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Superluminal neutrinos: an OPERA in three acts

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Abstract. In September 2011 the OPERA experiment at the Gran Sasso Laboratory, Italy announced that they had evidence that the neutrinos in the CERN-to-Gran-Sasso (CNGS) beam line were travelling very slightly faster than the speed of light. If true this would have ranked among the most important discoveries of the 21st century. In the event it was not true and was rapidly discredited. This paper explains what the measurement entailed, the responses to it and the eventual explanation, and discusses whether the initial publication and the subsequent reactions were appropriate.

1. Overture: neutrinos, the CNGS project and the OPERA experiment

The Standard Model of particle physics (see for example, [1]) is an extremely successful description of the particles and forces acting in the subatomic world (it does not include gravity but on the subatomic scale gravity is so weak that it can safely be neglected). The matter particles of the Standard Model—the quarks and the leptons—are arranged in three “generations” with the particles in each succeeding generation having similar properties but typically greater mass so that stable matter is made up of first generation particles (the up and down quarks and the electron).

Neutrinos are the lightest of the matter particles in the Standard Model and the only ones with no electric charge. All three neutrinos are extremely light, probably less than one millionth of the mass of the electron and all appear to be stable (in contrast to the other matter particles where the heavier particles of the second and third generations decay to first-generation equivalents). They interact extremely weakly, and therefore very intense sources and very large detectors are required in order to make successful experimental measurements. Neutrinos are unique among elementary particles in that they change their identity in flight: a neutrino produced as the second-generation ν_μ may be observed after travelling some distance as either the first-generation ν_e or the third-generation ν_τ. This phenomenon is known as *neutrino oscillation* and is of great theoretical interest (the 2015 Nobel Prize in Physics was awarded to Takaaki Kajita and Art McDonald, the spokespersons of the two experiments which established the reality of the effect).

The CERN Neutrinos to Gran Sasso (CNGS) project [2] was intended to investigate neutrino oscillations between the second and third generations, $\nu_\mu \rightarrow \nu_\tau$. The mean neutrino energy was 17 GeV (2.7 nJ), and the distance from the beam production point to the experiments was about 730 km. The principal experiments on the CNGS beam line were OPERA [3] and ICARUS [4]. Both experiments were of course designed primarily to detect the appearance of ν_τ (identified by the production and decay of a heavy τ lepton) in a beam which initially consists of nearly pure ν_μ, but the detected neutrino interactions (‘events’) are accurately time-stamped using GPS, so a very precise measurement of the neutrino travel time and thus the neutrino speed is also possible.

2. Act 1: the result

A neutrino beam is produced by allowing high-energy protons to strike a suitable target. This produces large numbers of charged pions. The positive pions are focussed by magnetic fields into an approximately parallel beam and then allowed to decay in flight. As the pions decay to a muon plus a ν_μ, this yields a nearly pure beam of ν_μ.

Accelerators do not produce a continuous stream of protons. Instead the protons are produced in discrete bunches; in the case of the CNGS beam the bunches are 10.5 μs long with a sharp rise and fall at the beginning and the end of the bunch, and some complex internal structure which is not important. Since any given neutrino could have been produced by a proton from anywhere in the bunch the finite width of the bunch means that the travel time for an individual neutrino has a corresponding uncertainty; however, if all the event times are plotted relative to the known start time of the corresponding bunch, the resulting time distribution should mirror the original proton time distribution and the time offset between the two then gives the neutrino travel time with a precision determined by the sharp rise and fall of the bunch rather than its width. This coupled with the accurately known distance between the target and the experiment yields the neutrino speed. A schematic diagram of this is shown in figure 1.

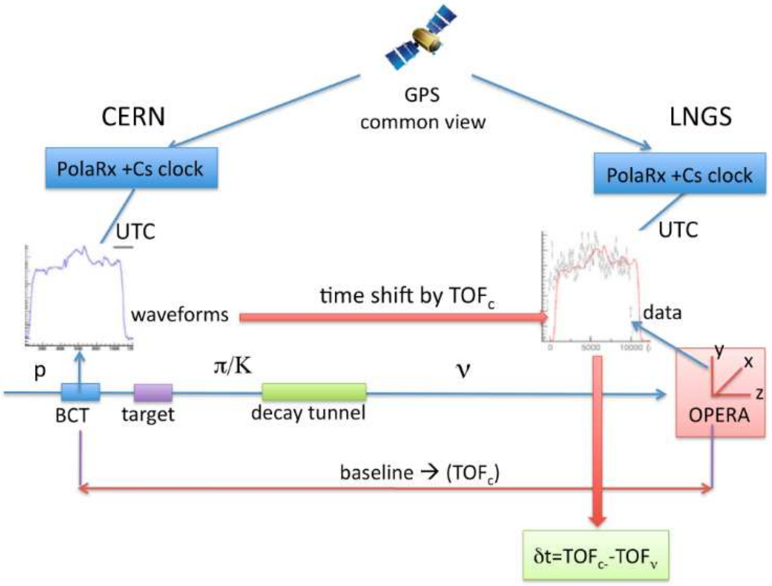

Figure 1. Schematic diagram of the neutrino time of flight (TOF) measurement. TOF$_c$ is the expected time of flight if neutrinos travel at the speed of light; TOF$_\nu$ is the measured time of flight. "Common-mode" GPS (using the same satellite) is more precise for relative timing than standard GPS. Figure from [5].

In practice it is not as simple as that. The principal problem is that the Gran Sasso Laboratory is deep underground in order to reduce the cosmic-ray background which would otherwise swamp the rare neutrino events and GPS signals do not penetrate underground. Since GPS is required for both the time-stamping of the neutrino events and the precise measurement of the baseline this presents a problem.

For the distance determination GPS positions are taken at both ends of the tunnel leading to the Laboratory and the distance from the GPS receivers to the experiment is determined by standard high-precision surveying. The result is believed to be accurate to ±20 cm.

Time-stamping is more of an issue since each recorded event needs to have an individual time-stamp whereas the survey is a one-off measurement. The GPS time signal was transmitted to the experiment via an 8.3 km-long fibre-optic cable; as the signal takes some time to traverse the cable this introduces a delay, which must be corrected for in the analysis. In addition to this the time signals at both ends of the experiment (CERN and OPERA) must be processed through electronics, which also takes a finite time. All these time delays must be measured and corrected for in order to produce an accurate travel time measurement. The time delays at the OPERA end of the measurement are shown in figure 2.

The analysis was actually done using an uncalibrated reference time so that the fitted offset did *not* directly correspond to the neutrino travel time. A different team then applied the calibration to calculate the final result. This technique, known as a *blind analysis*, is commonly used in particle physics analyses to reduce the risk of analyses being compromised by unconscious bias. After all corrections were applied the final result was

$$\delta t_c - \delta t_\nu = (60.7 \pm 6.9 \pm 7.4)\ \mathrm{ns},$$

where δt_c is the time difference expected for a particle travelling at the speed of light, δt_ν is the observed time difference, the first uncertainty is statistical and the second is systematic. This value differs from zero by 6.0 standard deviations and its positive sign indicates that the neutrinos were travelling faster than the speed of light. The implied difference in speed is

$$\frac{v - c}{c} = (2.48 \pm 0.28 \pm 0.30) \times 10^{-5}.$$

This result was announced in a seminar at CERN on the 23rd September 2011 with the simultaneous release of a preprint on the open-access ArXiv server which provided full details of the analysis [5].

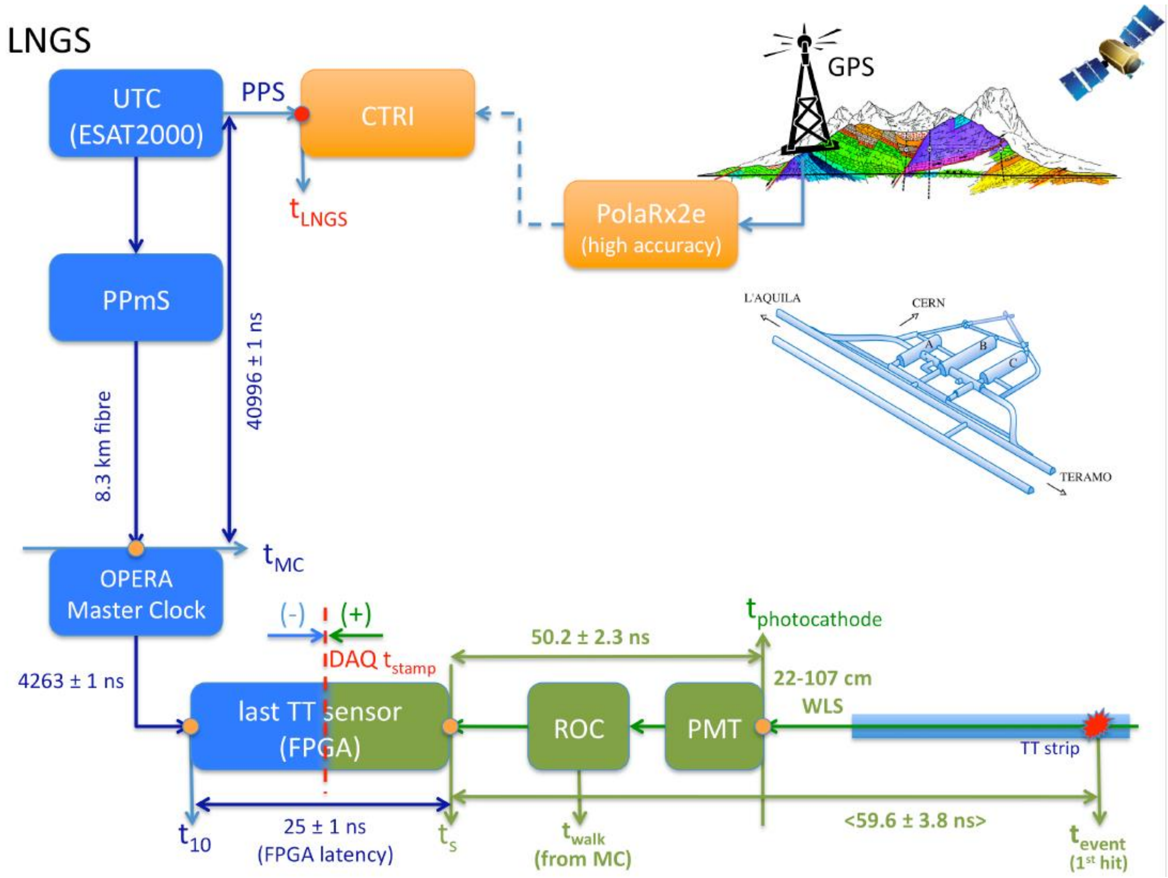

Figure 2. Schematic showing the timing corrections at the OPERA end of the measurement (more corrections have to be applied at the CERN end). Delay times in blue are part of the time-stamp distribution and are subtracted from the "raw" δt, so increased values would lead to decreased δt. Delays in green are part of the detector response and are added to δt; increased values would lead to increased δt. Figure from [5].

3. Act 2: the response

The preprint and accompanying seminar were carefully low key with the preprint conclusion being, "*Despite the large significance of the measurement reported here and the stability of the analysis, the potentially great impact of the result motivates the continuation of our studies in order to investigate possible still unknown systematic effects that could explain the observed anomaly*." Nevertheless the result if taken at face value was so startling that it received immediate attention both from the press and from the particle physics community.

In general the response from the experimental community might best be described as politely sceptical. The analysis appeared to have been carefully done, but "*extraordinary claims require extraordinary evidence*" and the strength of the evidence did not seem sufficiently extraordinary. Although the result was weakly supported by an earlier measurement by the MINOS experiment in the USA, which had found $(v - c)/c = (5.1 \pm 2.9) \times 10^{-5}$ consistent with OPERA's result but also (at 1.8σ) with zero, there was a serious inconsistency with the 1987 observation of neutrinos from a core-collapse supernova in the Large Magellanic Cloud 156,000 light years away. In that case the neutrinos had preceded the first observation of light from the explosion by only three hours (note that the neutrinos are *expected* to precede the light because they escape from the core of the supernova more easily), leading to a limit $(v - c)/c < 2 \times 10^{-9}$. These neutrinos were of much lower energy than the CNGS neutrino beam, so if the effect were real it had to be strongly energy-dependent—but OPERA had tried dividing their sample into low and high energy neutrinos, and had seen no difference, which constrained the amount of energy dependence at GeV neutrino energies. This indicated that the effect had to "turn on" at some point between the ~10 MeV energies of the supernova neutrinos and ~10 GeV energies at CNGS, which presented a theoretical challenge.

Clearly the highest priority on the experimental side was a replication of the experiment. To this end CERN reconfigured the proton beam to provide extremely short bunches (~3 ns) with very sharp rise and fall optimised for timing measurements, and the other main CNGS experiment, ICARUS set up a comparable analysis. The results of this would take some time to come in as the experiments would need to run in the new beam configuration for long enough to record sufficient statistics.

Meanwhile theoretical speculations abounded with dozens of theory papers uploaded to the ArXiv server. Some of these were sceptical: in particular Nobel Laureate Sheldon Glashow, one of the original architects of the Standard Model, was a co-author on a paper [6] that argued that such superluminal neutrinos would rapidly lose energy by radiating e^+e^- pairs, which would distort the neutrino energy spectrum at the experiment in a way which was not observed. However, most of the theoretical papers chose to assume that the effect was real and seek explanations, ranging from the fairly mundane (a superluminal group velocity arising from interference between mass eigenstates, e.g. [7]) to exotica such as extra dimensions (see [8] and references therein) via violation of Lorentz invariance (e.g. [9]) and non-standard neutrino interactions (e.g. [10]). Despite proceeding on the assumption that the result was correct most of the theory papers did acknowledge the urgent need for experimental replication.

4. Act 3: the resolution

The dedicated short-bunch CNGS run took place from the 22nd October to 6th November 2011. Initially OPERA reported a result consistent with their initial measurement [11]. However, the ICARUS experiment found $\delta t_c - \delta t_\nu = (0.3 \pm 4.9 \pm 9.0)$ ns [12] completely consistent with the expectation that the neutrinos should travel at a speed indistinguishable from c (in principle since neutrinos are not massless, their speed should be very slightly less than c, but their masses are so small that the difference is negligible).

In the shutdown after the dedicated run OPERA remeasured their entire timing chain, including the fibre optic cable delay [13]. The result of this measurement was:

2006 (original measurement)	delay 40995.5±0.3 ns; jitter 3.2 ns
2011 (first measurement)	delay 41068.6±0.5 ns; jitter 6.0 ns
2011 (after fibre reconnection)	delay 40994.1±0.3 ns; jitter 3.2 ns

The conclusion was clear: the timing anomaly had been caused by a faulty cable connection. An analysis using the timing of cosmic-ray muons seen in both OPERA and the neighbouring LVD experiment showed that the fault had developed around August 2008 when there was an abrupt change in the apparent time difference between observations of the same muon in the two detectors and had then remained stable until the fibre reconnection in December 2011. It had therefore been present throughout the period used in the original OPERA analysis and in the dedicated timing run in October/November 2011. Correcting for this effect led to a result of $\delta t_c - \delta t_\nu = (6.5 \pm 7.4^{+8.3}_{-8.0})$ ns completely consistent with zero for the original dataset and $(-0.8 \pm 3.5^{+9.9}_{-9.6})$ ns for the timing run.

This result was inevitably something of an embarrassment to the OPERA collaboration: both the spokesperson and the physics coordinator resigned. Questions were raised about why this problem had not been found before the initial announcement: as the single largest correction to the time measurement surely the fibre optic cable should have been checked earlier? However, this is rather unfair to OPERA. There was no particular reason to suspect that the fibre-optic cable connection was faulty and even if there had been, a faulty connection would be expected to result in a reduced signal amplitude, owing to losses at the bad connection, not a change in the propagation time. (In fact that is exactly what happened: the time delay was due to the way the OPERA Master Clock electronics reacted to the reduction in signal amplitude from the cable, not to the cable itself.) Although the press coverage was extensive, which of course intensified the subsequent backlash, both the initial preprint and the CERN seminar had been cautiously worded and were not sensationalist. It would have been very difficult to keep such an extraordinary result under wraps for a long time—particle physicists do gossip and in the age of the Internet rumours spread very rapidly—so a public announcement emphasising the preliminary nature of the result was probably the best action available at the time.

The community response also represents good scientific practice. The most urgent need was clearly for a replication of the measurement and CERN provided the facilities to do this very quickly: one month is a very short time in which to design and implement a new accelerator configuration. Less than ten months elapsed from the initial announcement to the release of OPERA's preprint explaining the cause of the incorrect measurement.

It could be—and was—argued that the many theorists who produced papers attempting to explain the result jumped the gun: surely they should have waited for confirmation of the measurement before rushing into print? However, the analysis *looked* sound enough; theorists are not well positioned to spot possible unrecognised systematic errors (indeed, to my knowledge, nobody identified in advance the exact source of the problem); and if the result *had* been correct it would have been important to explore all possible explanations (and anyone who had hit on the correct one would want to have established priority…). Some of the theoretical work done has value independent of what prompted it; at worst there are probably theorists out there with a paper or preprint to their name that they tend to omit from their list of publications!

On the whole the OPERA affair stands as a good advertisement for the self-correcting nature of science. The initial announcement was accompanied by a full technical paper—this was not "science by press conference"—the experimental community reacted appropriately and the theoretical community produced hypotheses which would have suggested ideas for further experiments if the initial result had stood up. Finally when the cause of the problem was found the OPERA collaboration published a full explanation of how, when and why it occurred, which will provide a useful case study for any future experiment which finds itself with a similar anomaly on its hands.

5. Coda: wrong results do not imply bad science

"*The consensus is that it does not exist. The discord has been resolved by a combination of finding errors in one set of experiments and a preponderance of the evidence.*"

This could easily have come from a 2012 paper or conference presentation about the OPERA result. But it does not: it is from a 1995 paper by Allan Franklin [14], reviewing an earlier mistaken result from neutrino physics—the apparent (but as it turned out not real) existence of a neutrino species with a mass of 17 keV/c^2 (about 17,000 times larger than the current upper limit on the masses of the three Standard

Model neutrinos). This one took several years to resolve and featured several apparent confirmations of the spurious signal, not all by members of the original team; interested readers should consult Franklin's paper for a detailed account. It is mentioned here because its trajectory, although it took much longer (closer to nine years than nine months), was not unlike that of the OPERA result: again a combination of negative results from other experiments and the identification of a previously unrecognised systematic error in the initial experiment finally resolved the controversy.

Incorrect experimental results are a fact of life in science: despite the best efforts of experiment designers and data analysts, unrecognised systematic errors are always a hazard. The OPERA result was not the first incorrect experimental measurement to find its way into the scientific literature (although in fact events moved quickly enough that it was never formally published) and will not be the last. This highlights the importance of replication including—in particle physics—enabling the *possibility* of replication: it is not an accident that the Large Hadron Collider is equipped with two general purpose detectors, ATLAS and CMS, not just one. Good science is self-correcting but the opportunity for self-correction needs to be provided.

Acknowledgments

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Note: this preprint was updated as the saga progressed, and exists on the arXiv site in four versions. Three of these, v1, v2 and v4, are significantly different (v3 has the same text as v4, but they forgot to update the abstract!). All three versions are cited separately because of the very different content.
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