6th Student Parabolic Flight Campaign
Preliminary results of the APTOVOL experiment (1052)

F. Guisset, S. Ovyn, G. Pfyffer, V. René de Cotret,
D. Bertrand and G. Grégoire

Institut de Physique Nucléaire
Université catholique de Louvain
B-1348 Louvain-la-Neuve

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I. INTRODUCTION

This summer, we were given the incredible opportunity to participate in the 6th ESA Student Parabolic Flight Campaign, an experience that taught us a lot not only in a scientific point of view, but also about team work, project leading, and experimental science as a whole. This document summarizes a description of what happened during the flight and the preliminary analysis of the data. Furthermore, some improvements to the original setup are proposed.

II. OBJECTIVES

The main purpose of the experiment is to check whether or not the velocity of light is affected by a gravitational field. One A. Einstein's fundamental postulate is that light must travel at a constant speed c, no matter the reference frame is considered. Several experiments have tried to show some variation of its value; if their results did not show any manifest modification in the velocity of light, they at least increased the knowledge of its numerical value and pushed further the limits by which this principle appears to be valid. Even if c retains a constant value independently of the relative speed of frames in the absence of gravity, the possibility is still open that in fact c could be a function of the *acceleration* of a given frame with respect to any other. Precisely, theoretical considerations (presented in the motivation document) established that a realistic model should let c vary as the square of the acceleration of the reference frame.

The basic concept in the design of the experiment is the monitoring of an interference phenomenon. An high-frequency amplitude-modulated laser emits a beam of light towards a receiver along a well defined flight-path. The modulation of the laser beam is generated by a frequency sythetizer operating at 450 MHz with a stability of about 10^{-6}. The phase correlation between the emitted and received signals is directly sensitive to a possible variation in the velocity of light. This phase-correlation is continuously monitored on a high-performance digital oscilloscope and regularly stored in the memory of a computer during the whole flight through an appropriate data acquisition system.

The resulting data stream is to be analysed off-line later. The whole experiment is designed to operate autonomously during the flight.

An accelerometer is attached to the setup and its signals are recorded together with the HF-modulated signals. The whole setup is mounted on a Cardan suspension equipped with a gyroscope. In principle, it would allow to check possible dependencies on the orientation of the light flight path with respect to the acceleration of the plane.

Considering the precision of measuring devices, the expected sensitivity is around a tenth of an interference fringe, translating into a large sensitivity to phase shift modifications and eventually to the variations in c. From this level of precision, it was established that even if no variation in the velocity of light was observed, at least it would be possible to improve the knowledge of its numerical value.

III. DATA ACQUISITION DURING THE FLIGHTS

At the loading of the experiment inside the aircraft, the fixation of the rack to the ground rails had to be revised, but it ended in a solid solution keeping the rack very stable in all directions.

During the first flight, it appeared that the reaction time of the gyroscope was not small enough to maintain the tube in a constant direction in space, namely the vertical direction toward the Earth'surface. Nevertheless, at this point it is not clear if such a movement of the tube is essential to observe the desired effect: after several discussions with the CEV crew people as well as ESA members at Merignac, it appeared that the tube doesn't have to rotate around the Cardan suspension. Actually, the flight configuration leads to an acceleration varying between 0 and $1.8\,g$ always directed perpendicularly to the plane ground, and not to the Earth's center as it was previously thought. This fact has still to be fully analysed as soon as we receive the flight presentation given during the briefing. For this reason, it was decided to keep the tube fixed vertically in the plane during the first part of the second flight, and to release it for the second part. Analysis of the data will determine if the two running conditions induced an effective difference, but at first we can expect the signals to be more stable during the fixed phase of the experiment.

Considering the data acquisition system, all devices worked as foreseen; the accelerometer even exceeded our expectations in terms of signal quality. Unfortunately, the storage program was conceived as to be started and stopped manually, and a mistake in the initialisation procedure on the first flight resulted in the absence of saved data.

Back on the ground, some modifications were made to improve the program, and the second flight was more successful: the computer stored indeed more than 4200 files, covering two hours of the flight. The acquisition started just before the first parabola and ended after the last one, with a 5 minutes break during the flight when releasing the tube. The signal from the laser receiver was sent to the AC-coupled first channel of the scope. The DC-coupled second channel contained the laser input reference signal used to modulate the laser. The slowly varying signal from the accelerometer signal was superimposed to the second channel. The recorded data also contain two time-tag informations, one from the computer and the other from the oscilloscope, from which we deduced that files were saved approximately every 1.5 seconds.

IV. A FIRST ANALYSIS OF THE DATA

The goal of this preliminary analysis is to correlate the variation of the phase shift between the two channels with the acceleration of the plane.

Starting from the whole collection of data, we extracted signals from channels 1 and 2 and calculated the mean value of the signal in each file. Please recall that the input signal is a sinusoïd centered around a zero DC level, while the output signal is a sinusoïd with the same frequency, but phase shifted with regard to the input, and superposed to a DC level proportional to the acceleration (see Fig. 1). From the tuned parameters on the scope it was deduced that the time span of the display exceeds four periods (i.e. about 10 ns).

As expected, the means in every files are distributed around zero for the channel 1. Discrepancy from exact zero level (of the order of 10^{-3}) represents the inaccuracy in trace grounding of the scope, as well as its stability. The mean values of channels 2 have a different behaviour, showing an average level different from zero and some peaks and gaps. This behaviour is precisely the signal of the accelerometer, and from now the mean value in channel 2 will represent the acceleration in arbitrary units (Fig. 2).

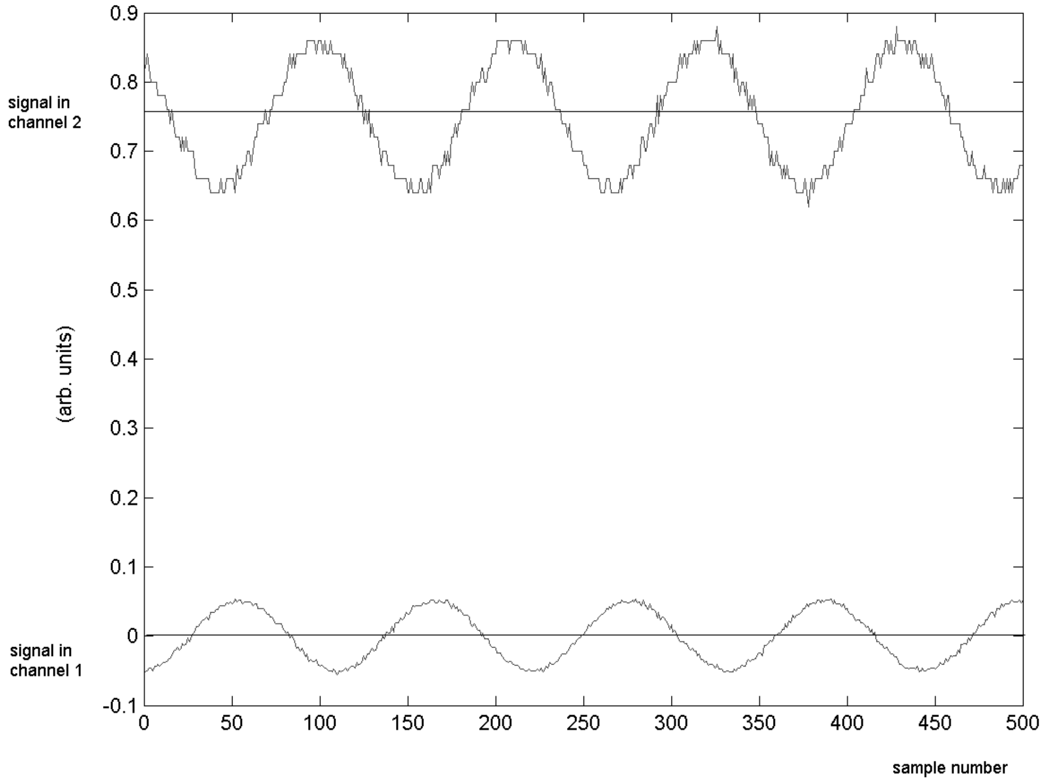

FIG. 1: Saved data in one amongst the 4300 files of the second flight. Each sinusoid represents one of the channels of the scope; the non-zero mean value of the signal at channel 2 is the DC level provided by the accelerometer.

Corrected input and output data are obtained by substracting their mean value in each file. They are then normalised to a unit amplitude. At this point we expect to have data of the form

$$\begin{aligned} y_{ch1}(t) &= \sin(\omega t) \\ y_{ch2}(t) &= \sin(\omega t + \phi). \end{aligned}$$

The goal is to extract the required phase angle and to test whether it changes significantly during the flight. This angle is obtained by independent Fourier analyses of each data file, based on the following identities:

$$\begin{aligned} \sin\phi &= \frac{2}{T}\int_0^T y_{ch1}(t+\frac{T}{4})\, y_{ch2}(t)\, dt \\ \cos\phi &= \frac{2}{T}\int_0^T y_{ch1}(t)\, y_{ch2}(t)\, dt. \end{aligned}$$

One period appears to cover 111 over the 500 saved points in each file for both channels (sampling rate is about 2 gigasamples/second); the numerical integration can thus be performed over four periods using a Simpson's algorithm:

$$\int_{x_1}^{x_n} f(x)\, dx = h\left\{\frac{55}{24}f(2) - \frac{1}{6}f(3) + \frac{11}{8}f(4) + f(5) + \ldots \right.$$
$$\left. + f(n-4) + \frac{11}{8}f(n-3) - \frac{1}{6}f(n-2) + \frac{55}{24}f(n-1)\right\} + \mathcal{O}(n^{-4}).$$

Both $\sin\phi$ and $\cos\phi$ allows us to deduce an unambiguous value of ϕ for each file. In the end this procedure gives us a distribution of phase shifts allowing the evaluation of averages and standard deviations corresponding to the different flight conditions, namely the 0g, 1g and 2g periods. We assumed that all measurements and their uncertainties follow gaussian statistics.

Practical results can be found using this preliminary analysis. Other, more precise analyses of the data are underway.

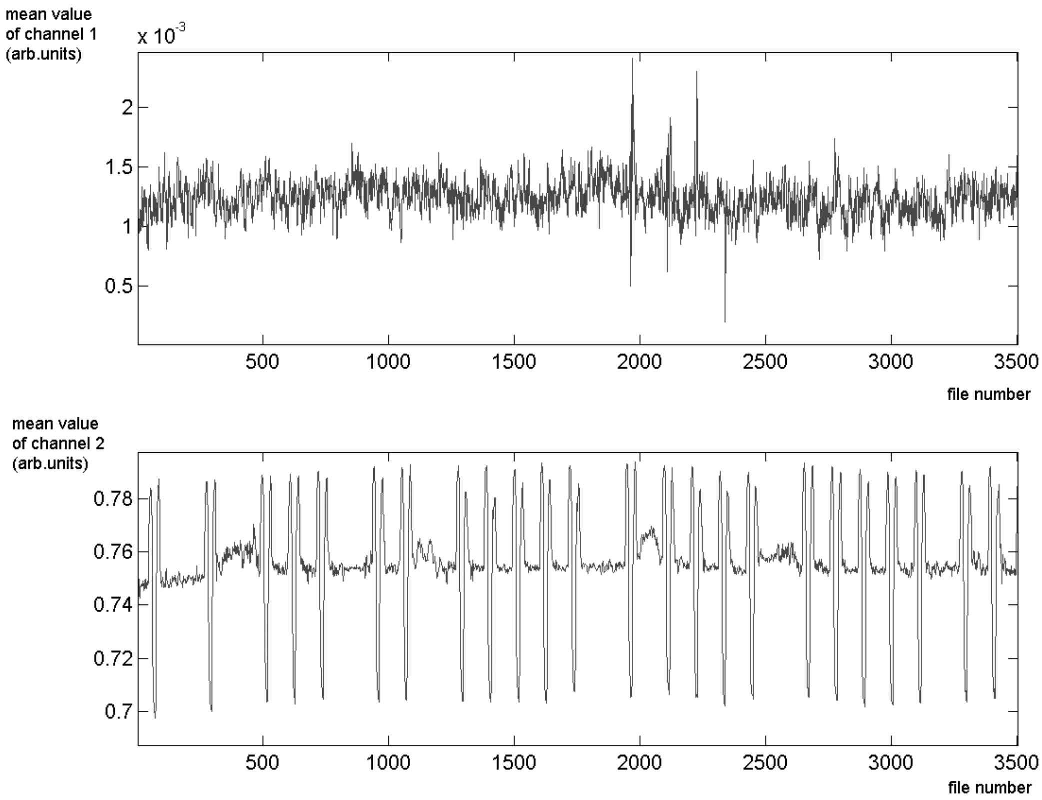

FIG. 2: Mean values of the signals in channels 1 and 2 vs. the number of the file arranged chronologically.

V. PRELIMINARY RESULTS

The results are displayed on the graphs below. For completeness we should mention that in Fig. 4 we have separated results from parabolas when the tube was fixed or not –see the legend of the graph.

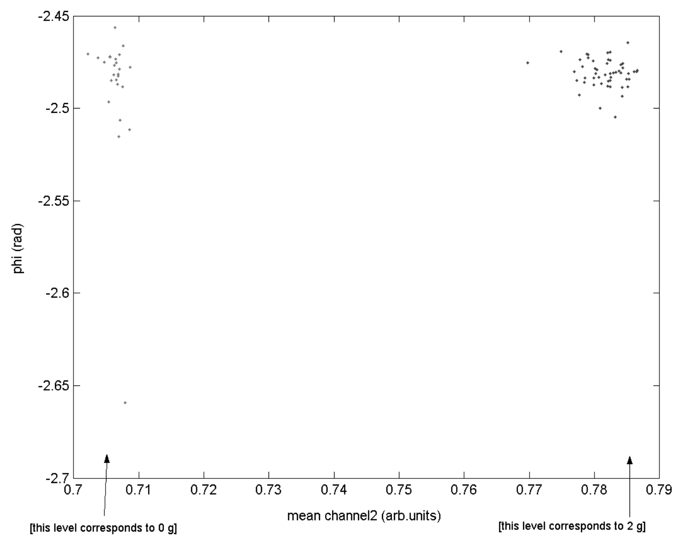

FIG. 3: Mean values of the phase angle vs. acceleration. This acceleration is given by the mean value of the signals in channel 2.

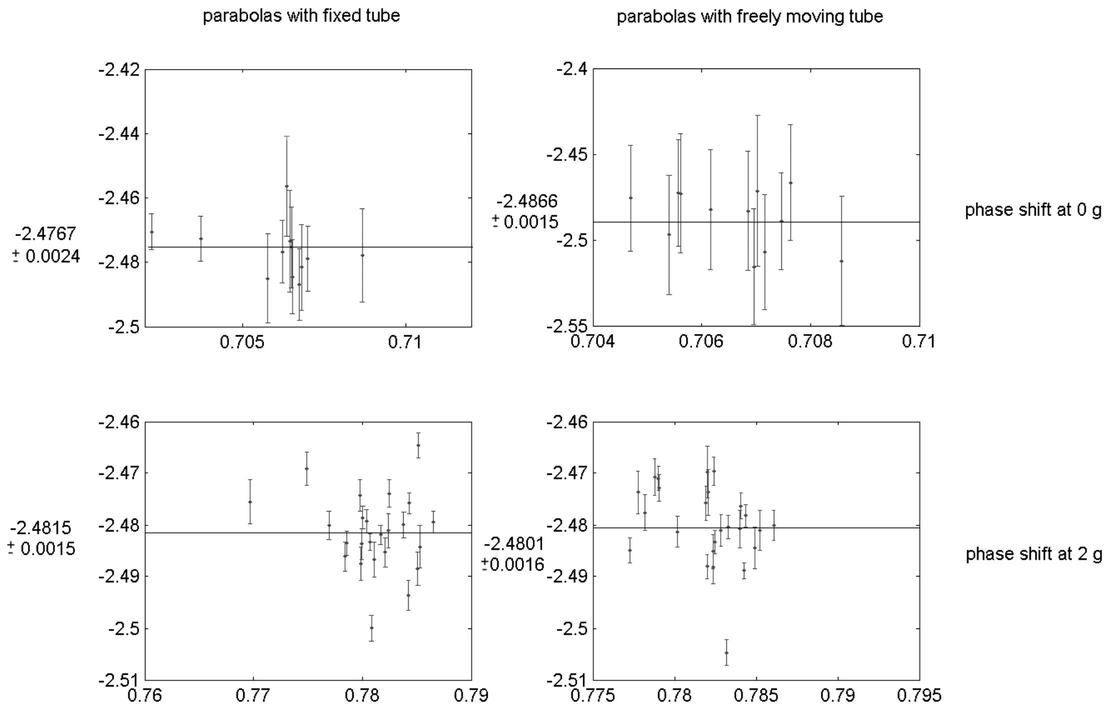

FIG. 4: Mean values of the phase angle vs. the acceleration. Graphs of the first column represent data from the parabolas when the tube was kept fixed, those of the second column are data when the tube was free. Graphs of the first line are obtained for 0g periods and those of the second line represent data from the 2g periods. Horizontal lines show averaged values of the phase angles, which are given with their standard deviation on the left of each graph.

The values of the phase angle were determined with a statistical precision of about 0.1%. Both values of the average phase angles at 0g and 2g agree within two standard deviations, so to say at a 95% confidence level. It also means that **there is a statistical 5% chance that the velocity of light changes with the acceleration of the reference frame.**

However it should be stressed that the numbers presented here are preliminary due to the lack of time to perform deeper analysis. We have to refine our understanding of the data and in particular we need to assess the statistical and systematic errors in a rigorous way. We should also compare our results with the precision of previous experiments.

VI. CONCLUSIONS AND PERSPECTIVES

Through this experiment we proved that this setup is able to detect or set an upper limit on a possible change of the velocity of light relative to the acceleration of the plane. Through minor refinements the precision could still be improved. Those refinements include a better (faster) data acquisition system and a larger gyroscope if it turns out that it is useful. It would also be extremely useful to perform the correlation study at various modulation frequencies, which should influence strongly the ultimate accuracy.

It should be kept in mind that the present good level of precision already reached was obtained during the "inaugural" flight with a setup that could not be thoroughly tested beforehand. The ultimate level of precision of the experiment is thought to be within reach with a further flight.

A second opportunity to fly would definitely allow us to send an optimally-tuned experiment up there. After this first campaign, we are already able to put an upper limit on the effect and we are now fully confident to constrain our conclusions to much tighter limits. That's why we hope ESA will allow us to take part in one of the next Professional Flight Campaigns.

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[1] C. Braxmaier *et al.*, *Phys. Rev. Lett.* **88** (2002) 010401.
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[3] G.M. Shore, *Nucl. Phys.* **B633** (2002) 271, and references therein.
[4] W.H. Press *et al.*, *Numerical Recipes in C*, Cambridge University Press, 1988.