Geophysical Research at the Norman Lockyer Observatory: Origins and History

Notes and Recollections

Romney B Duffey, 2023

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PhD student from 1963-67 at Exeter University, Devon, England

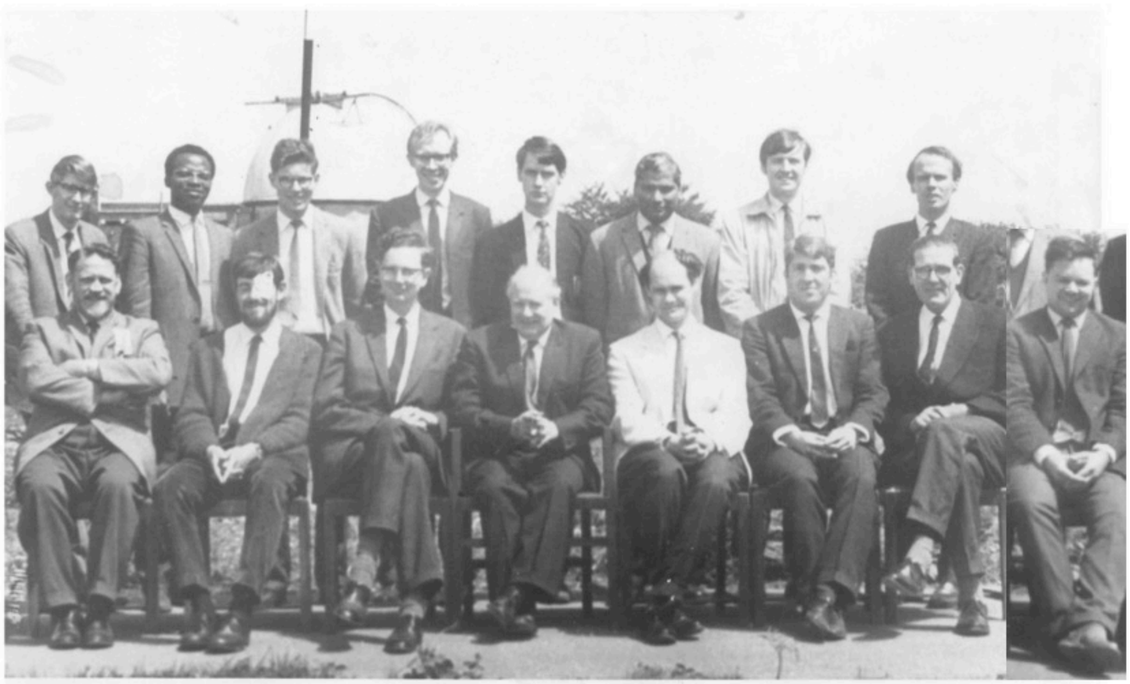

Figure 1

The only known photograph of the Exeter University geophysics staff and post-graduate students taken at the NLO, Sidmouth, Devon in 1965

Front row (seated L-R): R Duncan, Unknown, A W Nicholl, K Weekes, D M Schlapp, N J W Webber, A J Denner, (inset) R W Smith

Rear (standing L-R): C.Osgood, S J A Addy, Myles, R B Duffey, Unknown, H N Jha, G H Davey, A J Burley

The Astronomical Origins of the NLO

The Hill Observatory was formed and built circa 1913- 1920 by Sir Norman Lockyer, the founder and first Editor of Nature, co-discoverer of the Helium lines in the Sun, and of the astrological significance of the Great Pyramid and other temples in Egypt. The site then also included a 'cottage' for overnight use, and workshops. Unfortunately, the original c1920 grand plan to extend the astronomical telescopes by installing a 30 inch mirror telescope[1]

[1] The silver-plated spade used by Prince Arthur to cut the first sod at the site for the new telescope was still on display at the NLO in the 1960's,

(which would have been the largest at the time) had been overtaken by larger 100-inch Mount Wilson reflectors and others, and the whole site had not been updated. The full astronomical history has been well recounted in A.R. Hutchings 1982 article in J. Brit. Astron. Soc., 93(1), which also documents the ultimate serious financial decline and transfer of the NLO to the University of Exeter. But that article has no significant mention of the subsequent geophysical program, simply stating "This and other work has been published elsewhere" but does not indicate where. These notes try to correct that omission and also provide an inside perspective on the geophysical research activities and important results obtained at the NLO from 1960-1982. This background explains how and why Dr Kenneth Weekes initiated the radar ionosonde, satellite signal propagation and magnetospheric work at the NLO.

Geophysical Program Origins: Cavendish and Weekes

The Cavendish Laboratory, Cambridge, history is well known, and had a prestigious staff, with many Nobel Prize winners. The relevant period is covered in Malcolm Longair's magnificent history ("Maxwell's Enduring Legacy") and in K G Budden's UK Royal Society biography. Budden (1915-2005) who was a major ionospheric wave propagation theorist, and much later was my PhD external examiner – some more on that below.

Dr Kenneth Weekes was an ionospheric and atmospheric/radio wave propagation theorist, received his BA in November 1933, and remained at the original Cavendish Laboratory, Cambridge. Weekes worked there as a graduate student with the famous Edward Appleton before WW2, discovering the lunar tides in the E-layer of the ionosphere, which was published in 1939 (see also Special Collections, Coll-37, CSAC 82/6/81, C.182-C.191 Lunar Tides, Papers of Edward Victor Appleton MS.2300, University of Edinburgh)[2]. Being the world's premier atomic physics centre, Weekes also worked alongside many famous scientists and Nobel Prize winners in the heydays of British physics.

Appleton was Professor and Director from 1934-1939, and pursued independent ionospheric work, being awarded a Nobel Prize for the discovery of the "Appleton Layer" in the ionosphere. In a lesser known but key role, in 1939 at the advent of WW2 he became the head the prestigious Department of Scientific and Industrial Research (DSIR) charged with developing wartime research. In this capacity, he

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but apparently he did not provide the hoped-for funding to actually build it.

[2] Appleton, E. V. and Weekes, K., 1939, 'On Lunar tides in the upper atmosphere', Proc. Roy. Soc. A171, 171-187 is the classic paper

helped put in place UK/US cooperation on secret atom bomb development, then code-named "Tube alloys" and the Manhatten project, travelling to USA in 1943 with the express permission of Winston Churchill who was "glad Appleton was coming".[3] After leaving the DSIR, Appleton later became Chancellor of Edinburgh University

A brilliant theoretician, during WW2 from 1939-1945 Weekes worked on key aircraft guidance systems, radar and ionospheric wave propagation aspects, all part of a vital Allied wartime effort. Along with other Radio Group staff members from Cambridge, Weekes was heavily involved in the major warfare radar developments at the famous Telecommunications Research Establishment (TRE) under J A Ratcliffe. In 1945, Weekes with Budden, Ryle, Findlay, Booker and others returned to join the Cavendish Ionospheric Group headed by Ratcliffe. His research work continued on radio waves and ionospheric propagation, having a Senior Award from the DSIR, and on satellite signal observation.

Having been interrupted by the war, Weekes was awarded a Cambridge PhD in 1949 for his thesis "Some observations of region E of the ionosphere."

His few publications include classic and key papers on ionospheric physics with J A Ratcliffe; and a pioneering paper co-authored with Wilkes, the designer of one of the first computers, EDSAC, referred to in the paper as a "differential analyzer" (see Bibliography).

In Malcolm Longair's comprehensive history of the Cavendish (I visited him as part of this research in June, 2018), Weekes is listed as Assistant Director of Research of the Radio Research Group at the Cavendish in 1950, along with other famous staff, Martin Ryle and K G Budden, all under J A Ratcliffe now as Reader as well as Head of the group. According to Dr Longair, Ratcliffe effectively ran the Cavendish Laboratory research activities, while Bragg was officially the Professor.

In June 1960, Ratcliffe announced that he would be leaving to take up the appointment as Director of the Radio Research Station at Slough. As a result, Martin Ryle became the head of the Radio Group as a whole, and the main focus shifted to radio astronomy. Senior members of the ionosphere group left for posts elsewhere, and Kenneth Weekes went to Exeter University in 1960, appointed as Reader in Geophysics, to help revitalize the NLO.

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[3] Source: Franklin D Roosevelt archives at www.fdrlibrary.marist.edu/_resources/images/atomic/atomic_03.pdf

Weekes appears in the official Cavendish staff photographs in 1938 and 1939, and then from 1947 onwards, shown to me by Dr Longair[4] hanging in the halls of the new Physics Department building at Cambridge (Figures 2 and 3). From being in the back row as a research student, he progressively moved forward as he became a full member of the staff.

Figure 2 The earliest known image of Weekes at the Cavendish as a research student in 1938 (back row fourth from left)

Front row L to R: D W B Lewis N. Feather A C Davies J A Ratcliffe J J Thompson Lord Rutherford F W Aston M E Oliphant J D Cockcroft E I Dee

At the end of WW2 W B Lewis FRS (front row left in 1938) became superintendent of the TRE, Malvern, after Weekes and Ratcliffe's departure. In 1947, Lewis then went to Atomic Energy of Canada Ltd (AECL) at Chalk River and became the "father" of the commercially successful CANDU reactor, being a VP and then also The Principal

[4] Malcom Longair is a distinguished astronomer and astrophysicist, and from 1991 to 2008 was the Jacksonian Professor of Natural Philosophy in the Cavendish Laboratory at the University of Cambridge.

Scientist. In another twist of fate, in 1999 AECL recreated this position for me to occupy, which I did until 2011- without ever realizing our so-close Cavendish connections.

Figure 3 The 1947 post war Cavendish staff, with the ionospheric group (Weekes is second row, first on left, now being a staff member).

The Founding of the NLO geophysical program

The key article is in the New Scientist no 293, for 28 June 1962, under Notes and Comments, p686 that says:

"*A Devon observatory rejuvenated*

A small Devon astronomical observatory is shortly to undergo a radical change in emphasis. After 50 years of routine observations with barely adequate apparatus, the Norman Lockyer Observatory at Salcombe Hill near Sidmouth is to be completely re-equipped with apparatus more suitable to the 20th century. Its main task will be radio investigation of the upper atmosphere and ionosphere.
The changes have come about at the instigation of Exeter University, which takes a substantial interest in the observatory and whose professor of physics, Professor G K T Conn, is its Director. The existing telescopes, of which the largest is a 30-inch refractor, never

yet assembled, will be retained for some visual work, but it has been felt that studying the Earths; electrical environment should yield more of value than the limited astronomical results possible from a observatory of this size.
Much work will be done on the modulations of satellite signals and the deduction of the electrical variations from these results, but it is not proposed to devise satellite experiments as is being done by some British universities under the Anglo-American program. The observatory will confine its function to observation. Dr Kenneth Weekes, Reader in Geophysics at Exeter, will supervise the changeover, and it is hoped that when completed both post-graduate students, and eventually undergraduates will undertake studies at the observatory."

Conn himself was a physicist and was not seen much personally at the NLO itself, always parking his vintage Rolls Royce at the Physics Department in the Washington Singer building. His article in Nature (see Bibliography) shows his dedication to the preservation and to the future of the NLO. He invested heavily to ensure all the improvements indeed happened, and updating and revitalizing the historic site commenced immediately. As Conn stated: "The site is large enough for astrophysical work and for an extensive programme of research and teaching in geophysics, a growing interest of the University's Department of Physics, and of geomagnetism, an interest of the Department of Mathematics." After refurbishing the buildings (the large workshop and the cottage), with 240V power replacing the old DC wiring from batteries, the electronic and mechanical workshops were upgraded by installing vital equipment, and a technician and research students were added. The main road was paved, but the paths to and from the domes remained as tracks surrounded by thorny gorse bushes, huge and colorful rhododendrons, and home to the occasional adder.

Dr Weekes was appointed to the University in 1960, and had many senior technical and professional connections, which also explains how many wartime surplus valves, radar oscillators, phase sensitive amplifiers, recording gear, fluxgate magnetometer (loaned from SRDE, Christchurch), and assorted equipment found their way to kick start these new NLO research activities. Weekes' personal interest in tidal movements in the ionosphere also continued. He supervised many MSc and PhD students, and cooperated with Dr Schlapp and Eric Butcher on ionospheric tides. Dr Nicholl was the electronics expert, and Dr W G V Rosser was also involved in electromagnetic theory and analysis.

The Initial NLO Geophysical Research Program and Projects

The areas of research Weekes developed were focused on:

- Ionospheric probing using a pulsed EM Oscillator at a few MHz with horizontal aerials, to examine E-layer lunar variations. Continuing Weekes earlier discoveries, this ionosonde study used a system that was based on an ex- WW2 radar pulsed oscillator of high power with gigantic glass valves. I recall Eric Butcher and Richard Whaley working on that system and helping to string ¼ wavelength aerials between poles on the site.

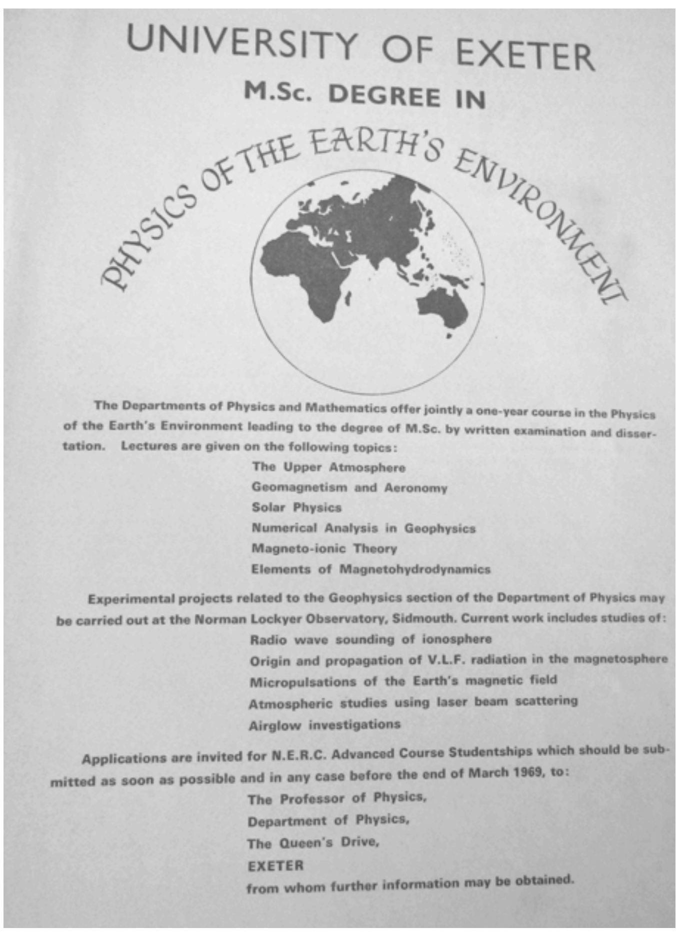
- Upper atmosphere airglow measurements, initially of doubly-ionized oxygen, O_{16}^{++}, vertical density variation using pulsed laser excitation and a photomultiplier detector mounted on the 30" mirror (still at the NLO). We tried hard not to damage the mirror as it could not be replaced, so it was laid on the floor, and is today on display at the NLO. The time variation of the excited intensity was a measure of the ion population and an indicator of auroral activity (more later). Initially started in 1962 by post-doc Harry Llewellyn who then left for a position in Saskatchewan Canada, this became Roger Smith's project and he later mounted a then unique quadruple photometer on the Mond telescope.

- Ionospheric effects on wave propagation of low-level satellite signals. Observations were linked to satellite signal propagation and measurements, since the van Allan radiation belts (of magnetically trapped high energy particles) had just been discovered. State-of-the-art phase-sensitive amplifiers were built to record extremely low-level satellite and radar transmission signals. I did not know much about this work, except Alan Burley told me that launch delays and failures (including US satellites "Anna" and S66) often caused serious problems and uncertainties in reliable data collection. Once again, lunar tidal variations were studied in the near 2.5MHz signals from Rugby, Paris and Prague.

- Geomagnetic fluctuations, micropulsations and hydromagnetic wave propagation in the exosphere and earth, using every type of magnetometer (see Technical Appendices). There was an old fluxgate working in the cottage for relatively slow daily field variations (chart recording at about 1" an hour). This was later used by a student from India, Professor Jha for his thesis and by others. Helium and rubidium vapor magnetometers were another type being developed by Myles, and later used as a gradiometer by Chris Osgood. With complex electronics, this method relied on the vibration of the excited atoms and was extremely sensitive and accurate. I took up the design and building of two induction magnetometers (see the notes at the end) being determined to make the most sensitive measurements ever of quasi-periodic fluctuations of about one part in a billion of the main magnetic field.

The MSc Course and other geophysical and geomagnetic research

The year I started at the NLO an advertisement appeared in the New Scientist No 348, p159, on 18the July 1963, as follows:
"***Postgraduate Course in Physics of the Earth's Environment***
A one –year course to the degree of MSc examination and dissertation will begin in October 1963. The course, which will be provided jointly by the Departments of Mathematics and Physics will include lectures on the Upper Atmosphere, Geomagnetism, Aeronomy, Solar Physics, Magneto Hydrodynamics, and Numerical Analysis in Geophysics. There will be experimental work at the Norman Lockyer Observatory, Sidmouth. The DSIR has accepted this course as suitable for the tenure of its Advanced Course studentships. Applications may be obtained from the registrar…"


UNIVERSITY OF EXETER

M.Sc. DEGREE IN

PHYSICS OF THE EARTH'S ENVIRONMENT

The Departments of Physics and Mathematics offer jointly a one-year course in the Physics of the Earth's Environment leading to the degree of M.Sc. by written examination and dissertation. Lectures are given on the following topics:

The Upper Atmosphere
Geomagnetism and Aeronomy
Solar Physics
Numerical Analysis in Geophysics
Magneto-ionic Theory
Elements of Magnetohydrodynamics

Experimental projects related to the Geophysics section of the Department of Physics may be carried out at the Norman Lockyer Observatory, Sidmouth. Current work includes studies of:

Radio wave sounding of ionosphere
Origin and propagation of V.L.F. radiation in the magnetosphere
Micropulsations of the Earth's magnetic field
Atmospheric studies using laser beam scattering
Airglow investigations

Applications are invited for N.E.R.C. Advanced Course Studentships which should be submitted as soon as possible and in any case before the end of March 1969, to:

The Professor of Physics,
Department of Physics,
The Queen's Drive,
EXETER
from whom further information may be obtained.

Figure 4 The actual MSc course leaflet announcement (Source: EU Special collections NLO Archive)

The courses started the next year, so other students came and went. This was the course that Norman Webber, Chris Osgood, Alan Burley and others joined (see Figure 4). Although I did not have to take the lectures I thought they were too good to miss so attended the whole series and also wrote a review paper on micropulsations and their origins as part of my PhD requirement. The lectures were outstanding, exhaustive and complex, and I recently found my complete and detailed hand-written transcript of them all. They covered then state-of-the-art topics:

Upper Atmosphere and Ionospheric Physics (2 sets) - K. Weekes
Solar Physics- D. M. Schlapp
Geomagnetism and Aeronomy – A T Price
Measurements, Waves and Magneto-ionic theory - A W Nicholl

I had the privilege of actually seeing Weekes write out one of his entire and complex lectures on ionospheric physics completely from memory an hour before giving it. His office was one huge pile of papers, correspondence and notes, and I often rummaged through his mail heap to reclaim the weekly Hartland Magnetic activity indices. He went to another lab desk to write out his notes and I happened to be asking him about some of my new results. On another occasion, I had a theoretical problem on dispersion analysis in ionospheric transmission that I raised with him, and the next day he handed me the full solution written out in his own hand.

The Research and the Students

As my practical project for the final year of my Physics BSc I had worked on building a nuclear magnetic resonance magnetometer. In 1963, I was invited to join the geophysical programme now in its second year as a PhD research student under a Science Research Council grant. There were initially only two post-grads already working at the NLO, and this number also grew as the Master's program began (see Figure 1). Weekes' sole instruction to me was: "There are some rapid micropulsations and I want you to build a magnetometer to take a look at them."

Everyone focused on their own research project but helped others when problems or questions arose. In those days you built *everything* you needed for your equipment and recording yourself from scratch using the machine shop and laboratory facilities in the Long House, near the Cottage. The Cottage contained a kitchen, dining space, bunk bedroom, bathroom, darkroom, and the major geomagnetic equipment and records, while the domes now housed the various electronics and experimental apparatus. The telescopes were fully at our disposal as there was no formal astronomical activity.

Photographs of equipment, and actual records from that time are now very rare, surviving only in some of the theses and my personal collection, as well as the EU and NLO archives, on which these recollections are based. There are no photos from that 1960-1980 time of the interior of the Cottage and the Long House that were filled with multiple equipment builds and test gear, and accumulated piles of electronic components.

The cottage, domes and annexes were also full of cabinets, desks, shelves, displays and files of Lockyer's work and fantastic memorabilia, old photos of every eclipse they had been to, plus old equipment and notebooks. I used some of the ebony parallel rulers for my graphing. Plus the site gem – one of the only two extant complete copies of the journal Nature from the very first issue, that Lockyer had founded (the other set was with the publisher) was in the Mond dome. This complete and impressively bound set is now back at the NLO where it belongs, but in my day it was just there to read and thumb through the pages looking for classic papers.

In what was originally called the Long House, next to the old DC battery building, there was a mechanical workshop for metal bending and drilling for power supplies, lathes for machining and turning. There were open rooms with benches for electronic chassis building, amplifier design, recording methods, and even individual testing of resistors and capacitors to ensure meeting the 1% tolerance values needed (we had heaps of discards). I did not know much about electronics originally, but soon learned, from making your own regulated power supplies from scratch to the challenge of winding about a million turns of wire. I commandeered my own bench to build, assemble and test all my electronics- see pictures in the thesis. The now-unused telescope domes acted as equipment centres for many of the highly sensitive amplifiers and detectors.

We post-graduate students were a loose knit group, all in our early twenties, but bound by a common purpose. We took turns driving the commute from Exeter to the NLO each day in a van, stopping off to buy pasties, sandwiches and the like to carry us through the day. We would usually avoid the steep Salcombe Hill out of Sidmouth, except when we had to go into town for equipment or supplies. The cottage kitchen was our gathering point, and also provided bunks for necessary overnight observation stays, so I made the cottage also the location for the 24-hours-a–day magnetometer recording equipment.

At our disposal for help with major construction issues was Robert Duncan, an ex-Navy technician who later helped me with the task of coil winding after I had designed and proven the process. There was also John Denner, who had been the Attendant there for many years (since 1943) and was an indispensable handyman, helping me to build the concrete blocks for the magnetometers and the fencing around them.

But the main Library was at the University, so I spent much time in the basement stack going through past copies of the Journal of Geophysical Research, Annales de Geophysiques, Reports on Ionospheric and Space Research in japan, Journal of Atmospheric and Terrestrial Physics, Terrestrial Magnetism and Atmospheric Electricity, etc. Since Weekes was the Reader in Geophysics, every Saturday morning in the Washington Singer we all (staff and students) sat down with all the latest copies of the journals and summarized their contents in formal 'read-throughs'. Some of these journals from that time are in bound volumes, which are now somewhere in the NLO library.

Building the Million Turn Induction Magnetometers

The research was a journey of both personal and technical discovery. Some earlier magnetometer designs were helpful to me, but there was no published manual on "How to build an induction magnetometer", and what I now had to do was now find out how and to write one!! That design and the fascinating ULF types I observed formed the basis for my PhD thesis. I commandeered the McLean dome annex as the site for my field pre-amplifier and filter equipment as the closest but farthest point (about 60 meters) from where the coils would be deployed. The telescope[5] was still operable and there for my own private use, so I could – and did - scan the planets and stars any night or weekend I was there.

There was a minimum of direction, and the research was fascinating and open-ended and I was encouraged to follow any discovery unfettered. I found out that induction magnetometers were being designed and deployed by the Lockheed Missiles and Space Corporation under US government contract (main authors Tepley, Wentworth and Amundsen), for detecting the magnetic effects of atmospheric nuclear explosion tests. They had deployed many around the world and found interesting ULF signals that were incidental to their main task! I also found out that because the wavelength of the micropulsations were of order of the earth's radius that ULF waves could be used to communicate underwater world-wide via the oceans.... and that a 1000 mile dipole was already laid off the US East coast. This apparently lead to the UK military having a research contract with the NLO, since they even turned up at the site for a

[5] I did not know until 50 years later that Captain McClean was a truly famous pioneer aviator, and friend of the Wrights, Shorts, Brabazon et al

few days making geomagnetic signal measurements using a portable trailer.

For the induction magnetometers, as for much of the research, none of the many practical problems (let alone their solution) were in any manuals or papers, and were found out by continuous experimenting, building trial equipment and trial-and–error testing. Luckily, solid-state electronics had just emerged commercially, and I made good use of a whole (and nowadays) confusing array of high 300V DC and low 12V voltages, hybrid valve- solid-state circuits and transistor/zener diode technology, and also the latest operational amplifiers. There were many false start and signal processing problems that had to be found and then solved, each a small victory, especially as any small external electrical interference or switching was detected. Unwanted electrical oscillations from 'earth loops" came from inadequate grounding protocol since there was a few millivolts difference between the cottage and the McClean dome grounding, which was enough to swamp the microvolt magnetometer signal. Plus whenever the electric stove was turned on for tea or lunch in the Cottage, or the RF system fired, or a thunderstorm happened the equipment detected that transient. The 50Hz power frequency was everywhere and had to be filtered out.

The induction magnetometers work on the same principle used in airport walk-through security gates for finding anything that caused magnetic disturbance, except my detectors had to be super sensitive. I did the calculations and worked out the size and scale needed for detecting fluctuations down to one billionth of the main magnetic field. Winding the needed 2,500,000 turns of wire coils for two systems took about three months, using thermal-free solder for the joints, 80 kg of thin silk-covered 40-gauge copper wire, and much patience. The coils were then mounted by sliding over a central core of a 2m length of expensive magnetic Permalloy B alloy that I had bought for the required sensitivity. The magnetometers were placed outdoors on concrete slabs inside a weather shield (asbestos sheeting in those days!). With the open terrain, wind and weather induced vibrations had to be stopped as a fraction of a millimeter movement would drive the recording equipment off-scale. So wooden fences were also built around the concrete blocks, and anti-vibration mountings (sorbo-rubber balls) used to eliminate the coupling to any ground shaking (Figure 5).

Long cables were strung on stiffened struts to avoid induced currents from movement across the main magnetic field. The signals ran from the coils to the McClean dome; and after pre-amplification and filtering through over 100m of coax cables from there to the Cottage, where the main recording equipment was located. The two component data was recorded on strip charts using both Evershed-

Vignoles and Sefram chart recorders, and I made custom controllers and amplifier drivers for them all, plus for a special very slow speed tape recorder. Nowadays all data recorders come with built-in amplifiers with flexible programmable settings for all-digital recording- not then!

The detectors were so sensitive I found that I could not approach the equipment without emptying everything metal or conductive from my person, and just carrying a single coin in a pocket could be detected about 100 m away. The magnetometers indeed exceeded their design sensitivity, and could and did detect fluctuations of order a billionth of the main magnetic field at frequencies from 1Hz down to 0.001Hz, right down to the smallest background variations. After two years of hard work they were then the most sensitive magnetometers in the world. By comparison to the coarse and slower fluxgate records, it was clear the system was working well. I tried never to turn the equipment off, following the usual superstition and practical reality of electronic equipment that when it was working you left it alone. During my spare time I also repaired the fluxgate magnetometer, whose valves had expired and it had sat there sadly off-scale for about a month. No one asked me to do it, but it seemed a shame that no one was -even Jha who was supposedly using the device was seldom around and did not touch it.

The biggest problem was because geomagnetic data occurs 24/7 non-stop and the high frequencies of micropulsations needed a chart speed of 2.54cm (1”) a minute and hence required daily replacement of the strip charts. I had special length chart paper rolls made that would last a whole day, and as a big victory found (by assuming that such a thing must exist) a special chart-folding machine. Not only did that avoid the laborious hand folding, but also you could just leaf through the records just like a paperback book.

The research students had a room with desks and chairs in the Washington Singer building, then still home of the Physics Department, and I again commandeered a desk and surrounded it with piles and piles of my chart records that I poured over once a week (Figures 6 and 7).

I estimate that I analyzed visually and counted micropulsation occurrence and cycles (by hand) over a length of about 5 miles of chart records from the intervals when I had good data in 1965-1966. Indeed, an unintended pun appears in the EU Annual Report for 1965-1966 stating, “Detailed analysis of the results is in progress but is a lengthy undertaking”.

Figure 5 The detector head and coils of one 2m magnetometer in a sealed Perspex tube and lying on its concrete block, showing the anti-vibration mounts (This picture taken in 1965 during the installation of the wind shields and fencing.)

Figure 6 Some typical PC3 micropulsation waveforms that had frequencies centered on about 30mHz and magnitude about 10^{-5} of the main field

Only occasionally the chart would just run out, and often had to be replaced at the weekend; or a power failure would upset the calibration; or one day the dome door blew open and the equipment drifted off-scale with the cold. The signal cables were even inadvertently cut when the site was plowed to remove the big gorse bushes and plant grass in 1965, requiring emergency repairs and even more wind shielding.

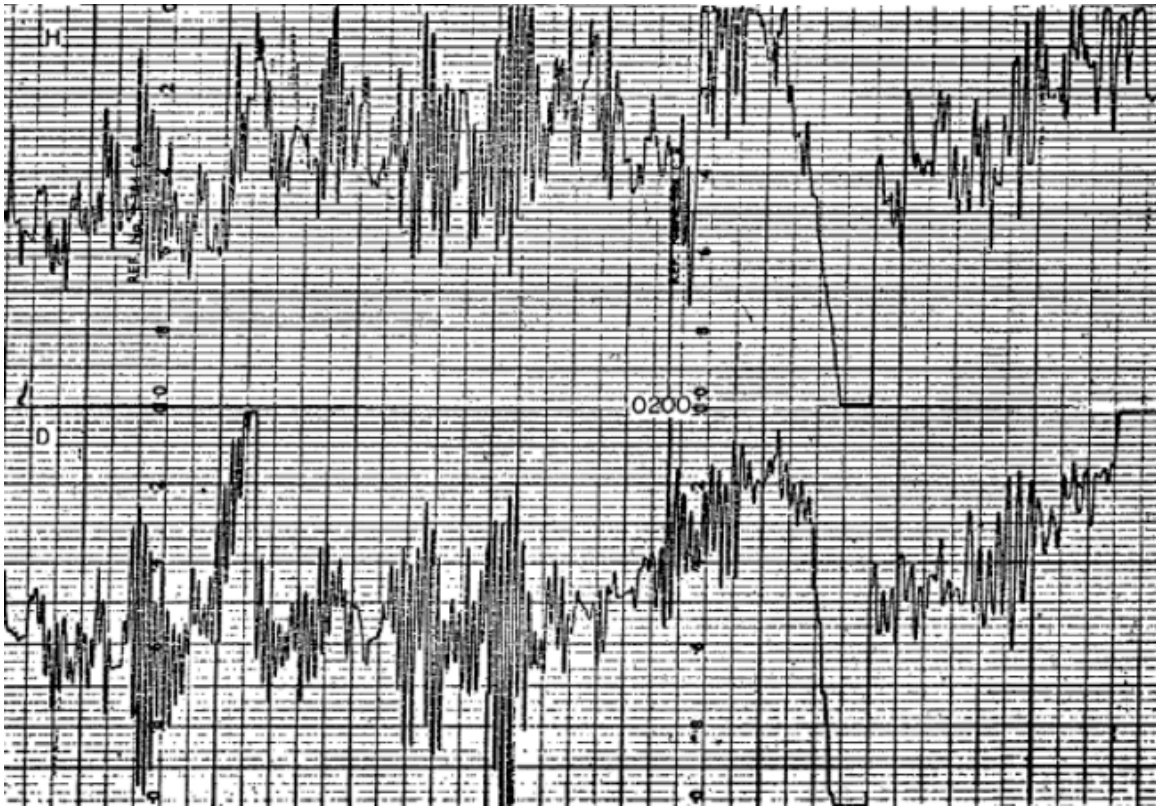


Figure 7 Some typical Pc1 micropulsations that had frequencies of about 1 Hz and magnitude of about 10^{-8} of the main field (Note the time marker for 2am in the morning).

Research advances and new discoveries rely on unexpected findings and perseverance, and each week the charts showed up more new data. Every now and then a set of my daily records had strange semi-continuous low-level fluctuations that went on for hours that I did not recognize and certainly did not fit with known prior observations. So I made a heap of those on the side, and when the pile became too big to ignore I analyzed them separately (Figure 8). The oscillations turned out to be a totally new type that had not been really distinguished before. I confirmed this with Weekes, and also went to talk to Professor A T Price, of geomagnetic harmonic field theory fame, in his office in the tower of the Math Department. He had not seen anything like them before either, and that alone made all the hard work worthwhile.

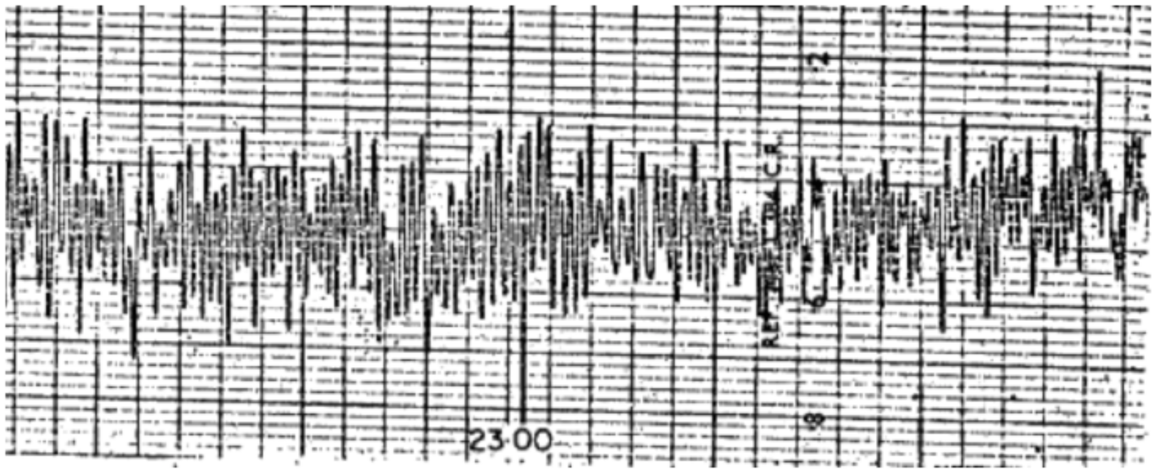


Figure 8 The then new semi-continuous micropulsations recorded at 11pm

The results of the induction system research work are all recorded in the 1967 PhD Thesis “Studies of geomagnetic micropulsations using induction magnetometers” and the two subsequent journal papers (see list of publications at end). The induction magnetometer data were analyzed and interpreted in terms of theories of hydromagnetic wave transmission and resonances in the exosphere and ionosphere. Of the original thesis copies one good copy is in the Archives of Exeter University, one original and several e-copies are in the Duffey family archive. One copy each was given to K G Budden and to K Weekes. A new bound and a digital file copy are now in the library archive at the NLO, including the photos and papers

Other key geomagnetic research

People, projects and visitor open-days with many hundreds of visitors came and went as research projects changed and theses were completed. Norman Webber was initially an MSc student, and when Weekes asked what could be his project, I suggested he build a loop induction magnetometer around the site for capturing the vertical (or Z) component. My two machines were capturing horizontal N-S (H) and E-W (D) and I just did not have the time to construct the third vector.

Figure 9 The three-component induction magnetometer system in operation from 1965, with the two horizontal NS and EW units alongside the vertical Z-component added in 1967 in the big white box. Note the windshields and fencing, with the signal cable support being the horizontal wooden strut on the left. There is a complete absence of gorse bushes due to the site being plowed and grassed, and the hedge and field behind are where the induction loop cables were buried.

I gave Norm all my electronic diagrams, spares, circuits and layout to use that had taken me two years to perfect, but took just 3 months to reproduce. Then we calculated it would need about two 10-wire cables laid around the entire perimeter of the NLO that would give 20 loops and a massive effective area of 20 times the entire site. We hired a Post Office cable layer, and buried the cable, joining the ends together to make it the continuous loop. It all worked well, the results fitted the H and D vectors, and were part of Norm's MS thesis.

Given the great induction magnetometer sensitivity and Norm's use of my designs, after I left he literally cut one of my magnetometers in half, and mounted it vertically on a frame beside the two horizontal detectors (Figure 9). This formed part of his later PhD thesis where he acknowledges my help in the "construction of the equipment", repeating many of the details given in my thesis of the induction heads and amplifying equipment design and builds. So he and others could continue to run the systems I had also made very detailed notes on the "Operating instructions for the induction magnetometers" in March, 1996, well before leaving. I had completely forgotten about that hand-written document until it surfaced fully preserved and clearly much used in the Exeter University NLO archive[6] where I found the seven pages of notes 53 years later!

Meanwhile, the lunar tide in the English Channel was found to contribute to daily magnetic and electric field variations (see Figure 10). Weekes had found this strange variation in the magnetic field at Sidmouth, and had recognized it as possibly due to the tides. The sea is an electrical conductor, and as it flowed up and down the English Channel off Sidmouth it created its own magnetic field too, and this then induced electrical currents in the earth currents.

To measure this effect, Chris Osgood was the one who developed a gradient rubidium magnetometer linked by telephone between the NLO and the University [7]. In the published paper he states: "However, during 1968, Dr. K. Weekes began to suspect that the variation, of lunar semidiurnal period, which he had found in the magnetic total field data from Sidmouth, had its main origin in the tidal motions of the water in the English Channel."

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[6] EU Special Collections NLO grey folder MS 72/3/7 (see Technical Appendix)

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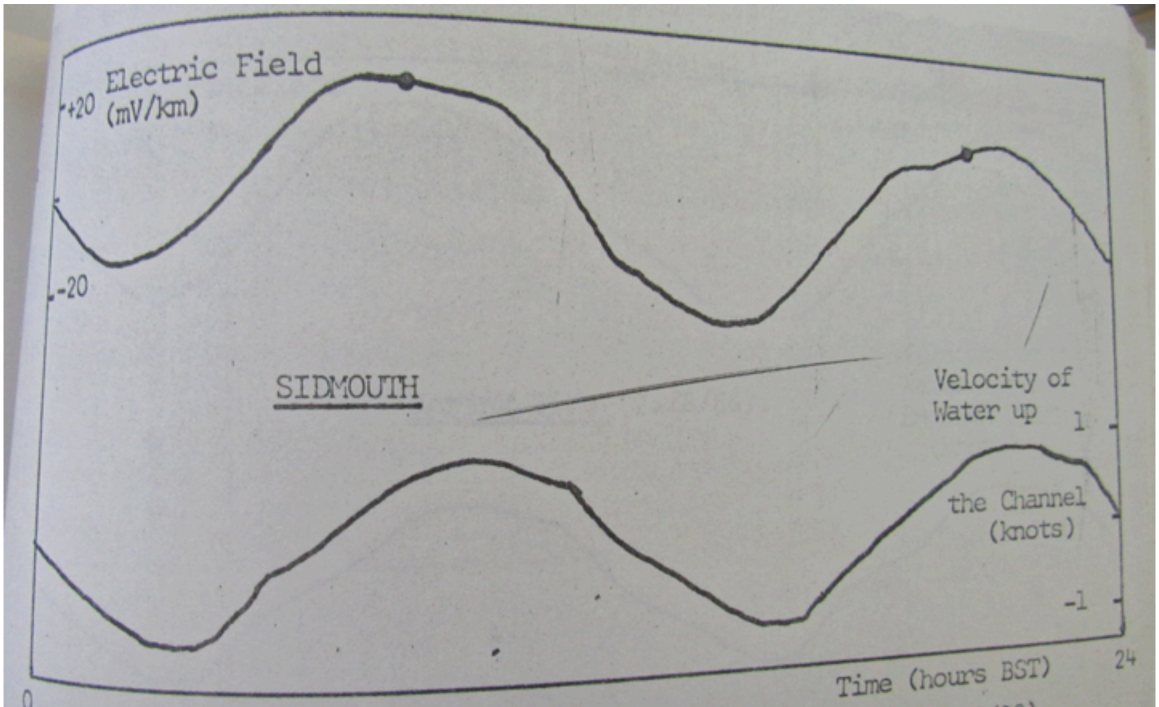

Figure 10 Original and rare chart plotted by Norm Webber for 6th October, 1968 proving the tide up and down the English Channel and the NS electric field variation are tightly coupled

As often happened, Weekes did not publish this then new discovery himself, but many others, especially Rosser at Exeter, later explored this topic in more detail (see also selected publications listed, and paper abstracts in Geophys. J.R Astro. Soc., 1977, 49, pp245-312). In fact, many later papers exploited this finding. I do not know anything more except the published gradiometer work given in the Bibliography listing.

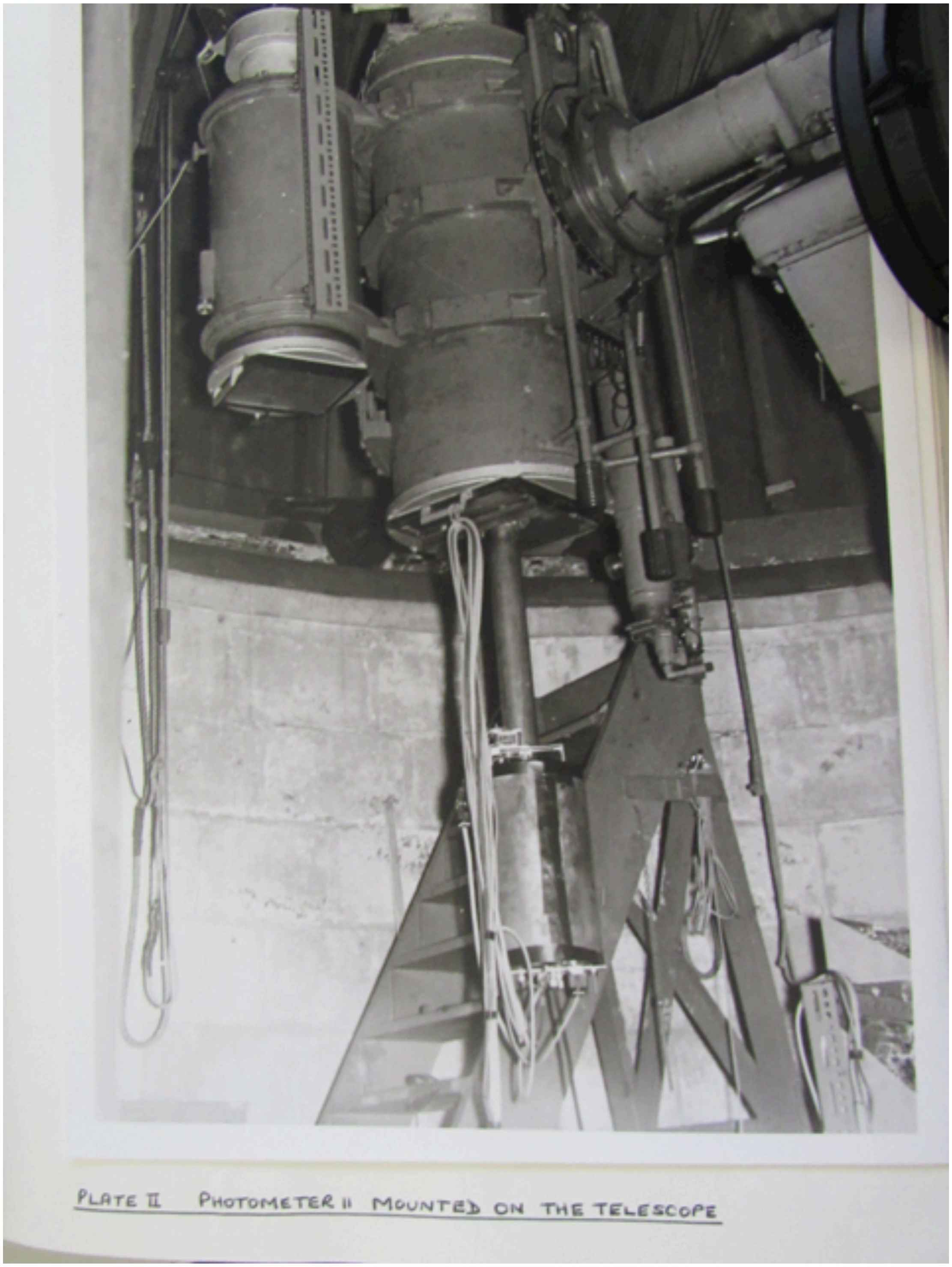

Figure 11 The sensitive photometer for detecting "airglow" mounted on the Mond telescope in 1965 by Roger Smith

Meanwhile, my contemporary colleague Roger Smith, after unsuccessful trials using the laser backscatter and the 30" mirror, had now mounted very sensitive photomultipliers on the Mond telescope (Figure 11). He also built a full-sky field-scanning version outside, with four detectors and using parts from a six-inch telescope for the mount and movement.

Using these devices he was able to deduce the vertical and sideareal variations in what is called "airglow", which derive from recombination of oxygen and nitrogen at great heights in the ionosphere and this is reported in his thesis. Very late one night Roger did also observe an extremely rare overhead aurora. It drove his sensitive optical detection equipment off-scale, so he drove down into Sidmouth to have the local police look up and officially observe and record it as he knew his word alone would not suffice. My magnetometers confirmed this was one of the larger upper atmosphere "storms" due to the solar wind. Roger was elated by making this observation at such low latitudes.

We were both awarded PhDs in the same year, and are standing together directly behind Conn in the 1967 Physics Department graduation photograph (Figure 12).

Dr Kenneth Weekes had truly passed on the torch to the next generation.

Figure 12 Exeter University Physics Department 1967 graduation photograph with Schlapp, Weekes and Conn 6th, 7th and 8th from left in the front row, with Duffey and Smith 5th and 6th of the PhD robes in the second row (Source: EU Special Collections archive).

Postscript and history after 50 years

I left the NLO in August 1966, having been offered a post-doc position with Van Allen in the US, but took a job in the UK instead. Following upper atmospheric research would have meant leaving as did Smith to the University of Alaska, Butcher to Latrobe University Australia, and Webber to BP (Alaska) Inc. My thesis was submitted in 1967, and the external examiner was the famous KG Budden. I travelled down to Exeter and entered a room with Weekes where Budden had the thesis in front of him. This I have read, he said, and immediately laid it aside. But he would like to ask me questions about electromagnetic and hydrodynamic waves. So over the next hour or so he proceeded to actually ask nothing about any of the magnetometer work and its results!!

Weekes distinguished colleague and co-author J A Ratcliffe, CBE FRS had now retired, and gave the EU invited Harland lecture "Between Earth and Sun" in 1968. But research funds were starting to decline - especially for the government related projects.

The Exeter University Annual reports from 1960-1982 contain brief notes on the programs and activities at the NLO, written by Conn always under a separate Corporation heading[8]. These notes show that after 1967 research activities clearly continued in magnetic micropulsations, magnetic field effects and analyzing satellite signal analysis, some funded by the DSIR (recall Weekes knew its first head, Appleton) and also some projects from the military.

I know little details (other than what is listed in the Bibliography, published papers and Annual Reports) of the subsequent geophysical history and studies at the NLO but the work of Schlapp, Rosser and Weekes afterwards further examined the lunar tidal and other electro-magnetic effects. ELF signal and ionosonde studies continued as recorded in the very few later theses. The laser backscatter experiments, reaching to heights of 70 km, were continued from 1967 by Nicholl using an improved laser, but I have not found any published papers. The number of research students peaked at 12 in 1967, but reduced to about six after 1972, and finally two, mainly working on the spatial geologic and tidal conductivity effects that influenced variations in geomagnetic micropulsations.

The EU Annual Reports also show clearly the sudden death of Professor Conn in 1975 decreased not only the geophysical program importance, but reduced the Corporation's administrative priority, and Nicholl also left for the University of Bath. There was some renewed interest in astronomy by the Sidmouth and District Astronomical Society, using the Mclean dome. From 1975-1980 the University support for the Corporation and research funding continued to decrease as Physics Department and overall funding

[8] The University Annual Reports covering this period are all in the EU Special Collections, and I made copies of the relevant pages and have given them to the NLO Trust for their archives.

priorities shifted to other areas. From 1976, only essential maintenance was being carried out at the site, but no improvements.

After 20 years, Weekes retired in 1980, but I have found no note beyond that brief statement in the Annual Report on p115 acknowledging his efforts in making the NLO "a valuable centre for geomagnetic and radio measurements". So far I and other archivists have not found any Obituary or other official notice.

The very same Annual Report also states "shortage of resources and rationalisation of the work...led to a substantial contraction of the work at the Observatory." At that same time, the sale of the historic NLO library was being considered to raise funds for essential roof repairs. By 1982 the University support for the Observatory had declined to the point that it highly symbolically cut off the power at the site, rendering it useless[9]. The University was even offering the McClean telescope around to anyone who was interested. The 1983 report even states on p145: "One of the proposals under active consideration is the disposal of the site and the use of the proceeds for the funding of an Annual International Seminar on Astronomy", while also noting the Landmark Trust is interested " in maintaining part of the site as an Observatory."

I visited the reclaimed and renovated NLO site at the invitation of David Strange and accompanied by Iain Grant of the new Trust. I heard the story of how the entire site and domes were almost plowed under to make way for a housing development. The NLO was saved for posterity by the intervention of Patrick Moore; by the historic preservation listing of the domes that stopped their demolition; and by heroic local and county fund raising efforts and major donors. As a result of their dedication, enthusiasm and major donations, the NLO remains the truly amazing place it is today, a truly living story.

The extensive records and charts were all mainly of the paper variety until digital recording and analysis came in after 1970 or so, and are all now missing in the change and demise of the NLO Corporation. So none of the amazing induction magnetometer paper charts seem to have survived the many years and all the changes in administration over the last 50 years. Photos of the gear and site are all in my thesis, now scanned as a pdf file and in the NLO and EU archives, as all the equipment has since been scrapped, lost and/or removed. All the equipment except the concrete blocks has disappeared. Only the photos I had taken remain as a visual record, which were hand-developed by myself in the same NLO cottage darkroom which Lockyer himself had used.

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[9] Claimed to be due to the inability and cost to bring the electrical system up to present safety standards, when it had served so well for many years.

It is odd the think of yourself as a part of history, and almost lost history at that! I walked the now tended and signposted NLO site in 2017. With the aid of the photos we found my old friends the concrete blocks still standing but hidden beneath dense gorse and rhododendrons (Figure 13). Their use and purpose had been long forgotten.

Amazingly, 50 years later I was asked: “What are these cables we have found in the ground?” Of course I knew exactly that they were the wires we trench-buried near the site fence for the horizontal loop magnetometer, and they had never been lifted and were still there.

Figure 13 The NS and EW induction magnetometer mounting blocks rediscovered at the NLO 50 years later, and still in surprisingly good condition.

The story and the results of the geophysical program had been lost, so that is why I have written these notes as a small record of this now historic past.

Only the concrete blocks and the memories remained, so in 2022 the NLO Trust erected a descriptive plaque at the magnetometer site (Figure 14), and in 2023 Kenneth Weekes was entered into the AstroGen archive.

Figure 14 The NLO Trust has installed a descriptive plaque marking the site of the magnetometers

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The first part of the paper describes the circumstances under which tidal energy supplied to the atmosphere through the action of tide-producing forces can be trapped between a certain stratum (usually where the temperature has a minimum) and the ground. The results are then applied to discuss in general terms the types of free oscillation which an atmosphere with a given temperature distribution may possess. It is pointed out that Kelvin's hypothesis that the atmosphere has a resonance in the neighbourhood of 12 solar hours leads directly to the conclusion that the temperature must fall again to a low value at some level above the hot region inferred from observations of the anomalous propagation of sound. In the second part of the paper results are given of numerical calculations made with the aid of a differential analyzer to determine to what extent the requirements of the resonance theory restrict the possible temperature variation in the atmosphere. The results of Appleton & Weekes (1939) on lunar tides in the E region are discussed, and it is shown that there is no difficulty in reconciling them with oscillation theory provided a suitable temperature distribution in the E region is assumed.

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Drafts and correspondence.
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C186 Correspondence from Weekes, 1937, 1939.
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E146 correspondence from Weekes

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APPLETON, Sir Edward Victor, K.C.B. cr. 1941; M.A.,D.Sc ., Hon. L.L.D. (Aberdeen) , F.R.S. 1927 ; Secretary Department of Scientific and Industrial Research since 1939; *b* Sep. 1892;
s . of Peter Appleton, Bradford , Yorks; m. Jessie, d. of late Rev. J. Longson; two d. Educ. Hanson School, Bradford;
St. John's College, Cambridge (Scholar and Exhibitioner); Natural

Science Tripos, Parts 1 and II (Physics), 1913 and 1914; Wiltshire Prizeman 1913; Hutchinson Research Student, 1914. Served European War 1914-18, West Riding Regt. and Capt. R.E.; Assistant Demonstrator in Physics, Cavendish Laboratory, 1920; sub-lector, Trinity 1922; Wheatstone Professor of Physics, University of London, 1924-36; Jacksonian Professor of Natural Philosophy, Cambridge University, 1936-39; formerly Fellow of St. John's College Cambridge; Chairman of British National Committee for Radio-telegraphy; Morris Liebmann Memorial Prizeman (1929) and Vice-President (1932) American Inst. Radio Eng. ; Hughes Medallist of Royal Society, 1933; President International Scientific Radio Union. Publications: various original papers on electricity and the scientific problems of wireless-telegraphy. Address: 4, Exeter House, S.W.l5. Club: . Athenaeum.

Special Collections listings
University of Exeter
libspc@exeter.ac.uk
EUL MS 72 Norman Lockyer Observatory papers – 70 boxes
EUL MS 114 Papers of Sir Joseph Norman Lockyer and the Norman Lockyer Observatory (Royal Astronomical Society) – 14 boxes
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Dr Roger Smith (1942-2017), Professor of Physics and Director, Emeritus of the Geophysical Institute (deceased age 75 in Fairbanks, AK) continued his interests in optical and visual measurements of the upper atmosphere. "Roger Smith served the University of Alaska Fairbanks with distinction in teaching, research and public service from 1984 to 2011. His outstanding research career, centered around the dynamics of the upper atmosphere, has led to significant advances in understanding these phenomena; and is highly regarded nationally and internationally as an expert in the field, which resulted in a leading role in several national and international research committees" (Source: www.uaf.edu/commence/2011/emeriti/smith/).

Dr Eric Butcher joined the new Physics Department of Latrobe University in Melbourne, Australia, in 1967, and specialized in main magnetic field effects in the ionosphere. He published papers with Schlapp and others and continued to work on experimental and analytical investigations of the properties of the ionosphere, magnetosphere and thermosphere using radio and optical techniques, air-glow and auroral physics, solar-terrestrial relationships, etc. He is now listed as Emeritus Scholar, but not responding to e-mail in late 2018 (Source: https://50years.latrobe/history-physics-department/ and http://www.latrobe.edu.au/chemistry-and-physics/staff).

Dr Romney B. Duffey left geophysics for an international career in the UK, US and Canada in safety analysis, risk assessment and nuclear systems design. He has published over 450 papers and articles, and is a co-author of two original texts on errors in technology ("Know the Risk" and "Managing Risk"), of the first ASME text on supercritical heat transfer and fluid flow in engineering applications, many book Chapters, and author of "Dreams of Life", a lifetime anthology of poetry. He contributed extensively to the Generation IV International Forum, and was a member of the ASME President's Task Force on Fukushima 2011, Principal and Founder, DSM Associates, North America, 2011-2017. From 1997- 2011 he was The Principal Scientist, Atomic Energy of Canada, AECL, 1996 - 1997 Director, South Carolina Universities, Research and Education Foundation, 1991 – 1996 Chairman and Senior Advisor, Department of Advanced Technology, Brookhaven National Laboratory, NY, 1987 – 1991 Deputy Department Manager and Group Manager, Energy and Systems Technology, Idaho National laboratory, 1977 – 1987 Senior Program Manager, Electric Power Research Institute, Palo Alto, CA and 1967 – 1977 Section Leader, Berkeley Laboratories Central Electricity Generating Board, U.K.

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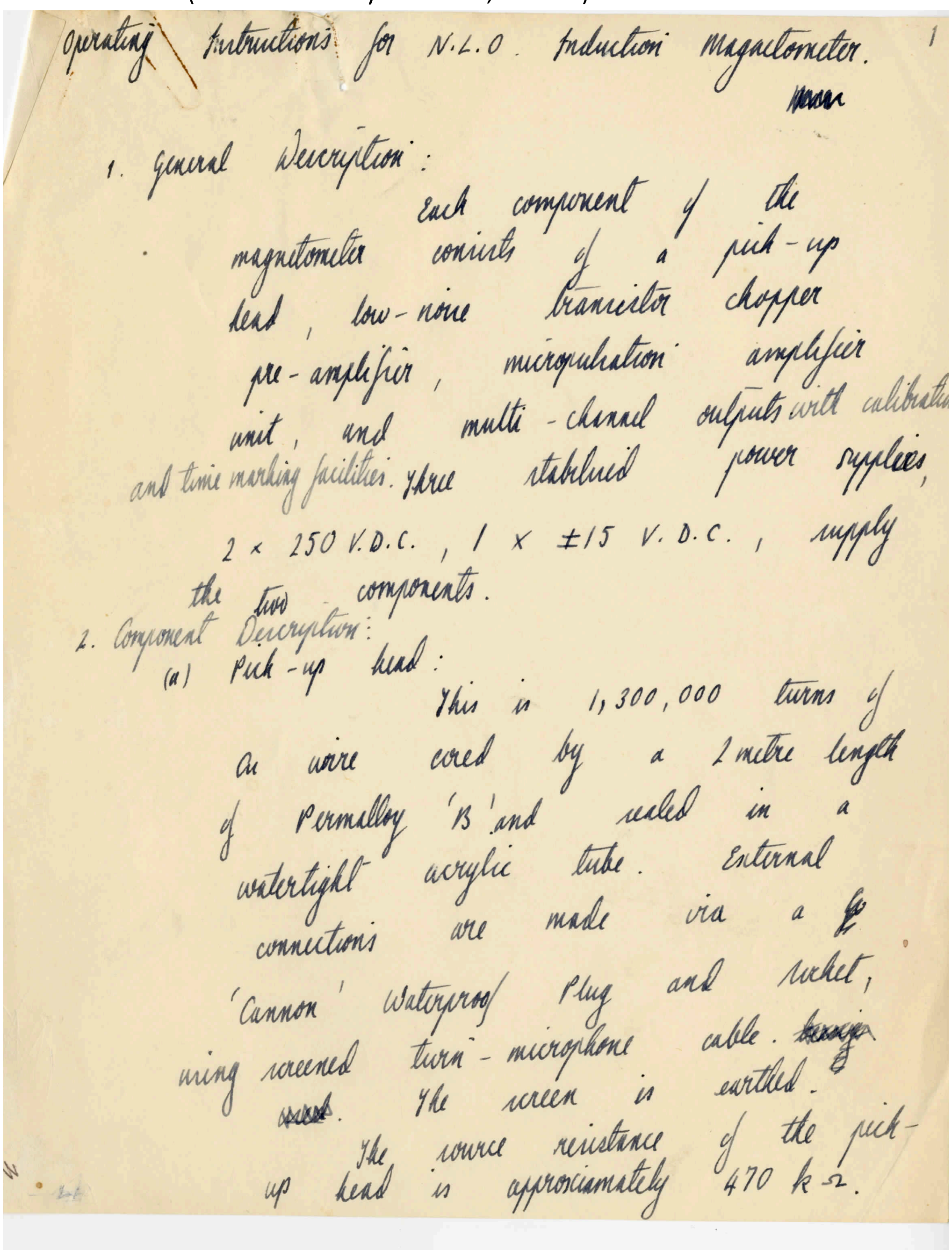
Technical Appendices

A. Geomagnetic micropulsations

The Earth and its magnetic field are bombarded by the solar wind, whose energetic particles causes hydro-magnetic disturbances of many different types. Beautiful ultra-low frequency (ULF) waves occur which are a sensitive indictor of solar storms and of the propagation of waves through the ionized outer atmosphere and exosphere.

These micropulsations or ULF waves have been systematically classified into different Pc (continuous) and Pi (impulsive) types, according to the frequency, magnitude, duration and waveform. The frequencies correspond to resonances in the hydromagnetic transmission characteristics of the magnetosphere, ionosphere and exosphere that surround the earth. The systematic diurnal variations of amplitude or occurrence probability are due to day-to-night changes in ionization concentrations and magnetic field orientation. Magnetic storms are the direct result of increases in solar activity impacting the magnetosphere, and cause simultaneous increases in micropulsation occurrence, types and magnitude. In addition, the observed polarization is also influenced by the presence and structure of the land/sea geography and geology and their electrical conductivity variations.

B. Sample introductory page of handwritten Magnetometer Operating Instructions (R. B. Duffey March, 1966)



Operating Instructions for N.L.O. Induction Magnetometer. 1

1. General Description:

Each component of the magnetometer consists of a pick-up head, low-noise transistor chopper pre-amplifier, micropulsation amplifier unit, and multi-channel outputs with calibration and time marking facilities. Three stabilised power supplies, 2 × 250 V.D.C., 1 × ±15 V.D.C., supply the two components.

2. Component Description:

(a) Pick-up head:

This is 1,300,000 turns of Cu wire cored by a 2 metre length of Permalloy 'B' and sealed in a watertight acrylic tube. External connections are made via a 'Cannon' Waterproof Plug and socket, using screened twin-microphone cable. The screen is earthed. The source resistance of the pick-up head is approximately 470 kΩ.

C. Summer Meeting of Royal Astronomical Association 1966

THE OBSERVATORY

Vol. 87 FEBRUARY 1967 No. 956

THE SUMMER MEETING OF THE ROYAL ASTRONOMICAL SOCIETY AT EXETER

1966 September 12–14

At the invitation of the Council of the University of Exeter, the Royal Astronomical Society held its Summer Meeting at Exeter. The programme was organized with the co-operation of Professor A. T. Price, the Department of Mathematics and Physics, and the Corporation of the Norman Lockyer Observatory. The opening day of the meeting, September 12, was devoted to the History of Science discussion and a public lecture given by Dr. T. F. Gaskell on "North Sea Exploration". After dinner, participants and their guests met the members of the Mathematics and Physics Department of the University of Exeter and the Norman Lockyer Observatory. On Tuesday, September 13, there was a geophysical discussion on the "Solar Wind" and the "Solar Effects on the Upper Atmosphere". In the evening the Harland Public Lecture was given by Professor C. W. Allen, entitled "The Race for the Solar Ultra-Violet". This was followed by a dinner given in honour of the Royal Astronomical Society by the Councils of the University of Exeter and the Corporation of the Norman Lockyer Observatory.

The morning of the final day, September 14, was taken up with an excursion to the Norman Lockyer Observatory at Sidmouth. In the afternoon the meeting of the Society was preceded by a showing of the films taken by Ranger VII and IX on their Moon missions.

This brought the Summer Meeting to an end. The Geophysical discussion together with the Geophysical public lecture will be reported in full in the *Quarterly Journal*.

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