ADVANCES BY USING COMPUTERS AND LAST GENERATION OPTICS DEVICES IN EXPERIMENTS AND DEMONSTRATIONS

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Abstract. In Optics, as well as in other disciplines, use of computers and sophisticated apparatuses is now common, both for collecting and elaborating data and for demonstrations of basic experiments and training of students. Both advantages and disadvantages arise from the use of these complex apparatuses. In general, the advantages are enormous. Here we will consider a number of examples, including a negative one, which received large resonance in the international community in recent years.

Key words: optics, computers, advanced optics, microscopy, adaptive optics

1. INTRODUCTION

In many scientific disciplines, use of sophisticated apparatuses driven by computers is now common for measurements, for collecting and elaborating data, for demonstrations of basic experiments and for student training.

In Optics Laboratories great progress was made by utilizing computers and advanced optics equipments. Recent advances in the availability of equipments allowing production and measurement of micro and nano objects, as well as the development of laser pulses of decreasing lengths, from picoseconds to femtoseconds and more recently to attoseconds (10^{-18}s), opened new research fields, for instance in living materials.

Advantages and disadvantages arise from the use of these complex apparatuses. In most cases, the advantages are enormous, allowing great advances in research, but sometimes problems can arise. Here I will describe some examples of different research cases. I previously considered training of students at Conferences ETOP-2013 and ETOP-2015.

2. GENERAL CONSIDERATIONS BASED ON EXPERIENCE

My experience spans over many decades, from the beginning of the computer use up to now. Initially, there were big advantages of using computers. They mainly were on using computers for numerical evaluation of theoretical formulas.

Computer also became important for collecting data and their elaboration; at first, we needed to develop procedures, programs and subroutines to utilize statistics formulas by ourselves. At that time, it was also possible to check the programs step by step, by producing initial samples by utilizing subsets of data.

Subsequently, larger computers and subroutines developed in the literature became available, so that it was possible to utilize more data, and to broaden the research field. However, although the work became easier, it was less controllable. I will go back on this point subsequently.

Use of personal computers connected with "on purpose measuring elements" allowed one to build simple apparatuses to make laboratory measurements. For instance, by using photomultipliers and a small PC we made measurements of intensity fluctuations of a laser beam after propagation in the atmosphere with accuracy and rate impossible with previous apparatuses.

Subsequently, by using lateral position sensors connected to a personal computer we set up an apparatus for simultaneous measurements of fluctuating positions and intensities of up to four laser beams. We used this apparatus to test the stability of lasers and, mostly, to make propagation measurements in the turbulent atmosphere and in laboratory produced turbulence. The set up was very simple and compact and also easy to be transported and to be moved in different outside locations, for instance to increase the path during measurement sessions. Programs on purpose were developed by us allowing us to obtain accurate results in real time or to collect large amounts of data for subsequent elaborations.

To have an idea of the power of the system, a photo of the screen of the computer (a simple PC) is reported in Fig 1, showing the scheme and the start of the measurement operation.

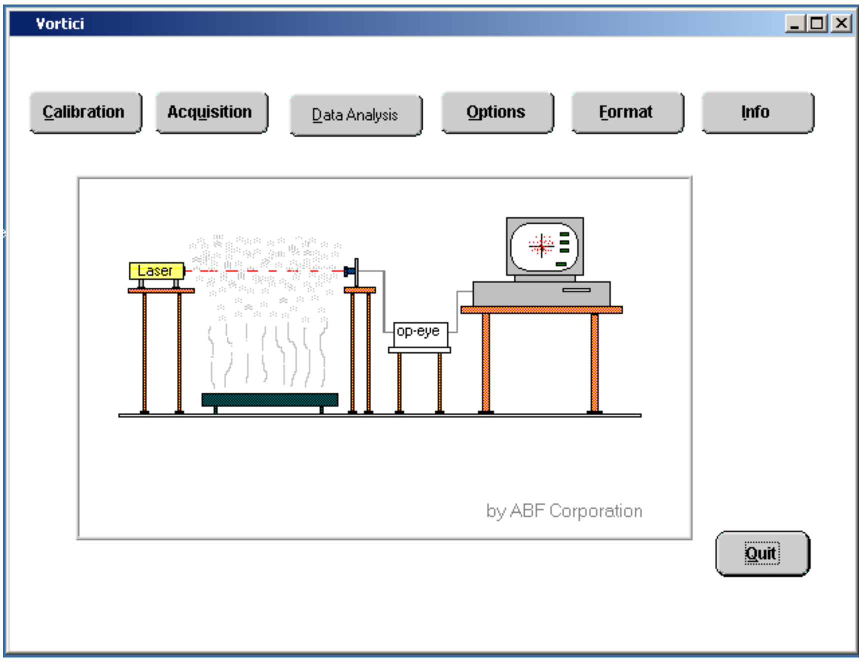

Fig. 1 - Scheme of the measurement set up and programs

The six keys in the upper row show the different operations available. The first key starts the initial program called Calibration, which allows one to center each incoming laser beam on the corresponding sensor and also to obtain averages and positions and intensities in short real time. The Acquisition key starts the measurements, where acquisition rate and duration of the measurement can be chosen. The subsequent data analysis is run by the third key; this program, as well as all others, allows a number of different choices. For instance, one can make measurements with only one beam or more up to the total of four.

This system gave us great flexibility, for instance for developing laser methods to measure the characteristic parameters of the atmospheric turbulence, and their statistics. In 2005, in experiments [1, 2] on lateral fluctuations of wandering of thin laser beams, we were able to measure position fluctuations of the order of fraction of mm allowing measurements of lateral gradient of the atmospheric refractive index of $2\ 10^{-9}$ mm^{-1} that is nano-values per millimeter of the refractive index gradient. Description of the results of this research was already presented at ROMOPTO 2010 [3], a complete description of the apparatus and use for training students is reported in the Proceedings of ETOP 2007 [4].

Utilization of optics advanced sensors and computers allowed us to advance much in our research and to make measurements otherwise impossible.

3. ADVANCES IN OPTICS AND MICROSCOPY

The invention and use of more and more advanced optics techniques for production and measurement of micro and nano objects, as well as the development of laser pulses of decreasing lengths, from picoseconds to femtoseconds and more recently to attoseconds (10^{-18} s), have opened new research in many fields, for instance in the microscopy of atoms as well as of living materials

During ROMOPTO 2015, we listened to a plenary paper by Stefan Hell, the author of the "resolution revolution" in optical microscopy.

On this subject, I would like to start with some personal memories, having followed the development of the fluorescence microscopy since the beginning. In 2000 Stefan W. Hell received the ICO Prize, the award of the International Commission for Optics devoted to young outstanding researchers "*in recognition of his innovative work on increasing resolution in far field optical microscopy*". As a member of the ICO Prize Committee, I was very impressed by his inventive and continuous work on improving the resolution of microscope. The report, written in the ICO Newsletter [5] announcing the award, ended with this sentence: "Stefan Hell's vision is to devise and realize far-field optical microscopes that will ultimately enable the *non-invasive* observation of the mechanisms of life at the tens of nanometer scale". His work gave rise to subsequent collaborations and developments, and, in 2014, to the Nobel Award in Chemistry to Eric Betzig, Stefan W. Hell and William E. Moerner, "for the development of super-resolved fluorescence microscopy"[6]. One can now speak of "nanoscopy".

The invention of the "super-resolved fluorescence microscope" is based on advanced optics and computers but, mostly, on an important "intuition" by Hell taking profit from stimulated emission of light. The well known diffraction resolution limit of Abbe, d, is d = λ/(2n sinα), where λ and the part in parenthesis (2n sinα) denote the wavelength and the numerical aperture of the microscope, respectively. In optics the limit d ~ λ/2 is of about 200 nm; a resolution not enough for molecules. Use of simple fluorescence is important for sensitivity not for resolution.

The idea of Hell was to send the molecules, surrounding a given small region, in a "dark state" that is a "ground state" by stimulated emission. This is called STED (STimulated Emission Depletion- microscopy), which can allow one to resolve single molecules. A clear description of the principle and subsequent developments of the "super-resolved fluorescence microscope" can be found in the Nobel Lecture "Nanoscopy with Focused Light" [6] delivered by Stefan Hell, on the occasion of the Nobel Award delivery, December 8, 2014. In the lecture

From the Nobel Lecture 2014 by Stefan W. Hell

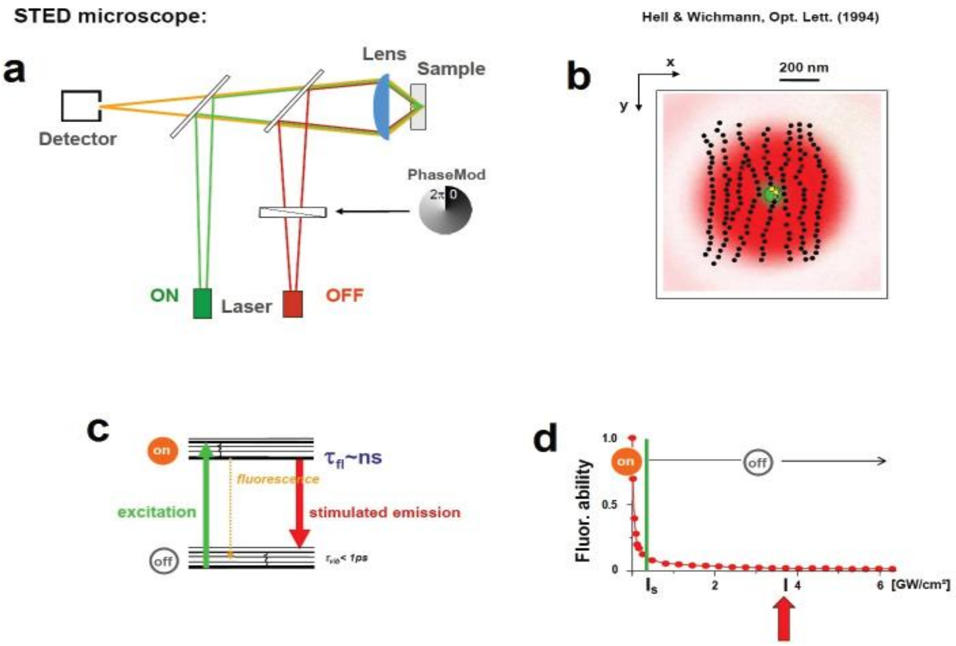

FIGURE 7. STED microscopy. (a) Setup schematic. (b) Region where the molecule can occupy the "on" state (green) and where it has to occupy the "off" state (red). (c) Molecular transitions. (d) For intensities of the STED light (red) equalling or in excess of the threshold intensity I_s, Molecules are effectively switched "off." This is because the STED light will always provide a photon that will stimulate the molecule to instantly assume the ground state, even in the presence of excitation light (green). Thus, the presence of STED light with intensity greater than I_s switches the ability of the molecules to fluoresce off.

Fig. 2 - Scheme of the principles of **S**timulated **E**mission **D**epletion- microscopy, STED

applications in different fields, mostly biology, and insight to future developments are also presented.

In the Fig.2 form Hell's paper, the schemes of part "a" and "b" allow us to understand the principle. An excitation beam, ON, and a depletion beam, OFF, impinge on the sample. The OFF beam is shaped in such a way that the field is vanishingly low in a small central part; this is obtained by a phase plate along the path of the OFF beam, giving rise to a singularity in the center. In "b" the dots are row of molecules in the diffraction pattern of the microscope; the pattern is filled by the stimulated emission of the molecules apart from the small central portion. The small internal green spot is the emission from the molecules in the central region, which are resolved from all others. Part "c" explains the mechanism of the emission from the molecules and part "d" gives information on the energy I_s needed to activate the stimulated emission.

As a result, the resolution can reach values of few tens of nanometer and single molecules can be resolved. This is the reason why one now speaks of nanoscopy.

4. LARGE APPARATUSES PROBLEMS

Before going further, a break is included to go back to the point already noted from my past experience about the result controllability.

Large advanced apparatuses are difficult to be controlled. Small errors/malfunctioning, difficult to find, can give rise to wrong results. A famous example, in 2011, was the "OPERA" apparatus problem. I mean the measurement of the neutrino velocity, which seemed larger than the light velocity, a result that caused great sensation and comments, not only in the scientific community, but also in popular magazines.

From measurements of the neutrino time of flight on the path from CERN in Genève to LNGS (Laboratori Nazionali del Gran Sasso, Italy), the scientists of the OPERA collaboration deduced that the neutrino velocity was higher than light velocity. In reality, the value found was slightly different from light velocity, and higher that the possible random error, however it was higher. The scientists presented it openly to the scientific community asking for confirmation. There was the need of subsequent measurements by other groups, e.g. ICARUS, which questioned the results on the velocity. Great effort, lasting several months, was needed to understand the reasons of the OPERA findings. At the end, checks of the OPERA experimental apparatus showed evidence for equipment malfunctioning, due to systematic errors. The main source of the erroneous measurement was found to be in the calibration of the connection of an optical fibre to a computer [7]. Some people complained about the error of the scientists and the two scientists responsible for the research resigned. Shortly they found new prestigious positions.

On the matter I much appreciated the comments of the Editorial of Nature [8] entitled **"No shame",** published in the issue of 19 April 2012. I copy here some portions of the editorial, which remembers the way scientists proceed and the way research is done and results shared.

“...... Late last month, following a vote of no-confidence in their leadership, OPERA's two top scientists resigned. Yet both men, along with the rest of the collaboration, can hold their heads high.

....

Contrary to everything taught in modern physics, the neutrinos seemed to be arriving 60 nanoseconds faster than light speed. A small sub-team of researchers responsible for the measurement spent months systematically checking OPERA's detector and could find no reason for the discrepancy.

When the smaller group shared their result with the full OPERA collaboration, it leaked to the Italian press. Faced with growing interest, OPERA's leaders — Antonio Ereditato and Dario Auterio, the duo who have now resigned — decided to go public with a seminar.

Scientists both inside OPERA and out have since fretted about what such a high-profile misstep might mean for funding, reputation and the public's perception of science. In fact, OPERA's handling of the incident, at least publicly, was a model for how scientists should behave. Ereditato and Auterio acted responsibly when speaking publicly by sticking close to their data and avoiding over-interpretation. They shared their work with their competitors, and did their best to quickly address outside criticism.

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Media coverage generally sided with the researchers for admitting they were wrong, and no one has called for funding to be cut.

Science can fall victim to human frailties. ....

The OPERA collaboration is not exempt from the human condition. Some collaborators believe that publication was rushed out of a desire to beat the competition. But OPERA nevertheless conducted itself openly and properly.

The no-confidence vote and resignations are a matter for the collaboration's internal processes, and have no bearing on the quality of the collaboration's science. But beyond OPERA itself, scientists should celebrate the way in which the results were disseminated and the findings ultimately refuted. The process was open and deliberate, and it led to the correct scientific result. In an era in which politics, business and celebrity fixate on spin, control and staying 'on message', OPERA's rise and fall make science stand apart. The message here is that scientists are not afraid to question the big ideas. They are not afraid to open themselves to public scrutiny. And they should not be afraid to be wrong.”

5. ATMOSPHERE AND ADAPTIVE OPTICS

Use of the most advanced optics techniques and building of large apparatuses using computers have given and are still giving rise to impressive results in Astronomy and Astrophysics in general.

As is well known, we see stars twinkling due to the effect of the atmospheric turbulence. The continuous air movement spoils the wave front of the radiation from the stars and, as a consequence, it gives rise to reduction of resolution. Laser light also twinkles when a laser beam propagates through the atmosphere.

To overcome this effect, the Astronomical Observatories were, and still are, built in high level locations, where the turbulence is lower. They are also free from light pollution. Methods to correct images deteriorated by turbulence were also developed, such as post-detection correction.

A more recent approach is now the "Real Time Compensation". A way of compensating in real time the wave front deterioration was proposed by Horace W. Babcock [9] long ago, in 1953. Many years later, computers and advanced optics gave rise to optical systems, called Adaptive Optics Systems, and in general Adaptive Optics. Adaptive Optics is now a technique useful in many fields such as eye testing. Here we are interested in Astronomy and Astrophysics applications.

In Figure 3, the scheme is represented of an Adaptive Optics set up for an Astronomical Telescope, which is also useful for a general description. The beam from the telescope, whose vawefront is deteriorated by turbulence, is sent to a deformable mirror and reflected to a beam splitter. The imaging system behind the splitter gives rise to a deteriorated image. The reflected part from the splitter is sent to a wavefront measuring system. The system sends signals to the deformable mirror so that the mirror assumes a shape conjugate, "opposite", to that of the wavefront. If the procedure is "fast enough", the wavefront of the beam impinging now on the mirror did not change in the mean time, the reflected beam is corrected and the imaging system gives rise to a corrected image.

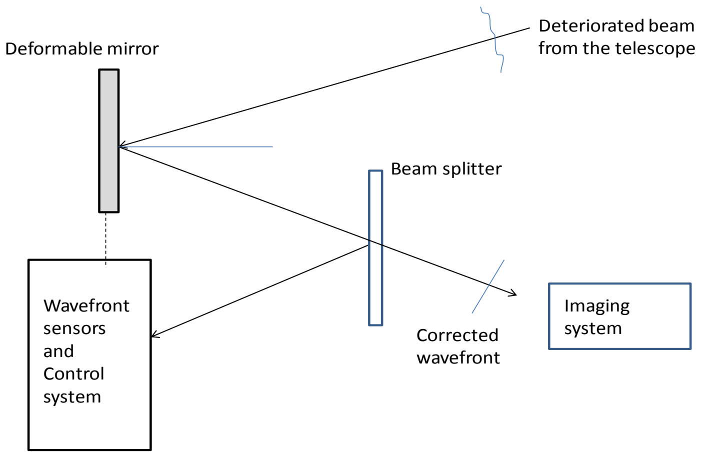

Fig. 2 - Scheme of adaptive optics procedure

There are a number of important steps needed to produce the adaptive optics correction. First, measurement of the wavefront deterioration is made. Then production of the signals to be applied to the deformable mirror and, at last, application of the signals to the mirror and production of the correct image are made.

There are stringent requirements and, mostly, everything should be in real time. The above "fast enough" means that the entire operation must take place in few milliseconds, being the millisecond the characteristic time of the deterioration due to the atmospheric turbulence.

Adaptive correction in optics requires involvement of advanced measuring optical procedures and devices and elaborated mathematical methods with computers.

5.1 Short Notes on Adaptive Correction

To be precise, the concept of "adaptive correction" appeared the first time for radiofrequency and microwave applications. In 1964, in a special issue of the Journal IEEE Trans. on Antennas and Propagation, AP-12, several papers appeared on the matter. At these frequencies, wavefront deterioration was measured by heterodynes techniques. Subsequently, the feasibility in the infrared was also shown.

Due to the enormous development and applications of adaptive optics in many fields, the initial rise of the adaptive optics technique is now completely forgotten. I have a precious document, on the evolution up to 1978, in a Degree Thesis [10] of one of my students in the University of Firenze, in Italian**.**

If I remember correctly, I firstly saw the practical realizations of adaptive optics at the 1974 OSA Topical Meeting on Optical Propagation through Turbulence, in Boulder CO, USA. A scientist from the Hughes Research Laboratories, Malibu, Ca, presented a movie showing the time behavior of the image of a laser beam after horizontal propagation, both with and without correction, Applied Optics [11]. I was very impressed because, working with propagation of laser beams in the atmosphere, I immediately realized the power of the adaptive optics techniques for atmospheric applications.

5.2 Adaptive Optics with Telescopes

Adaptive Optics is now playing a major role in many fields including industry and medical optics. Here, on account of my experience with atmospheric turbulence, I would like to consider some of the great research results obtained in astronomy and, mostly, astrophysics and, in general, in space research.

Basic steps in space research were also space telescopes, starting from Hubble, which, after 25 years, was still sending space images. Many of us still remember the initial problems with the mirror shape and the subsequent correction on site, a great result. Famous photos of Nebulae or dying stars (one on 27 July, about one month ago) are from Hubble. Another space telescope is Kepler.
Space telescopes "up to now" do not have adaptive optics.

Great development in astronomy was made by using ground based telescopes equipped with adaptive optics. Now, many Large Telescopes using Adaptive Optics, AO, are in use. They measure and correct in real time both the effects of the atmospheric turbulence and of the near instrument turbulence and in some cases the mirrors shape. We do not enter the details of the measurements and the way the wavefronts are corrected. Worth is mentioning the "production" and use of laser stars, needed as references for the adaptive systems.

A first example of results, from ground based adaptive optics systems, were images of Urano, its rings and moon Miranda, obtained by the Keck Telescope, Haway, 9 July 2004. On 10 September of the same year, the Very Large Telescope (VLT) of the European Southern Observatory (ESO) in Paranal, showed an "Intriguing Object near Young Brown Dwarf" (eso-0428 Science Release), which was argued could be the "first observations of a exoplanet".

Ground based telescopes equipped with adaptive optics produced many spectacular images of Nebulae and Galaxies and went down inside very far objects, up to hundreds of million light years. Many images can be seen in the sites of the different astronomical observatories or institutions involved in the research, such as ESO, Gemini, Keck, just to mention some.

Research for exoplanets, which are planets moving around a star (a kind of solar system), is based on the use of both Space Telescopes, in particular Keplero, and ground based Large Telescopes. As space telescopes do not have adaptive optics, they only measure intensity. They are able to reveal the presence of one or more "objects", can follow the intensity evolution, therefore finding exoplanets. Ground based adaptive optics systems can take images of the found objects. More than two thousands exoplanets were found, and recently much attention was paid to the "potentially habitable" ones, called "hearth like planets”.

The last success in searching for exoplanets is of the beginning of the present year, 2017, when "near system" of a star with seven exoplanets, some of which potentially "hearth like", was found.

6. CONCLUSION

In this paper, a short insight was given into some fields where use of advanced optics and computers produced great advances. In particular, I considered the advances in the infinitely small, microscopy, and infinitely large, astronomy, astrophysics and in general "space". Very large adaptive optics astronomical systems have reached galaxies several hundred million light-years from earth, have shown formation of stars and star dying and are still progressing. Search on exoplanets is in great developments, especially for "hearth like" exoplanets.

There are many other fields, not included here, where advanced optics and computers are playing a basic role. I would like to mention here biology, medicine and industry where enormous progresses were made and are still going on.

As a last point I would also like to highlight the research results reached on attosecond laser [12] that are opening the new fields of research "attophysics" and of course also "attoptics".

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