Beyond the sixth place of decimals :From Michelson to Large Ring Lasers

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It is never safe to affirm that the future of physical science has no marvels in store which may be even more astonishing than those of the past; but it seems probable that most of the grand underlying principles have now been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice ... An eminent physicist has remarked that the future truths of physical science are to be looked for in the sixth place of decimals. (A. A. Michelson University of Chicago Quarterly Calendar 10 (August 1894): 15)

Abstract. The development of large ring lasers introduces new levels of accuracy many orders of magnitude beyond the *sixth place of decimals.* We sketch some of these developments from the original University of Canterbury CI ring laser ($\sim 1m^2$) through to its successors, the NZ/German CII, the German Grosse Ring ($16m^2$), the NZ/German/US UltraG Ring ($\sim 370m^2$) and look to the future of much larger rings. We emphasize the extensive international collaboration involved in their production, current and future applications and the close parallelism between Michelson's evolution of the interferometer and that of large ring lasers. A proposal to mark the Centennial of the celebrated 1925 Michelson-Gale Clearing large interferometer experiment with the completion of a $10000m^2$ ring laser is mooted.

1. Introduction

The development of large photonic ring lasers introduces new levels of accuracy many orders of magnitude beyond the sixth place of decimals. We sketch some of these developments from the original University of Canterbury CI ring laser and through its successors, the NZ/German CII, the German Grosse Ring (G), the NZ/German/US UltraG Ring ($370m^2$) and look to the future of much larger rings. We emphasize the extensive international collaboration involved in their production, current and future applications and the close parallelism between Michelson's evolution of the

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interferometer and that of large ring lasers. A proposal to mark the Centennial of the celebrated 1925 Michelson-Gale Clearing large interferometer experiment with the completion of a $10000m^2$ ring laser is mooted.

2. Michelson and Table Top Experiments

Michelson was born in the small Polish town of Strzelno, not very far from our conference centre. His birth is marked in Strzelno by a plaque.

**In this town on
19 December 1852
Albert Abraham
Michelson was born.
Professor of the University
of Chicago.
Nobel Prize Laureate.
With his famous experiments
on the speed of light he
started a new era in the
development of physics.
This plaque was funded by
the Polish Society of Physics
to commemorate the great
physicist.**

Michelson received the Nobel prize in Physics in 1907. We read that:-

- "The Royal Academy of Sciences has decided to award this year's Nobel Prize for Physics to Professor Albert A. Michelson of Chicago, for his optical precision instruments and the research which he has carried out with their help in the Fields of precision metrology and spectroscopy".

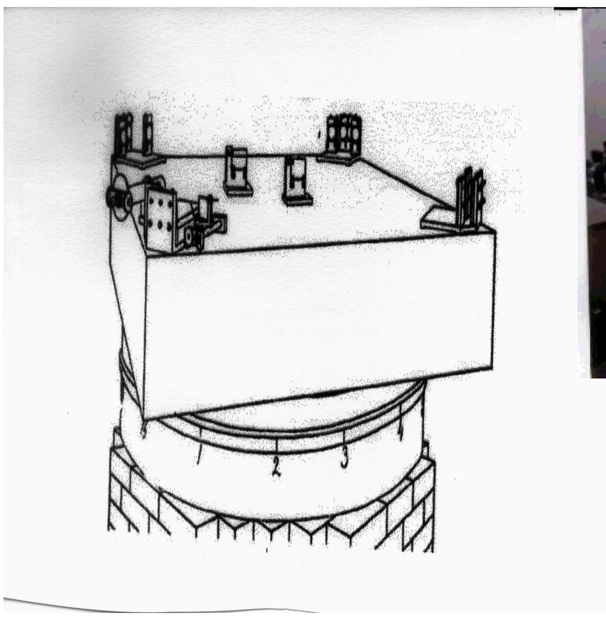
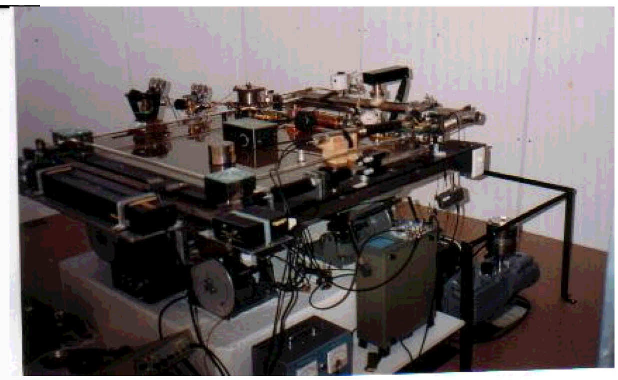
and note there is no mention of the Michelson-Morley experiment neither in the citation nor in Michelson's Nobel Lecture. Michelson has always been associated with precision measurement and interferometry. Something of the special character of Michelson comes out in Edison's nomination to the prestigious US National Academy of Sciences

- Thomas Edison was invited to exhibit his phonograph at the April 1878 meeting of the US National Academy of Sciences. He was not considered for membership until the 1920's.
- Edison was nominated by the engineering section, and at the 1926 annual meeting Robert A Millikan rose to endorse the nomination. But when Millikan said (he thought rhetorically), "I am sure that no physicist would wish to oppose Mr.

Edison's nomination." A. A. Michelson, then thought to be the greatest physicist in the world, rose and said, "I am that physicist."

- Edison, with his more than 1000 patents, was rejected that year but was elected to membership in 1927, four years before his death.

The much celebrated Michelson-Morley experiment of 1897 was very much a table top experiment and just over a 100years later we, at the University of Canterbury performed another table top experiment involving the successful operation of the CI ring laser.

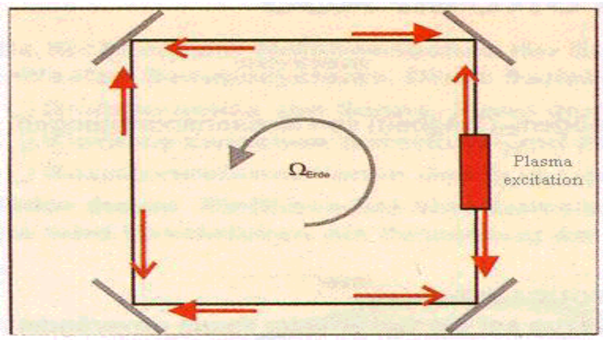



(1a)Michelson-Morley experiment (1887) (1b)The CI Ring Laser (1989)

3. The Sagnac effect and Ring Lasers

Small ring laser gyros have been used in aircraft and ships as an essential navigational tool for many years and are the basis of a multi-billion dollar defense industry. As a navigational tool they have the advantage over the traditional magnetic compass of vastly greater accuracy and freedom from the effects of magnetic fields and working efficiently in polar regions.

The Sagnac effect is basic to the construction and operation of a ring laser. A general review on the Sagnac effect and earth-rotated interferometers has been given elsewhere[1]. The principles of a ring gyroscope, with the Sagnac formula for the beat frequency between the counter propagating laser beams is given in the following schematic a basic ring laser. A measurement of the Sagnac beat frequency leads directly to a measure of the angular rate of rotation of the ring.



Schematic of a Ring Laser
Super-reflecting corner mirrors (> 99.9998%)
He-Ne gas mixture lasing at 474THz (638nm)
Sagnac frequency

$$\delta f = \frac{4(\Omega \cdot A)}{\lambda P}$$

Ω = **angular rate of rotation of the ring.**
A = **Area of ring,** P =**Perimeter of ring.**
λ = **wavelength of laser light.**

4. In the beginning: The C-I Ring Laser

In 1985 Stedman[2] published a review of ring laser gyros and suggested a number of interesting research possibilities that would follow if one could construct a ring laser much larger than aircraft gyros. Hans Bilger, (Oklahoma State University at Stillwater) who had extensive experience in ring laser technology, read the review and suggested that a collaborative effort to construct a $\sim 1m^2$ ring laser be undertaken at the University of Canterbury. This was at a time when the dictum was that such a large ring would be too large to be stable. Initial design work was carried out by Bilger and Stedman with the practical construction being largely carried out by two exceptionally talented technicians, Morrie Poulton and Clive Rowe, aided by a PhD student, Li Ziyuan, from China. This device, named C-I, (after University of Canterbury-I) was built, and initially operated, on the eighth floor of the Physics Building. Its operation proved in principle that it was indeed possible to scale up ring lasers and to reach unprecedented levels of precision. However, like the early experience of Michelson, it was immediately apparent that a more stable environment was essential. Fortuitously a large concrete lined cavern, some 30m underground, had been excavated in the nearby Cashmere hills as a potential WWII military bunker and abandoned with the conclusion of the war. C-I was installed in the cavern, the first of several large ring lasers placed there. C-I was able to measure frequency splittings down to microhertz level which in terms of the optical frequency of the laser was 1 part in 5×10^{20}.

5. Construction of C-II

C-I was to serve as a valuable learning tool and as the prototype for subsequent developments. Hans Bilger had suggested, as the next stage in the development of large ring lasers, the construction of a $1m^2$ ring laser within a single slab of the low expansion ceramic 'Zerodur'. This was the beginning of C-II the successor to C-I. At that time the collaboration was extended to include the German Federal Agency for Cartography and Geodesy and the FESG of the Technical University of Munich. They were operating the geodetic observatory at Wettzell in Bavaria and had a special interest in precision measurement of the earth rotation. The instrument was built by Carl Zeiss, Oberkochen and installed in the Cashmere Cavern in January 1997. The Zerodur slab weighed 0.65 tonne and is dimensionally stable to 1 part in 10 million per degree Celsius. The corners are accurate to 10 arc seconds and the four corner super mirrors have a reflectance of 99.99988%. The decision to have Zeiss construct C-II was consistent with Einstein's words of 1925 in correspondence with Dr Anschútz whose firm built gyro compasses in Kiel

"*...As accuracies of* $10^{-4}mm$ *are required, the difficulties of manufacture are so great that only Zeiss is currently able to achieve this. Therefore, every gyroscope should be sent to Zeiss for surface grinding*" (A. Einstein, 1925).

During the development of C-II Ulrich Schreiber, from Wettzell, became a key member of the German collaboration and continues to be to this day. One of the early observations from C-I had been the measurement of the rotational component of seismic waves produced by an earthquake originating in Los Angeles. This was, for seismologists, entirely new data on earthquakes and the start of active collaboration with New Zealand seismologists and earthquake engineers[3,4]. The possibilities of exploiting interferometers in geophysical problems had not escaped Michelson who noted[5]

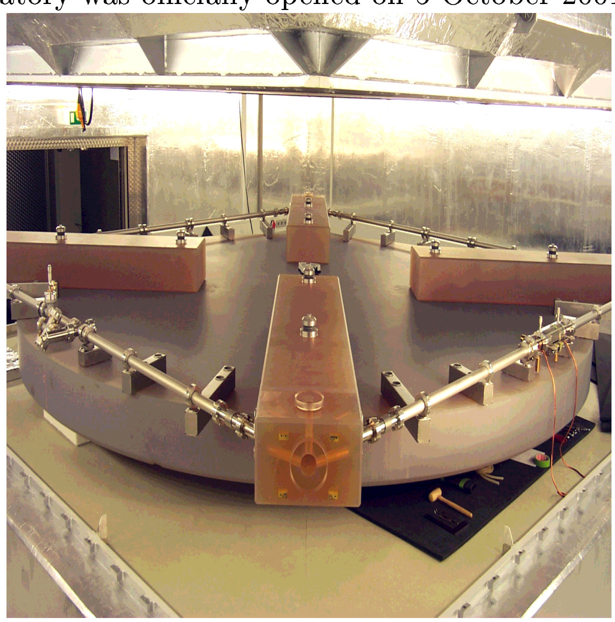
" *Occasionally ...earthquakes would cause the fringes to disappear for from ten minutes to half an hour. Once the effects of an earthquake were evident for about six hours. During three hours of this time the fringes were completely obliterated.*"

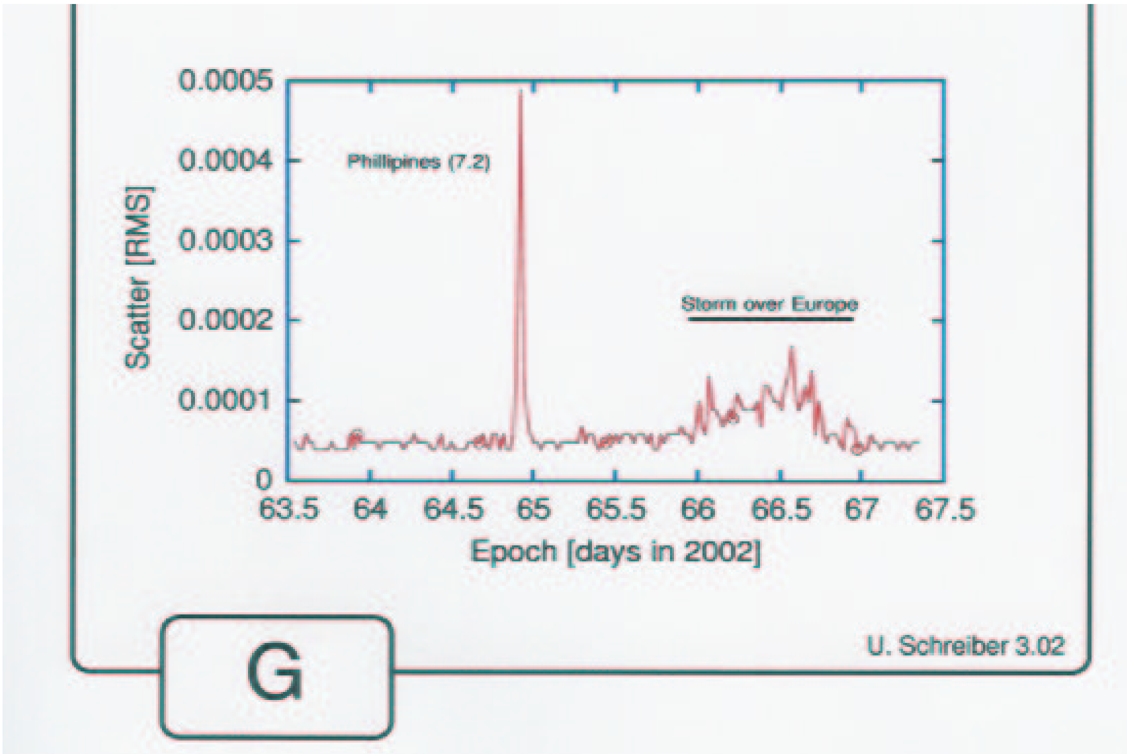
Not surprisingly C-II was a vastly more stable and accurate ring than its predecessor C-I. It had a Quality Factor of 6×10^{11}, a Finesse of 9.4×10^4 for an exit beam power of $2nW$. An Angular Rotational sensitivity of $4 \times 10^{-9} rad/s/\sqrt{Hz}$ and a Sagnac frequency of $79.4Hz$.

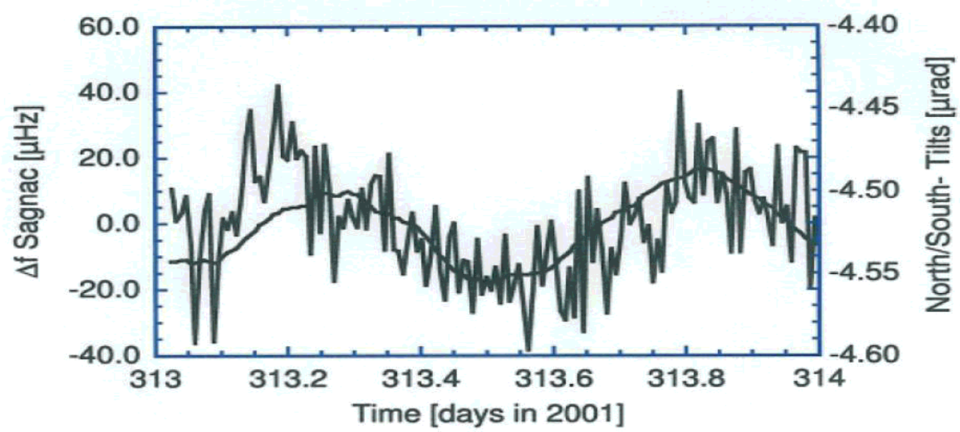
6. The Grosse Ring (G)

The success of the C-II ring demonstrated the feasibility of constructing large ring lasers that could ultimately achieve the ambitions of the Geodetic Fundamentalstation in Wettzell, Kötzting, Bavaria, Germany to be able to measure fluctuations in the earth's rotation. This led to the construction of the Grosse Ring (G), a $4 \times 4m$ ring. This drew on the experience gained in the construction of C-I and C-II. A prototype ring, dubbed GO, with area of approximately 12 square metres and mounted vertically was built at Cashmere, in 1997. This machine was able to reach 10 parts per million precision for several hours and showed in principle the feasibility of constructing the Grosse Ring. The construction of G was commissioned jointly by the Bundesamt für Kartographie and Geodäsie (BKG) Frankfurt/Main and the Forschungseinrichtung Satellitengeodäsie (FESG) with its principal goal of observing short term fluctuations in the earth's rotation.

The base of G was made from a 20tonne 4.25m diameter disk of Zerodur cast by Schott Glas, Mainz in 1992 as a telescope mirror blank. The raw disk was cut into two halves and the half for G, now of thickness 25cm, was heat treated to reduce the expansion of the block to 60 nanometres per degree Kelvin. Again the task of construction of G was assigned to Zeiss who completed its installation in a special purpose built underground laboratory at the Wettzell geodetic observatory. The laboratory was officially opened on 5 October 2001. The final G appears below.







It was not long before G was exhibiting tantalizing new data of geophysical interest. Above we show just four days of data of remarkable resolution. The rotational signal from a 7.2 Richter scale earthquake in the Philippines is clearly seen as an increase in the r.m.s. scatter of the Sagnac frequency measurements as are small seismic disturbances produced by storms over Europe.

Moreover, evidence is found for a signal at the period of 12.42 h corresponding to half a lunar day. This signal is generated by small orientation variations of the ring laser of about 80nrad peak to peak due to body tides. The lower diagram of the superimposed graphs of the tilt signal and the Sagnac frequency measurements shows an excellent correspondence. Similar tilt signatures appear also in the ring lasers in Christchurch with larger amplitudes because the earth tides are enhanced by ocean loading effects on Banks Peninsula. This earth tide signal is the first geophysical signal that became visible at the level of 2×10^{-8}, the 8th digit of the measurement quantity and we expect to see more as the stability of our ring lasers improves. These results would undoubtedly have excited Michelson[6] who had, in 1913, set up an interferometric experiment at Yerkes Observatory at Williams Bay, Wisconsin to measure the rigidity of the earth and to detect earth tides.

7. Present and Future Ring Lasers

Professor Bob Dunn at Hendrix College in Conway, Arkansas was able to successfully demonstrate a ring laser with a perimeter of $40m$ acting as a gyro. Working with him the enlarged New Zealand-German-US collaboration has successfully assembled in the Cashmere Cavern a simple ring laser dubbed Ultra-G, with an area of 370 square metres - half the area of the cavern. Although less stable than G, Ultra-G is expected to be more sensitive, and an excellent detector for seismic rotations. The ring lasers so far constructed have gone well beyond the pessimistic predictions of the 1980's. Much has been learnt and one has the feeling that the future of large ring lasers has barely begun. Certainly the limits of such devices are by no means reached. In the near future one can expect Ultra-G to be extended to about twice its present size. Perhaps for the Centenary in 2025 of the gargantuan Michelson-Gale 1925 large interferometer experiment could be celebrated with the completion of a $10000m^2$ ring laser.

8. Concluding Remarks

We have noted the parallelism between Michelson's original table top interferometric experiments leading to its culmination in the large Clearing experiment and the development of photonic ring lasers of ever increasing area. At each step new possibilities have arisen, mostly unseen at their beginning. Major obstacles have been often seen but have been systematically overcome making it fitting to end with a remark from Michelson himself.

- *"I have tackled problems thought impossible, or at least very difficult, and, curiously, I have usually found the solution to lie in something relatively simple, and rather obvious. Indeed, some of my colleagues say I never attempt anything unless it is so simple that everybody else has overlooked it!"* American Magazine **101,** January 1926

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