seem surprising. Indeed, if (for a given height) the fall lasts longer this means that the velocity is lower, but then the Coriolis force will also be lower. So, why should one get an amplified deflection?

In fact, the amplification occurs only if the eastward movement is uniformly accelerated. This can be seen by a simple argument. We denote by \( v_m \) the average vertical velocity. Then, for the sake of simplicity we replace the vertical movement by a stationary movement of velocity \( v_m \). Under such conditions the Coriolis force \( \vec{C} = 2m\vec{v}_m \wedge \vec{\Omega} \) is constant during the fall which means that the horizontal movement is uniformly accelerated with an acceleration \( \gamma_c = C/m = K v_m \). For such a movement the eastward deflection is:

\[
x = \frac{1}{2} \gamma_c t^2 = \frac{K}{2} v_m \left( \frac{h}{v_m} \right)^2 = \frac{K}{2} \frac{h^2}{v_m}
\]

The last expression shows that the smaller the vertical velocity the larger the deflection. In short, the amplification of the deflection occurs because of the quadratic time factor. When the vertical velocity is divided by 2 (for instance), the Coriolis acceleration \( \gamma_c \) is also divided by 2, but thanks to the time factor \( t^2 \) the deflection is multiplied by 4.

Now we must ask ourselves how a low velocity can be achieved practically.

**Ultra-slow falls**

How can one obtain a fall with a slow velocity? An answer is suggested by expression (1b) which shows that the only way is to reduce \( g \). How can one reduce \( g \)? Apart from doing the experiment in a spacecraft orbiting around the earth and in which there is a state of microgravity, an obvious way is to use the buoyancy in order to counterbalance \( g \). If a body of density \( \rho_1 \) falls in a fluid of density \( \rho \), it will experience a virtual gravity \( g' \) given by the difference between its weight and the buoyancy:

\[ g' = g(1 - \rho / \rho_1) \]

If \( \rho_1 \) is adjusted to become almost equal to \( \rho \) (but still somewhat larger) \( g' \) can (at least in principle) be made arbitrarily small. As a result, \( d \) should become fairly large.

**How can one reduce the effect of friction?**

---

3 This is true even for a movement in a fluid, at least until the drag becomes comparable to the driving force.

4 Actually, even apart from its cost, such an experiment may not be easy to carry out in an orbiting satellite. There is no uniform microgravity in a satellite. In fact, once released an object becomes a satellite in its own orbit slightly different from the one of the satellite itself. The connection between the two orbits may be fairly complicated, depending for instance upon the respective size of the satellite and of the object.
An objection arises immediately. Indeed, the expressions (1a,b) are derived from equations which do not take friction into account. How can one create buoyancy without friction? There are (at least) two possible answers.

(1) One way is to make the experiment in a fluid that has zero viscosity, for instance in superfluid helium-3 at a temperature under 2.1 degree Kelvin\(^5\).

(2) Another way to make friction small in comparison with the other forces is to increase appropriately the dimensions of the falling body. The argument goes as follows. The friction force is basically proportional to the area \(A\) of the section of the object that is perpendicular to the velocity, whereas the Coriolis force \(\vec{C} = 2m \vec{v} \times \vec{\Omega}\), and the reduced gravity force \(F = m \vec{g}\) are both proportional to the mass of the falling body. Thus, when the body becomes larger the relative importance of the friction force is reduced.

A confirmation of this argument can be found in the expression of the asymptotic velocity of a falling body, namely (Wikipedia 2011a) \(v_a = \sqrt{\frac{2mg}{\rho AC_d}}\) where \(C_d\) is the drag coefficient\(^6\). At this velocity the friction force is equal to the weight minus the buoyancy. This expression shows that when \(m/A\) becomes large the asymptotic velocity goes to infinity as is the case for a fall in vacuum. In other words, the fall of a big object is almost identical to what it would be in vacuum.

The increase of the ratio \(m/A\) can occur either through an increase in density or through an increase in volume. In our case the density is almost fixed because it must be close to the density of the fluid. Therefore it is the ratio \(V/A\). At this point one should observe that we need only to focus on the horizontal movement\(^7\).

The only role of the vertical movement is to generate the vertical velocity which is necessary for the Coriolis force to appear. For the horizontal movement, the ratio \(V/A\) is proportional to the length in the horizontal direction. For instance, if the falling body is a cylinder it should be a fairly flat one. We will discuss later how this condition can be implemented in practice.

What deflection can one expect?

The previous argument tells us that the falling module should be “rather big” but

\(^5\)Under standard pressure, helium-3 becomes liquid at 4.2 degree but the property of superfluidity appears only under 2.1 degree.

\(^6\)In a general way the drag coefficient depends upon the Reynolds number \(Re\) but it is almost constant (and equal to about 0.5) in the range \(100 < Re < 10^5\).

\(^7\)The movement along the horizontal \(x\) axis is described by the equation:

\[ \frac{md^2x}{dt^2} = 2m\Omega_h v_z - F_d \]

For the sake of simplicity the vertical velocity \(v_z(t)\) can be replaced by its average value \(v_m\). In this approximation the horizontal movement is exactly identical to the fall of a body in a fluid.
it does not say how big it should be. Moreover, before starting experiments one would like to know what is the magnitude of the deflection that can be expected. To this aim we made a computer simulation whose results are summarized in Fig. 1. Before considering these results one needs to realize that such a simulation can only provide a fairly rough picture because the description of the drag is known to be fairly inappropriate in several respects. In spite of these limitations one can draw the following conclusions.

1. The magnitude of the expected deflection is of the order of several millimeters which is about 100 to 1,000 times larger than for a similar fall in air.

2. For a light falling body the maximum of the horizontal velocity is reached

---

Fig. 1: Eastward deflection during an ultra-slow fall. The fall occurs in water over a height of 1 meter and has a duration of 250 seconds. The mass of the falling module is 280 grams. The velocity curve (broken line) shows that the horizontal velocity increases linearly during a first phase which lasts about one half of the total time. During this phase the Coriolis force is notably larger than the drag which results in a fairly constant acceleration. During this first phase the drag increases along with the velocity; this leads to a second phase in which the drag becomes almost equal to the Coriolis force with the result that the acceleration tends toward zero. During this second phase the velocity increase becomes slower and slower as the velocity converges toward its limiting value.

---

As mentioned in Appendix A, this description does not include the effects of turbulence. Moreover, the drag coefficient is only known in an approximate way.
much faster than for a more heavy one. For a weight of about 1 gram calculations show that the maximum velocity is reached in less than 10 seconds whereas for a weight of 250 grams the uniformly accelerated regime lasts about 250 s. Thus, for a light body it is useless to use a long falling time because the deflection will not be larger than for a much shorter falling time. This comes from the fact that, as observed at the beginning, unless the movement is uniformly accelerated one does not gain anything by increasing the the duration of the fall.\footnote{Of course, the deflection continues to increase even when the velocity has become stationary. But one does not gain anything in the sense that a shorter falling time would give a higher average vertical velocity and, as a result, the same deflection would be reached more quickly.}

The result about the length of the uniformly accelerated regime can also be seen analytically. The analytic form of the solution is (Wikipedia 2011 a)

\[ v_x(t) = \left[ \frac{2\gamma c m}{\rho C_d A} \right]^{1/2} \tanh \left( t \sqrt{\frac{\gamma c \rho C_d A}{2 m}} \right) \]

As for \( t = 1 \) the function \( \tanh t \) is already within 20\% of its asymptotic value we see that the length of the time interval for which \( \tanh(at) \) increases linearly is about \( 1/a \). In other words, the duration of the “useful” regime is \( \sqrt{(2/\gamma c \rho C_d)}(m/A) \). We see that it increases along with the ratio \( m/A \).

**Implementation of the experiment**

Here, as in many physics experiments, the main challenge is to reduce the level of noise. What are the main sources of noise?

**Sources of noise**

The following list proceeds in chronological order from the moment when the fall starts to the moment when the module hits the bottom of the tank (Fig. 2a, 2b).

- **Start** First, the module must be smoothly released from a set position. In the air this a tricky problem because even a low lateral initial velocity will develop into a fairly large deflection during the duration of the fall. In water this problem is much less serious because an initial horizontal velocity will be reduced fairly quickly due to friction.

  We have been using a system in which the start of the module could be obtained by adding just one drop of water. It seemed to work in a satisfactory way.

- **Residual currents** When the module falls it creates currents at different scales. Similarly currents are created again when the module is brought back to the surface for a new trial. How long should one wait before starting the next fall? 30 s, 2 mn, 5 mn or 10 mn. We do not know and this is a serious problem.
Fig. 2a: Ultra-slow fall. The fall occurs in a water tank over a height of 1 meter and has a duration of about 40 seconds. The diameter of the falling module is 61 millimeters, its height is 100mm and its mass is 255 grams. The water tank has a square section of $30\text{cm} \times 30\text{cm}$ and a height of 2 meters in two stages; in this experiment only its first stage was used. A fairly short fall duration was selected in order to minimize the effect of residual water currents.

Fig. 2b: Picture of the module after it has reached the bottom of the water tank. At the bottom of the picture one can see a small plumb-bob which is used to follow the horizontal deflections of the falling body. In this experiment the average eastward deviation over 40 falls was $\Delta x_m = 2 \pm 0.8\text{mm}$; in this result the error bar is the standard deviation of the average, that is to say $\sigma/\sqrt{40}$ where $\sigma$ is the standard deviation of the 40 measurements. This result should be compared with the expected deviation which, in these conditions, is 1.8mm. In the air, the deviation would be about 100 times smaller.

As a matter of fact, there is no single answer. If the module falls fairly quickly it is much less affected by the currents than when it falls in two or three minutes because (i) The currents do not have the time to deflect it. (ii) When the vertical force experienced by the module is fairly large it will not be much affected by the small forces due to intermittent currents.

With a waiting time of one minute, one observes that the standard deviation of the landing points increases with the duration of the fall\textsuperscript{10}. As an extreme case a module which floats under water in a neutral position will slowly drift from the middle of the tank to one of its sides.

\textsuperscript{10}For instance in one set of experiments the standard deviation was 7 mm for 65 s and increased to 10 mm for a duration of 100 s.
A possible way to estimate the effect of the currents is to make several series of measurements with identical falling times but increasing waiting times between the falls.

- **Asymmetries of the module**  When the module is suspended in water just before start, one can check whether or not it is really vertical. Even objects which have been produced or controlled on a lathe may not be completely vertical. When the axis of a module makes an angle $\theta$ with the vertical, it will have a tendency to follow that direction during its fall.

- **Turbulence**  With a size of the order of 10cm and a velocity of the order of 0.5cm/s, the Reynolds number $Re = \rho v D/\eta$ is of the order of 1,000 which means that one is far from laminar flow conditions. Nevertheless, the dispersion which comes with this level of turbulence seems to be fairly low with respect to other sources of noise. This can be seen from the observation that for falls performed in succession under identical conditions the results change by “batch”, by which we mean that after 5 or 6 falls having almost the same arrival point, there may be a new batch of falls centered around another landing point. This behavior is not yet clearly understood but it does not seem to be due to turbulence.

**Remedies**

The problem of residual currents can in principle be overcome by waiting long enough between successive falls. So, the most serious problem seems to be the asymmetries of the module. These asymmetries can be of a static or dynamic nature. By static asymmetries we mean those which show up in the fact that the module is not completely vertical when floating without motion at the surface. By dynamic asymmetries we mean those which result in asymmetrical friction forces which bring about spurious deflections during the fall of the module.

One way to mitigate this difficulty is to control for the angular orientation of the module at start and to check that it does not rotate during the fall. We followed this method when observing 40 falls in the sense that there were equal numbers of falls done with 4 initial angular orientations 90 degrees apart. In this way the effect of possible asymmetries should be averaged out. One drawback of this method is that it requires 4 times more trials.

**Shape of the module**

What shape should one give to the falling module? There are two conflicting requirements.

1. As noted previously the ratio $V/A$ (where $A$ is the vertical section) must be

---

1One solution may be to use a “ball” of oil in a solution of ethanol. In this case the spherical shape is assured by tension forces. However, even in such a case there may be defects in the form of small droplets of ethanol included into the ball of oil.
large which suggests a fairly flat module.

(2) However one must also minimize the deflections due to possible asymmetries which would rather suggests a long module of small horizontal section.

The challenge is to find a shape which fulfills these conflicting requirements.

Acknowledgment The author expresses his gratitude to Mr. Gen Li (Beijing Normal University) for providing useful advice and for his help in making the pictures which illustrate the article.

Appendix A: Theoretical formula for eastward deflection

For a body falling freely from a height $h$ the eastward deviation is given by the formula (Cabannes 1966, p. 65 or Goldstein et al. 2004, p. 179)

$$d = \frac{\Omega h}{3} \sqrt{\frac{(2h)^3}{g}}, \quad \Omega_h = \Omega \cos \lambda$$  \hspace{1cm} (A1)

where:

- $\Omega$: vector of angular rotation of the Earth: $\Omega = \frac{2\pi}{3600 \times 24} = 7.3 \times 10^{-5}$ radian/second.
- $g$: acceleration of gravity, $g = 9.81 \text{ms}^{-2}$
- $h$: height of fall
- $\lambda$: latitude of the fall.

This formula is not an exact result in the sense that it assumes that $\Omega t$ is small with respect to 1 (Cabannes 1966, p. 65). This means that the duration of the fall should not exceed $1/k\Omega$; with $k$ of the order of 10, one gets a limit of the order of half an hour.

The second-order term in the development corresponds to a southward deflection whose order of magnitude is $\Omega t$ times the first-order term (Wikipedia 2011b). This means that for times of the order of one minute this southward deflection is some 1,000 times smaller than the eastward deflection. In other words, this effect is much smaller than the eastward deflection due to the rotation around the Moon which is only 27 times smaller than the first-order effect.

Moreover it should be noted that that formula (A1) does not take into account the friction of the falling body in the surrounding fluid. This has two consequences, a first one which is of little importance and a second which is much more serious.

(1) The first consequence is that the friction will reduce the velocity. If one assumes that the velocity remains small with respect to the limiting velocity this will result only in a slight change.

(2) Much more serious is the fact that friction creates turbulence in the wake of the
falling body. This will provoke random changes in the pressure-field around which in
turn will provoke small random horizontal accelerations. Because of its randomness
turbulence cannot be modeled in an appropriate way, which means that this effect
cannot be included in formula (A1). It may be useful to keep in mind the following
facts which result from empirical observation. (i) Turbulence increases with velocity
(ii) For a given velocity, the effect of turbulence on the trajectory of the falling body
will be more serious when its mass becomes smaller.

Appendix B: Experimental results in air

Table B1 gives a summary of some of the historical experiments done in air.

| Physicist     | Year | Location    | Height [m] | Eastern deflection [mm] | Accuracy [%] | Predicted deflection (in vacuum) [mm] |
|---------------|------|-------------|------------|-------------------------|--------------|--------------------------------------|
| Guglielmini   | 1791 | Bologna     | 78         | 18.9                    |              | 10.7                                 |
| Benzenberg    | 1802 | Hamburg     | 76         | 9.0                     |              | 8.61                                 |
| Reich         | 1831 | Freyberg    | 158        | 28.4 ± 0.4              | 1.4%         | 29.0                                 |
| Hall          | 1903 | Boston      | 23         | 1.49 ± 0.05             | 3.3%         | 1.78                                 |
| Bähr et al.   | 2005 | Bremen      | 145        | 26.4 ± 1.4              | 5.3%         | 23.0                                 |

Notes: Latitudes (expressed in degrees) are given within parenthesis in the location column. The
number of falls performed were as follows: Benzenberg: 32, Reich: 106, Hall: 946, Bähr et al.: 120.
Formula (A1) for a fall in vacuum which was used to compute the numbers in the last column does
not include the effect of air friction. Therefore the accuracy column does not refer to accuracy with
respect to this formula; it gives the ratio of the measurement error (i.e. the dispersion of the impacts)
to the average deflection.
The probable error indicated as ± is given in Bruhat (1955) for the Reich experiment and in Hall
(1903b) for the Hall experiment. Actually, Hall gives two probable errors (depending on differing
assumptions): 0.05mm and 0.15mm.
Identification of the Coriolis force due to the rotation of the Earth around the center of gravity of the
Earth-Moon system requires an accuracy better than 1/21 = 4%. This would well have been within
the reach of the Reich experiment. However, as explained in the text, the error given for the Reich is
probably 10 times too small.
Sources: Benzenberg (1804), Bruhat (1955), Hall (1903 a,b)

Appendix C: Effect of turbulence in air

In previous papers (Poujade 2010, Roehner 2010) it was shown that for Reynolds
numbers over 1,000 the radius of dispersion for deflections of spheres due to turbu-
lence can be represented by the following semi-empirical formula:

\[ \Delta = 0.02 \frac{\rho H^{3/2}}{\rho_1 \sqrt{r}} \]  \hspace{1cm} \text{(C1)}

where:
\( \Delta \): Dispersion radius due to turbulence
\( \rho \): Density of the fluid in which the spheres are falling
\( \rho_1 \): Density of the spheres
\( H \): Height from which the spheres are falling
\( r \): radius of the spheres

Formula C1 was tested for falls of several meters in air and was found fairly satisfactory. However, it may not be applicable to the conditions of ultra-slow falls in a liquid.\(^\text{12}\)

It can be observed that both the eastward deviation (given in (1b)) and the dispersion due to turbulence contain the factor \( H^{3/2} \) which means that one does not gain much in terms of accuracy by increasing \( H \). What makes small values of \( H \) inconvenient and unpractical is rather the limitation of accuracy in the determination of the vertical. It is probably difficult to determine the vertical with an accuracy better than 1/100 of a millimeter. Thus, if one wishes a precision better than 1% the deflection must be at least 1mm which means a height of more than 10 meters.

If one applies formula (C1) to the Reich and Hall experiments one gets: \( \Delta = 44 \text{mm} \) and \( \Delta = 2.5 \text{mm} \) respectively. The accuracy on the center (defined as the average of the coordinates of individual impacts) then depends on the number of balls that have been used. If one can assume that successive balls fall independently\(^\text{13}\) the standard deviation on the average of \( N \) balls will be \( \epsilon = \Delta / \sqrt{N} \).

For the Hall experiment this gives: \( \epsilon = 0.08/\sqrt{946} = 0.08\text{mm} \) which is comprised between the two error levels given by Hall, namely 0.05mm and 0.15mm.
For the Reich experiment one gets: \( \epsilon = 44/\sqrt{106} = 4.4\text{mm} \). This is about 10 times more than the probable error given for this experiment and raises some doubts about the claimed accuracy.

The dispersion radius given by (C1) corresponds to random deflections which can, at least in principle, be eliminated by taking an average over a sufficiently large sample of falls. This averaging process can be illustrated by the Hall experiment. With \( \epsilon = 0.08\text{mm} \), the accuracy of the measurement is \( 0.08/1.5 = 5.4\% \). If one would

\(^{12}\)In such conditions one has \( \rho \approx \rho_1 \). If in addition one takes for instance \( r = 10\text{cm} \) and \( H = 1\text{m} \), one gets \( \Delta \sim 10\text{cm} \), which seems much too large.

\(^{13}\)Which means that the perturbation due to the fall of ball number \( n \) has been sufficiently dampened so as not to affect the fall of ball number \( n + 1 \).
like to increase the accuracy to 1% one would have to perform $5.4^2 = 29$ times more falls. As Hall already performed some 1,000 falls, this means that one would have to perform 29,000 falls. This is almost an impossible task except perhaps if it can be made completely automatic. However, it should be noted that by using platinum balls ($\rho_1 = 21.5\text{kg/liter}$) instead of bell-metal ($\rho_0 = 8\text{kg/liter}$) one would gain a factor $21.5/8 = 2.7$. that would reduce the number of falls to 10,700; still a large number.

References

Benzenberg (J.F.) 1804: Versuche über das Gesetz des Falls, über den Widerstand der Luft und über die Umdrehung der Erde. Nebst des Geschichte aller Früheren Versuche von Galiläi bis auf Guglielmini.

Bähr (J.), Logé (M.), Mechelk (K.), Operhalsky (A.-M). 2005: “Dreht sich die Erde?” [Account of an experiment made at a German space research installation allowing free fall in vacuum from a height of 145 meters; available on the Internet].

Bruhat (G.) 1955: Mécanique. Masson, Paris.

Cabannes (H.) 1962, 1966: Cours de mécanique générale. Dunod, Paris.

Goldstein (H.), Poole (C.), Safko (J.) 2002: Clasical mechanics. 3rd edition. Addison-Wesley.

Hall (E.H.) 1903a: Do falling bodies move south? Part I: Historical. Physical Review Vol. 17, no 3 (September) p. 179-190.

[Surprisingly a this historical review article gives almost no references to previous publication. The only reference that is given is to an article published in 1802 by Benzenberg in Annalen der Physik (Vol. 12, p. 367-373).]

Hall (E.H.) 1903b: Do falling bodies move south? Part II: Methods and results Physical Review Vol. 17, no 4, (October) p. 245-254.

Poujade (O.) 2010: Impact location broadening of a solid object falling in a fluid due to drag and lift fluctuations. CEA (22 January 2010). Unpublished paper, private communication.

Roehner (B.M.) 2010: Exploring turbulence behind a sphere through free-fall experiments. Part I: Spheres falling in air. Working report LPTHE (9 May 2010).

Wikipedia 2011a: Article entitled “Terminal velocity”.

Wikipedia 2011b: French version of the article entitled “Déviation vers l’est” (i.e. Eastward deflection).