COMPUTER REPRESENTATION VERSUS REALITY: WHICH HAS MORE VALUE OF TRUTHFULNESS?

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ABSTRACT

Due to mass production, many modern instruments are so simple to use that students are driven away from their inside complexity (and this fact can be very nice); but too often now students prefer to blindly accept those results, without any criticism. This happens also with modern computers. In modern physical measurements, computers can play a double role: the automatic management of data acquisition and the final analysis of data by dedicated software. Instead of being wonderful examples of "how things" work, they become just magic boxes totally outside the student comprehension. Of course these considerations can be applied to any study discipline. In this paper, we present only examples related to our direct teaching experience in experimental physics: first a few cases that came out when we introduced the use of GPS (Global Positioning System) both for space localization and extremely precise time synchronisation; then some anomalous behaviour of data analysis even with the most common spreadsheets, in simple situations; finally how can be artificially regenerated the "sound" of an interplanetary spacecraft like Cassini we recently recorded from the Italian radiotelescope in Noto. We also describe the teaching strategies we have verified to be more efficient to drive students in checking how closely the computer representation can match the reality.

KEYWORDS
Metrology, limits of validity in modern measurements, Global Positioning System

INTODUCTION

Teaching Experimental Physics in Modern Measuring Environment

We think that "good teaching" can be reached only when the students, after having received new information, can also get the tools needed for feeling the boundary limits of their new spectrum of knowledge, and for succeeding in the later process of integrating together new and older pieces of information.

From this point of view, Computer Learning, well due to its obvious boost in opening completely new capabilities, it also offers new challenges for a "responsible learning". As an example, it is quite common nowadays to find students (and even professionals) who give much more value of truth to a computer simulation than to the reality itself. Of course, experimental verifications are cumbersome, require time, additional costs, knowledge of technical details and even more: "manual skills". But without making systematic checks in all the relevant methodological cornerstones, in our opinion, new teaching technologies can be or very dangerous or simply fake.

We are focusing this science education challenge since ten years, with regard to university students in physics, following the first experimental physics course. We soon realised how hard it is for a teacher to point out the limits of validity of the modern measurements, especially if they are achieved with technologically complex instruments, then virtually "perfect". It is mandatory instead for students to understand that the measurement result is not only a "simple number", but a collection of information about how all the experiment has been made, and an estimation of its uncertainty.

At the beginning of the course, our students learn the theoretical background needed for a correct understanding of even the simplest kind of measurements. Then, by the use of simple instruments, they can immediately check their own level of comprehension, in a well-defined environment. Later in the year, they study some higher level of data analysis and can get into the real world of modern measurements by choosing to make one among different kinds of so-called "open experiments". Here, after a teacher's introduction, they are invited to proceed autonomously toward some original results (from their point of view). The last opened working area has been around measurements made by receivers for the Global Positioning System (GPS).

THE GLOBAL POSITIONING SYSTEM

The primary results of a GPS receiver are the Latitude and Longitude co-ordinates of the user, wherever staying, in any point of the Earth's surface or around it (Wells, 1987). Designed for military use, this is a system of more than 18 satellites, in circular orbits around the Earth, at an altitude of almost 20000 Km and a period of 12 hours, in such a way that, from any site and at any time, at least three satellites are visible above the horizon. Each satellite transmits two radio carriers (L1 at 1575.42 MHz and L2 at 1227.6 MHz), which are modulated by two pseudo-random codes (C/A, the coarse acquisition code, and P, the precision code), and by a navigation message. A Caesium atomic clock, on board of each spacecraft, controls the time synchronisation of the radio signals. The cheaper GPS receivers track the less precise, commercially available coarse code, or, in the most expensive units, both codes. For each satellite the receiver measures the delay between the time t_1 , when a signal was transmitted, and the instant of its reception t_2 at the user antenna. This time interval $(t_2 - t_1)$ multiplied by the propagation speed of radio waves in the atmosphere (which is closely related to the speed of light c), gives the distance d_i from each satellite to the user's antenna. This computation is correct only if the user's clock is synchronised with the GPS time. To avoid the need for the user of an expensive and complex atomic clock, it is sufficient to take an extra delay measurement, to solve for the synchronisation error. In conclusion, in a two dimensional localisation (Lat and Long), at least three satellites in view are needed. If more satellites are available, a solution in three dimensions is achievable.

The localisation accuracy, can spread from a few centimetres to a few meters [1], depending on many different factors. The most important ones are: the type of codes used, the particular geometry of the satellite positions in the sky and the uncertainties in their real orbits, the length of measurement time, the ionospheric and tropospheric delays, the quality of the receiving system, the level of sophistication of data analysis.

We started this research activity in 1994, when we bought the receiver XR4-PC from Navstar, which is a full size PC card (Caporaloni Ambrosini, 1995). More recently, we bought two Motorola VP Oncore modules. In both cases we chose GPS receivers that can operate both as a navigation aids (giving in real time Longitude and Latitude while the receiver is moving), and also as a source of an extremely stable time scale, if the unit is kept in a fixed place. The timing ticks come out in the form of a pulse, with one peak per second (1PPS) of repetition interval, made available to the user with TTL levels. The GPS theory and the manufacturers guarantee that this signal is synchronised within almost 50 nanoseconds from UTC.

EXAMPLES OF FALSE INTERPRETATIONS BY STUDENTS

Figure 1 shows the experimental set-up we built to allow students to compare, over different and properly selected time scales, the 1 PPS signal generated locally by a good quartz oscillator (directly projected and assembled by a couple of them) with the one obtained by a GPS receiver . These signals

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[1] Until May 2000, this intrinsic accuracy of the GPS technique was artificially degraded for military reasons down to a few hundred meters for civil users.

are inputted into an HP universal counter, which can be configured to measure both the frequencies or the time interval beteween the two signals.
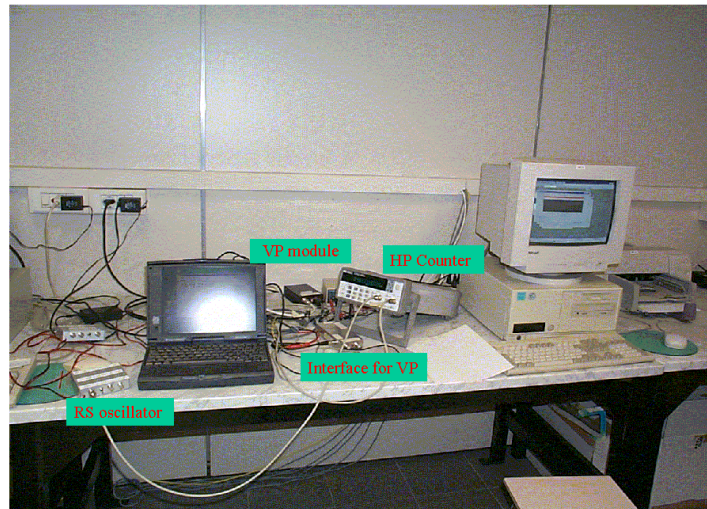

Figure 1. Our measurement chain: the frequency of the 1PPS made available by the GPS receiver (VP module) and by the quartz oscillator (RS oscillator) can be read in real time
both on the counter display and on the PC monitor

While the main students' activities are described in previous works (Caporaloni Ambrosini, 1999 and 2002), here we want to illustrate two cases where the results shown on the PC monitor, drove them to get wrong ideas, and give false interpretation of the reality. The first example refers to a set of frequency measurements done over rather short time scale (a few tens of minutes) of the 1PPS signal derived by the GPS receiver. Students' surprise was to discover that the GPS pulse didn't produce the nominally expected value of 1Hz (or better 1.000 000 0xx Hz): the first offset figure showed up in the sixth decimal place (see Tab.1), instead of the eighth one, in agreement with the manufacture's specifications.

Table 1. The GPS signal frequency read in real time on the display.
The up pointing arrow indicates the first gittering figure

GPS receiver
↓ offset
Frequency = 1. 000 001 341 Hz
↑ fluctuations

At this level, students did not show any doubt to believe in the results shown on the PC monitor. We had to guide them by critical discussions to get a correct comprehension of the reality: the GPS *has* to be trusted as an extremely accurate frequency standard. This consideration comes out from its main application: the navigation. Ships want to approach harbours with the same level of accuracy all year around! Nowadays, the system guarantees a localisation accuracy of a few meters also to civil users. By the help of a hand held GPS receiver (Garmin e-map), we made with students this check: walk with the GPS receiver in your hands and look at the arrow pointing at your position in the street where you are, then turn yourself of 180 degrees and again walk; after three-four meters you will see that also the arrow changes its direction of 180 degrees. If we express this uncertainty of, let's say, ten meters in space localisation, as a timing uncertainty in the arrival time of the GPS signals, we get around 30 ns.

All these arguments show that the GPS 1PPS signal is a reliable frequency standard with an accuracy better than 10^{-7}. Then the results shown on the counter display must be wrong. Where is the problem? It is in the accuracy of the time base reference of the frequency counter, that due to ambient temperature

changes and quartz ageing, can produce frequency offsets as large as a few parts per millions, according to the manufacturer specifications. In conclusion this explains the discrepancy of 1.3 µHz on the GPS frequency reading.   Then students, really aware of how things are going on, decided to adjust the internal reference oscillator of the counter manually, by the relative setting screw, until they could read on the display the correct value of 1.000 000 0xx Hz.

The second surprise for students was that the short-term frequency fluctuations of the GPS were larger than those of the quartz oscillator that they have been able to build by themselves.

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Table 2. The quartz oscillator frequency read in real time on the display.
The up pointing arrow indicates the first gittering figure

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Quartz Oscillator
↓ offset
Frequency = 1.000 000 793 Hz
↑   fluctuations

To substantiate, in a quantitative way, the real time impressions, students made two series of frequency measurements, one for the GPS and one for the quartz oscillator, along with 6 minutes, one data point every three seconds. The time scale in this example (360 seconds) was chosen long enough, to have a sufficiently high number of data points (low statistical uncertainty) and not too long to be corrupted by drift effects.

Then students used EXCEL to compute the mean values and the standard deviations. These are their results:

GPS	**<F>** = 1. 000 001 323 Hz	σ = 53 nHz
Quartz	**<F>** = 1. 000 000 791 Hz	σ = 0 nHz

The direct calculus of the standard deviation of the quartz oscillator data gave zero!
In spite of the fact that the popular spreadsheet we used allows to show up to 30 digits, it evidently does not make the calculus with all those figures. It was then necessary to adopt a trick: by subtracting 1 from each data point the standard deviation algorithm can work on the significant decimal figures, without wasting resolution on the large offset of the average value. The final, correct, result was

Quartz	**<F>** = 1. 000 000 791 Hz	σ = 1.9 nHz

This was another example for students to become aware that attention and criticism are needed to make good use also of popular spreadsheets, in order to get correct interpretation of the physical reality.

Finally we want to report a third, even subtler, example of computer misinterpretation. The off-the-shelf automatic data acquisition program we used to read the counter gave strange results when displaying the 1PPS data. To make the thing short, the reason of the error came from the fact that the program was reading the data at its own prefixed data rate, so time to time, it simply missed a data point!   The final message is rather clear: never use in an automatic system two independent time synchronisations. One action should wait for the completion of the other or you should use data buffers.

Another example opened up just a few months ago is the following. In January 2003 we have organized the Doppler tracking of the Cassini spacecraft from the Italian radiotelescope of Noto. The downlink radio signal was recorded at that time as an audio tone. Now the question to the students: how can you judge if that recording is the true Cassini signal? Can you identify its characteristics, reproduce them by a personal computer and compare it with the supposed original one? The music experts answered that two types of audio generators would have been needed at least, one for a tone with some sweeping capability (to emulate the variable Doppler) and another for the measurement noise, to be appropriately

filtered; a Labview code, developed to reconstruct the sound, showed that the *real* signal was even more complex than expected.

CONCLUSIONS

Teaching strategies for helping students' consciousness
In our ten year experience of teaching experimental physics, we met many situations where students were drawn to wrong interpretation of reality. This is mainly due to their absence of criticism of the new instruments and personal computers, which are considered virtually "perfect".

In order to point out the limits of validity of these modern devices, we have found very successful to divide the laboratory activities in two levels. In the first part of the course, simple instruments with different resolutions allow to critically discuss the theoretical aspects of each step of the measuring procedure. By the way, at this stage, we take great care in teaching a metrologically correct glossary. In the second part, several "open experiments" let the students to feel the emotion of research, and to become aware of a correct way of making measurements. Here the students utilise instruments of the most sophisticated technology. These are so easy to use and so complex inside that they can hide the real measurement limitations or even they can generate artifacts, very difficult to identify. Our teaching strategies aim to improve the student criticism toward the discovery of the range of validity of the experimental configuration, and the search of the random fluctuations and the systematic effects always present in real measurements. Modern computers offer in this regard a variety of occasions for misunderstandings. Putting their computing capabilities at some border line or simply toward some unusual situations, it can be rather easy to show how they can give wrong results. From this point of view we have found that the GPS technique is very attractive for the students and is fruitful of many didactic applications. The final result of this process is a better comprehension of the subject by the students. Proofs of that are their activities that they develop autonomously, like the design of the experiment from data acquisition to data analysis, the allocation of different tasks within subgroups, the final presentation of their results, both oral and in a written report.

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