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Evolution of the ionosonde

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Abstract
Almost 60 years' development of ionosondes and their data processing capabilities are described with emphasis on the authors' contributions from the early beginnings of ionospheric studies to the latest digital equipment to be used for the exploration of the magnetosphere.

Key words *ionosonde history – ionosphere – digital data – integration – 4-dimensional recordings*

1. Introduction

Looking back on this century's development of knowledge about the ionosphere we can see the development of instrumentation which created the data necessary for the understanding of the ionosphere. One important instrument is the ionosonde, *i.e.* a radio sounder which sweeps through a large range of frequencies, recording the range (and possibly amplitude and phase) of echoes reflected from the ionosphere to produce ionograms. In contrast, radar generally operates at a fixed frequency. It is fascinating to see how quickly technical capabilities made available by industry for communication and computer development were used for the ionosonde. New and unique methods were developed for the ionosonde to overcome technical limitations. Often these methods became the input for a new technical device. This interplay between technical progress and refinement in data processing and analysis is very interesting. It also allows us to look into the future and foresee technical developments as well as new data analysis and presentation methods.

2. Beginning of ionospheric studies

After Marconi established that radio communication is possible over long distances, Heaviside and Kennelly proposed as an explanation for this unexpected behaviour a reflecting layer in the high atmosphere. Appleton and Barnett (1925) and Breit and Tuve (1926) used two completely different methods to establish the existence of the ionosphere and to measure its height. The first method is the then called «frequency variation» method, now called «chirp», while the second is the pulse method. These two methods have been developed rather independently and are still being used alternatively, not only in ionosondes but also in radar applications. Radar is actually an outgrowth of early ionospheric experiments, but has developed much faster and to a higher level of sophistication because of its direct warfare applications. Ionosondes were also used during World War II by both sides for short-wave radio communication predictions. Slough in England was the first routine observation station in the world. But the most advanced system was built and operated in Washington, DC by Berkner *et al.* (1936). They used the smart idea

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of Gilliland (1934), an oscillator common to the transmitter and the receiver. While the oscillator frequency is mixed with a pulsed IF frequency to produce the transmitted frequency, the received frequency is mixed with the oscillator frequency to produce the IF frequency for further amplification. In addition to the mechanically tuned oscillator there was an antenna circuit, common for transmission and reception, tuned with three capacitors. The axis powers had sounding stations from Norway to Sicily. Excellent data were created in Kochel in the Alps. The stations were technically less advanced, but more powerful. One station in Northern Germany had a fancy way of transmitter antenna tuning by extending from two spools on a central tower a flexible bronze wire pulled by a weight on two end towers with a rope. Gravitational acceleration produced nearly the desired frequency variation; thus the start of the ionogram at high frequencies was a technical requirement. Only the brake on the spools had to be controlled. Rewinding after the sounding were accomplished by a simple motor. Because transmitter frequency control and receiver tuning was accomplished independently, it needed a 24 h shift of operators to produce the half hour sequence of ionograms. Receiver tuning required a quick turning-back of the receiver capacitor during band change. This was a good chance for a skilled mechanic to invent a sophisticated automatic gear. But there was still the human factor of precisely following the transmitter frequency. Because they wanted to sleep at night or do other things, some smart women of the night shift thought they could run all the night ionograms in a continuous sequence in the first two hours of the evening and then leave. Karl Rawer wondered about the peculiar daily variation with an abrupt collapse of the ionosphere in the morning after stability for many hours. Thus he installed an oscilloscope in his bedroom, connected by two cables for signal and synchronization and created the first real-time, long distance transmission of ionospheric data.

One new technique was introduced by the author in 1942. He replaced the band filters, always used in heterodyne receivers, by several tuned stages of equal band width and created the first «real pulse receiver». It has the important property of optimally reproducing the pulse shape of the transmitted signal without secondary ringing and to recover quickest after saturation by the local transmitter pulse. This avoided the «differentiation» of the received signals used on most stations and made the presentation of the signal amplitude as gray levels of the record possible. Properties of different filters (without mentioning the beneficial effect under saturation conditions) were investigated by Huber and Rawer (1951). Only recently has it become clear that a very large number of equally tuned circuits creates a Gaussian filter, often used in modern pulsed radars.

After the war significant progress was made in the design of ionosondes. Improving the new principle of a common oscillator for receiver and transmitter, Sulzer (1946) built an ionosonde without mechanical movements, with the exception of a small variable capacitor for the oscillator. This oscillator had a frequency range of 31 to 50 MHz, allowing a frequency sweep from 1 to 20 MHz in 30 s. But the untuned front end was not good enough for the high interference level in Europe and the beginning information battle of the cold war. More frequently, the C4 ionosonde, developed for the National Bureau of Standards, was used. Wright *et al.* (1957) reported 14 different ionosonde types being used during the International Geophysical Year 1956-1957. Importing the idea of a common oscillator, but tuning the receiver front end and the transmitter output, was the solution for the C4 and a new development in a French-German Institute near Freiburg, Germany. There the KRDSE 22 was developed and furnished by the author with standardized chassis drawers: power supplies, receiver, final transmitter stage, command unit, and oscilloscope (fig. 1b). Because the sounder had six bands, the oscillator variable capacitor had the same logarithmic plate shape as the other two tuned circuits and had to be tuned in three points of frequency. But the sounder still had three big drums for the six inductors which were switched in by rapid and powerful spring action, requiring a big machine shop. This ionosonde was installed at seven stations in the worldwide net of the French colonies and re-

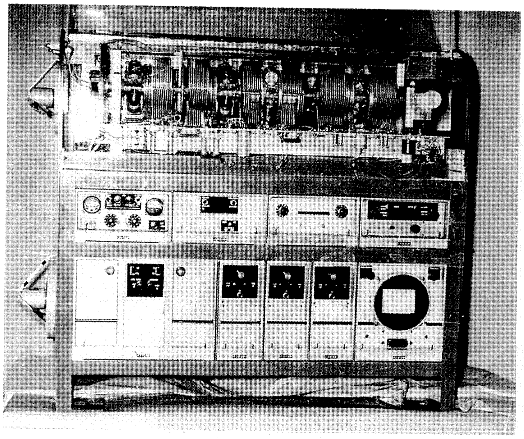

Fig. 1a. KRDSE 22.

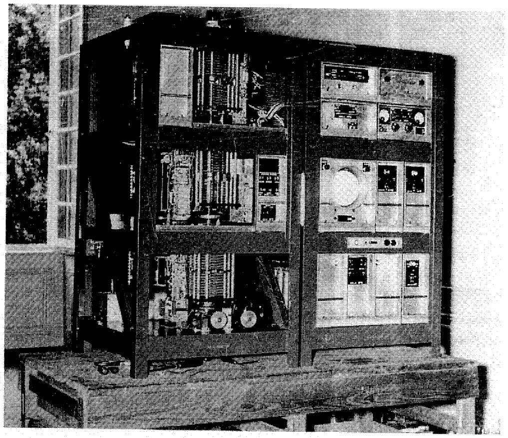

Fig. 1b. Panorama Ionosonde.

lated locations: in Dakar, West Africa; on board the boat «Commandant Cliquot» sailing to Terre-Adélie; in Freiburg, Germany; in Lwiro, Congo; in Djibouti, Somalia; in Nha-Trang, Vietnam; in Madagascar and in Kerguelen. The three equatorial stations formed a beautiful chain for several years and produced excellent data (see fig. 2). On the other hand, the most powerful and sophisticated ionosonde was in Lindau, Germany. It occupied three rooms: one for the receiver, one for the transmitter, and one for the recording equipment. With a more compact counterpart in South-West Africa it produced the most beautiful transequatorial ionograms, instrumental for studies of great circle deviation and of direct ionospheric radio propagation, avoiding a ground reflection, due to the equatorial anomaly.

3. The Panorama Ionosonde

In minimizing the mechanical complexity and allowing fast-speed ionograms (Bibl, 1951), the «Panorama Ionosonde» (fig. 1a) was a substantial improvement. It had only one mechanical axis. The complete tuning circuit was mounted on the rotor. There were three sets of inductors and capacitor plates for each of the receiver, the oscillator, and the transmitter tuning. Now, the oscillator capacitor plates could be shaped differently to make the tuning synchronism perfect between receiver, oscillator, and transmitter. The tuned circuits themselves had no internal contact. Their connection to the amplifiers was accomplished by silver rings divided into three sections. With the help of silver-carbon brushes they provided the switching of the bands as well. An automatic gear translated the change in direction of a synchronous motor into a change of speed, providing easily either 2 or ½ min ionograms. For oblique bistatic sounding the Panorama Ionosonde was modified to have higher frequencies and a linear frequency scale. This was easy because each frequency band could have different shapes for the capacitor plates. In addition, the synchronous motor was driven by a powerful quartz derived frequency source. Because of the substantial difference in the behaviour of the ionosphere over Freiburg and Athens, Greece, the first linear ionosonde pair was between these stations. The Panorama Ionosonde was employed successfully at several solar eclipses: first in Djibouti in 1951; in Bergen, Norway in 1954 on board a French frigate; and in Genoa, Italy in 1955. Its speed and precision solved the mystery of the finite minimum of ionization at totality. The excellent condition of the 1954 eclipse in Bergen (Bibl and Delobeau,

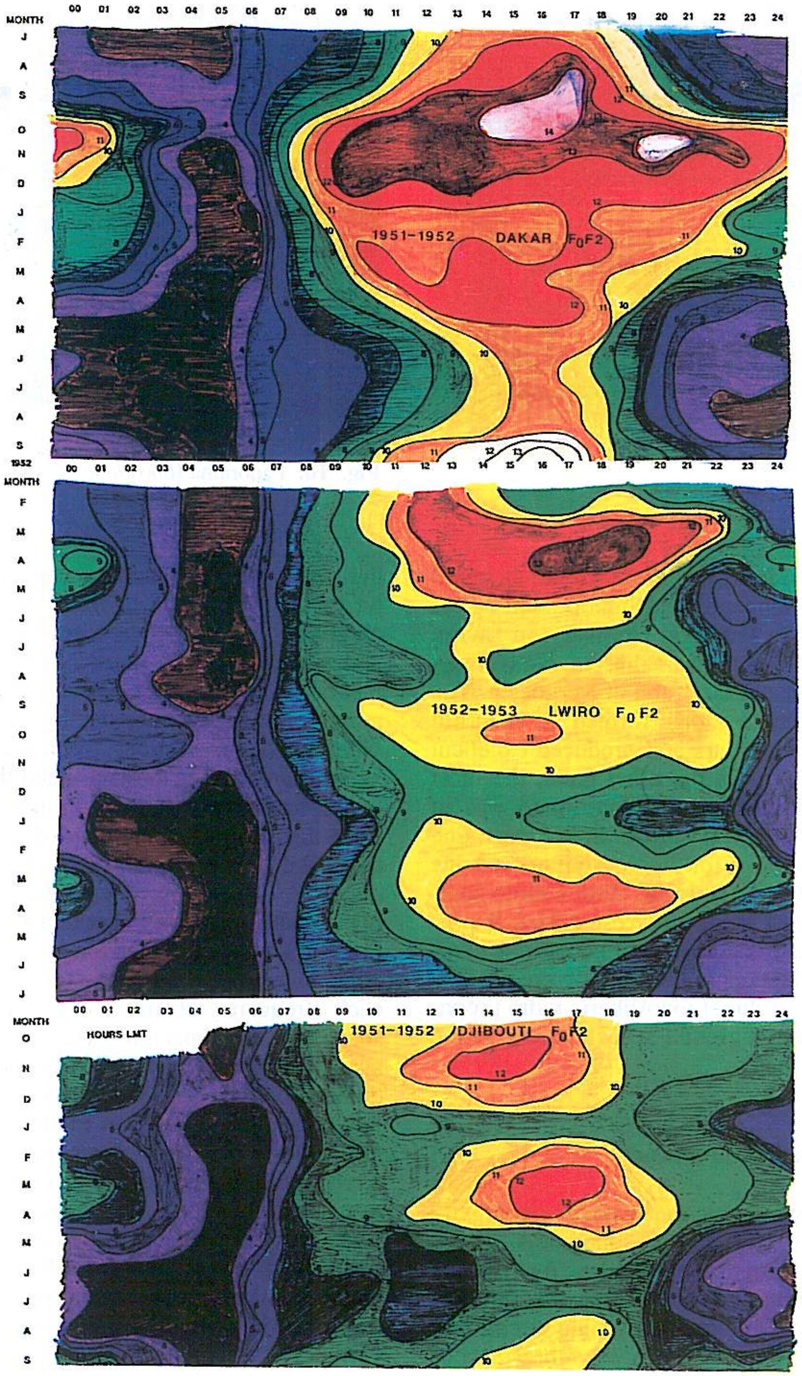

Fig. 2. Yearly plot of f_0F_2 on 3 equatorial stations.

1955), with noon time occurrence at sunspot minimum and slight sporadic E (E_s), showed a perfectly symmetric time behavior for f_0E and f_0F_1, the critical frequencies of the normal E- and F_1 layers. This proved that the recombination coefficient in those layers must be at least ten times larger than assumed before. These results extracted the remark: «very interesting» from Sir Edward Appleton who had for decades misled researchers to attempt construction of asymmetric occultation curves in their data. Only Piddington (1951) suggested that the recombination coefficient could be much larger then generally believed. Most discrepancies in analyzing solar eclipse data come from misinterpretation. After years of analyzing ionograms, Bibl and Rawer (1951) have come up with rules for analysis of f_0E. These rules require eliminating in the analysis dynamic effects which create layers with thickness far less than the respective scale height. Becker (1956) found even an increase in his E_1 data after the beginning of the eclipse. Elwert (1953) told the author that he had concluded theoretically: «die Sonne ist grösser als sie scheint». But many researchers kept their belief (Minnis, 1958). Results from Djibouti were also very interesting. The time-compressed movie produced by the Panorama Ionosonde showed that the ionization in the F_2 region disappeared only slowly, but drifts upwards. New ionization, created in the second half of the eclipse and thereafter, replaces the total F-region ionization by first producing an F_1 layer from where the F_2 layer is produced by diffusion. This was one input to a general theory (Bibl, 1962). On many stations the Panorama Ionosonde was used as a routine instrument monitoring the ionosphere continuously for years: in Dourbes, Belgium; Freiburg, Germany; Genoa, Italy; Athens, Greece; and for a limited time in Darmstadt, Germany. Following the idea of Nakata *et al.* (1953), three ionospheric parameters were continuously recorded on these stations. But because the interference level in Europe was so high that the critical frequencies of the F region were unreadable in the data compression format $f_0F_2(t)$, the MUF3000F replaced it. After the author (1956) discovered that the widely used Smith curve, representing the propagation factor as a function of virtual height was exactly an exponential curve if the frequency scale was logarithmic, the MUF3000F (t) was created by adding the voltage of a discharging capacitor to the linear range sweep.

In addition to standard ionograms and movies, the Panorama Ionosonde produces time dependent compressed data. Figure 3 top shows three traces: 1) MUF3000F; 2) virtual heights of the layers in the E and F regions; 3) critical frequencies in the E region as functions of time. In MUF and $h'f$, a wavelet of three regular oscillations is visible at night. They may represent a pulse event, an undocumented nuclear explosion in the atmosphere.

At Breisach near Freiburg, three records were added routinely. This station had a field of 12 overlapping horizontal rhombus antennas with 60° aperture and spacing in the form of a star. Three 50 kW transmitters with fixed frequency could each choose one of two or three of these antennas which were also used for reception. To distinguish the direction from which ground-scatter echoes arrived, a rotating color filter disk was added between oscilloscope and camera, switching synchronously with the antenna switch. In the opinion of the author, these are the first recordings using false colors in science, at least in raw data recordings. Thus a fourth dimension was recorded, presenting amplitude and direction of ground back-scatter echoes as functions of range and time. While the middle part of fig. 3 shows one of the best recordings of ionospheric movement produced by natural sources, the lower part shows the result of a nuclear explosion in the atmosphere which also has been reported by others (Obayashi, 1962). While the natural oscillations are rather random in sequence but form on homogenous surfaces, the three oscillations after the explosion form a real wavelet while the ionosphere before the arrival time was affected by direct radiation. In about 9% of the time, direct echoes at 500 km range appeared in back-scatter recordings at frequencies higher than f_0F_2, visible at the 12 MHz recording in the middle of fig. 3. It was determined that these echoes were picked up from the south. But, instead of an enhancement in the south, an ionization hole over the Alps was dis-

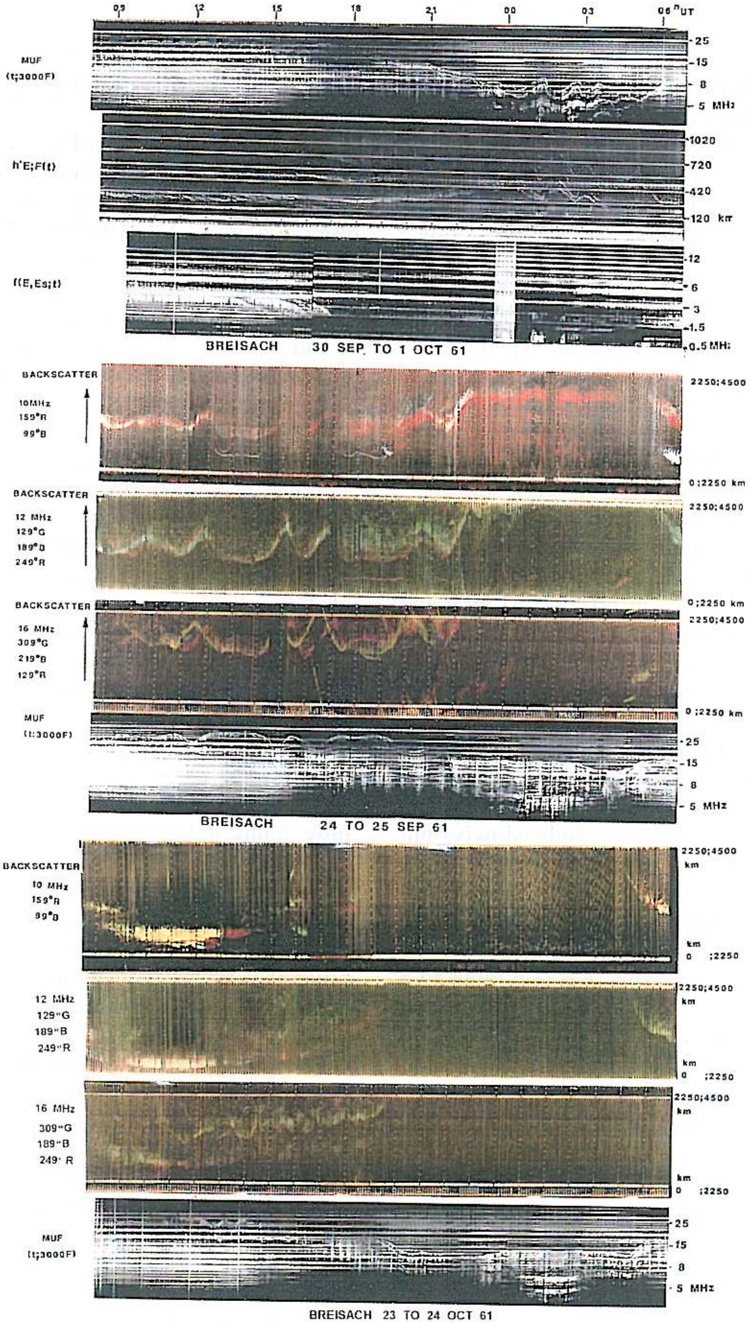

Fig. 3. Characteristics and backscatter recordings. Effect of nuclear explosion; natural oscillations; fE, $E_s(t)$, $h'E$, $F(t)$, $M3000F(t)$.

covered when maps were drawn from data of all European vertical incidence stations (Bibl, 1964). For those maps the Italian stations Genoa and Rome were crucial, showing the largest gradients between those stations most of the time. Dominici (1973) published the ionospheric data of the Rome station for 1948 to 1970. Anomalies in average f_0F_2 were studied by many authors, including Dominici and Mariani (1955). Together with movies, the continuously recorded data helped especially the study of «Transitoria» (Bibl, 1960), internationally named Traveling Ionospheric Disturbances (TIDs). Later-on, they were identified as caused by acoustic gravity waves. They can be followed by an ionospheric station network (Munro, 1949; Bibl and Rawer, 1959; Bibl and Olson, 1967) or by ionospheric drift measurements. The history of drift measurements is summarized in a separate paper (Reinisch, 1998, in this issue).

4. The Digital Ionosonde

After coming to the USA, Bibl and Olson (1967) proposed the first Digital Ionosonde. Digital integration was executed first on a fixed frequency sounder for J.W. Wright as one part of what he called the «Dynasonde». (The other part was an analog ionosonde). For the first time, phase measurements were made; it took some persuasion to have Bill accept the capability of phase measurements as a gift. At this time there existed no solid state computers. Amplifiers and flip-flops used tubes and the memories used magnetic cores which needed a lot of power. Technology was not available for a scientific instrument with limited budget. But soon, the first solid state memory, made by Sylvania, appeared on the market. It had a 4 by 4 matrix. Four of those were mounted on a Printed Circuit (PC) card, controlled by 12 other chips (fig. 4). 32 of those cards were required to store and update a sine and a cosine sample for each of the 128 range bins. There was also no digitizer available at that time, no digital comparator, and no digital adder. How could the data be integrated digitally to have a real digital ionosonde? 1) Logarithmic amplifiers were available to transform the data into a dB scale, thus allowing a 60 dB amplitude range presented by 8 bits. 2) A digital to analog converter was built from resistors and gates. 3) An analog comparator decided if the momentary data value was larger, equal or smaller than the stored digital value. 4) This memory value was put into a counter, changed by counting up or down depending on 3) and put back into memory. Honoring the name *Digitally Integrating Gonio-metric Ionosonde* (Digisonde 128), which also indicates 128 height ranges, the median of up to 128 complex amplitude samples could be formed. To succeed in the high noise environment of Europe it had a two stage vary-cap tuned input with serial tuning for a constant bandwidth in each band. Following an idea of B.W. Reinisch, the synthesized transmitter signal was cleaned by the same cir-

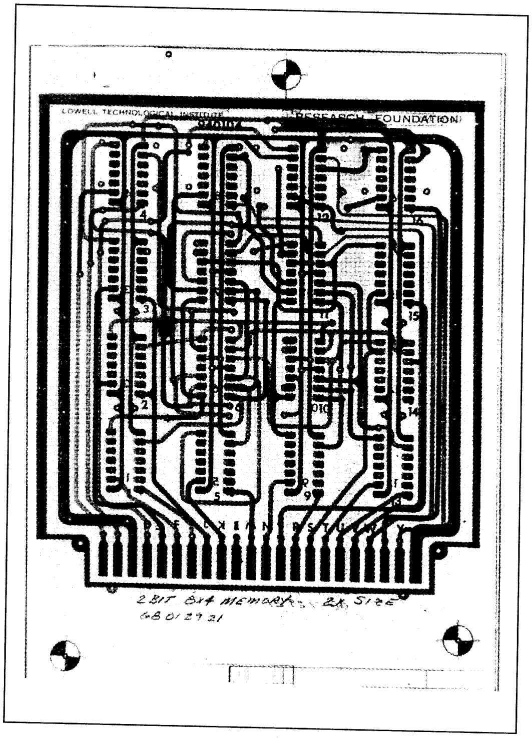

Fig. 4. First memory PC card.

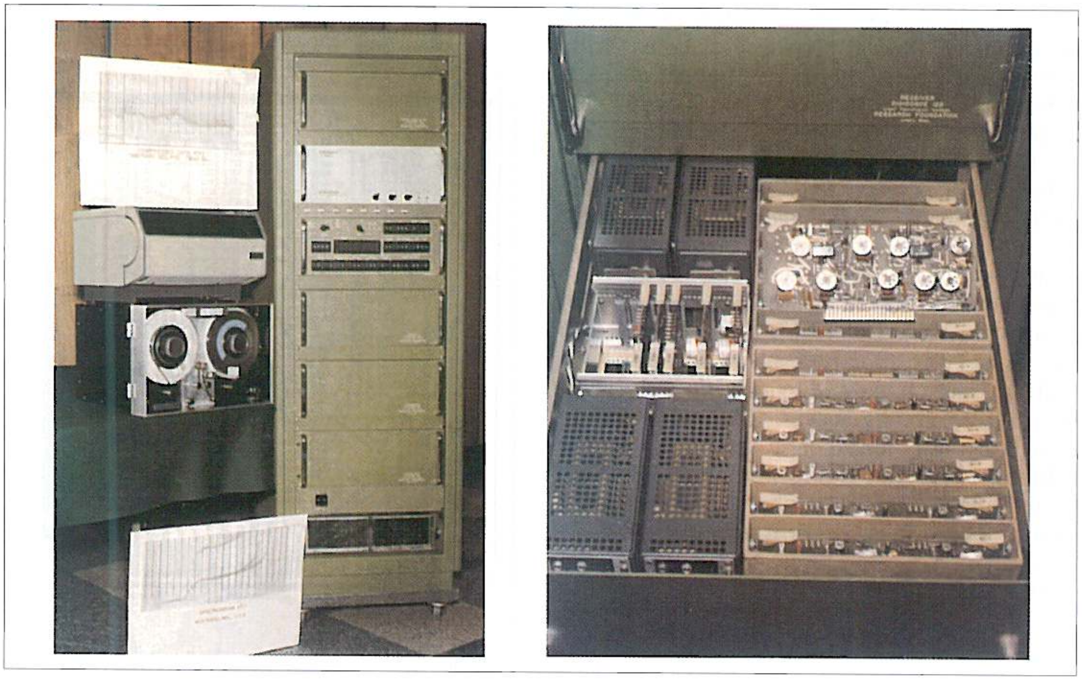

Fig. 5. DGS 128 and one of its drawers.

cuits. In fig. 5 the DGS 128 and one of its drawers are presented. Several of these instruments had been built: for the U.S. Air Force Flying Laboratory; for the U.S. Air Force station in Goose Bay, Labrador; for Dourbes, Belgium; for Breisach, Germany; for Rome, Italy; and for Athens, Greece.

For many stations the digital coherent integration was a substantial improvement in signal-to-noise (fig. 6). But in Goose Bay, the ionosphere changed so fast that a modification was necessary to integrate the power of the signal instead. This was unfortunate because the reflectivity was also low. Thus a better method became obligatory allowing spectral analysis of the coherently integrated signals. This was also considered necessary for routine ionospheric drift measurements (Pfister and Bibl, 1972). Recording of echoes from the same range, but different location, became a requirement for sensitive ionospheric drift analysis. It did not take very long for digital comparators to become available, Digitizer chips with 12 bits, and memory chips with vastly increased capacity and also with programmability. By parallel processing, the first (and only) Real Time Complex Spectrum Analyzer was thus conceived, requiring only the storage of the accumulated spectral amplitude values. The linear sine and cosine samples were digitized directly from the last IF of the receiver, three quarters of a period (3.3 μs) apart, and then logarithmically compressed in a look-up table. As functions of time, the arguments of the log sine and cosine function were continuously changed by simple counters. The harmonics of the trigonometric functions were created by adding the argument with itself as many times as the number of the Doppler frequency required. Consecutively, the arguments were transformed into a log sine and log cosine look-up table. To the log sine and log cosine of all considered Doppler frequencies the log sine and the log cosine of the data of each height range were added. Then, for every Doppler frequency, the four sums were transformed by an exponential look-up table into the linear domain. This value was added to the accumulated value of previous pulses. In fact, an important invention was made by the author in using the odd half frequencies of the Doppler spectrum. This simplifies the technical creation of the trigonometric function, but it also made any filtering of the data unnecessary, a source of controversy in mathematical optimization. It also solves the problem of the asymmetry at Doppler zero and the ambiguity at the highest Doppler frequencies. Furthermore, it distinguishes small positive and negative Dopplers. Operation in the logarithmic domain allows easy application of the Hanning weighing and the normalization, dependent on the desired number of integration, by a simple shift register. This on-line complex spectrum analysis was integrated in the Digisonde 128 PS (Bibl and Reinisch, 1978). In the DGS 256 it is one of the three special purpose computers of the system. A fourth computer, outside the main racks does the post-processing of the data. It is called the Automatic Real-Time Ionogram Scaler with True-height calculation (ARTIST). For display and editing of ionogram data the «ADEP» program was developed (figs. 7 and 8). Many Digisondes 256 have been built and used very successfully in Auroral (fig. 9), Polar, and Equatorial areas. The DGS 256 also became the instrument for a network of automatic stations for the US Air Weather Service (Reinisch *et al.*, 1997). Of extreme importance for the effective use of the fast growing network of digital ionosondes is the simultaneous development of automatic data analysis methods by Reinisch and Huang (1983); Huang and Reinisch (1996), multidimensional display (Bibl, 1973), and real-time data transfer and exchange (Reinisch, 1995). These features were drivers for the development of digital instruments.

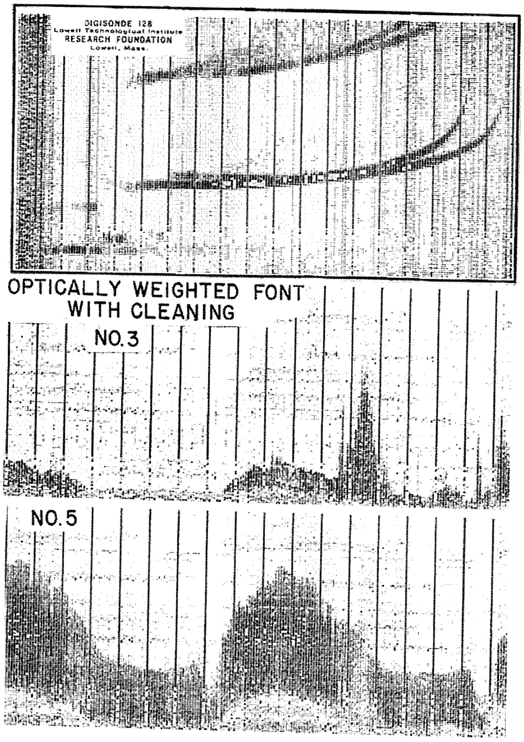

Fig. 6. One of the first digitally integrated, digitally displayed ionograms and computer processed compressed data: $fE + E_s(t)$ and $fF_2(t)$.

With the development of the Digisonde Portable Sounder (DPS 1 and DPS 4) started in 1990 by D.M. Haines and reported best in Reinisch *et al.* (1997), substantial progress was made not because the sounder is portable (fig. 10), but because it can analyze many more data simultaneously. Its use of long transmitter pulses with complementary 8- or 16-chip codes reduces the necessary transmitter power. Storage capacity was increased many times. This avoided the need for the special spectrum analysis, making the sounder part of a smart computer. There is still a special computer employed for the digitizing scheme with ¼ period samples. Cleaning the oscillator frequencies, filtering the transmitter output and tuning the receiver input have substantially reduced the produced interference and the susceptibility to strong local transmissions, requirements for the network of Australian stations supporting the over-the-horizon system. Substantial improvements in automatic processing and remote communication of data took place, including direct connection to the worldwide web (Galkin *et al.*, 1999). A station list is given on http://ulcar.uml.edu.

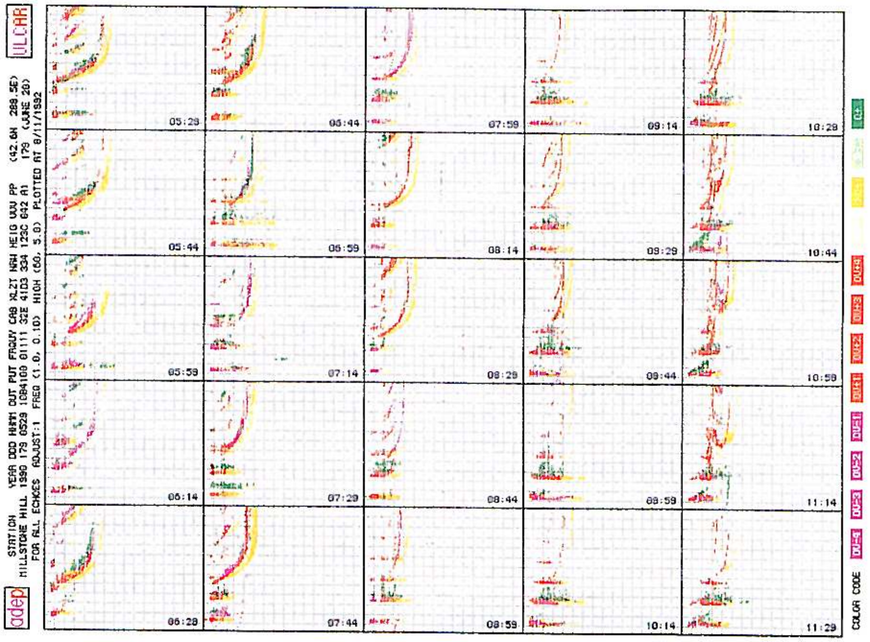

Fig. 7. Half-day half-hour ionograms.

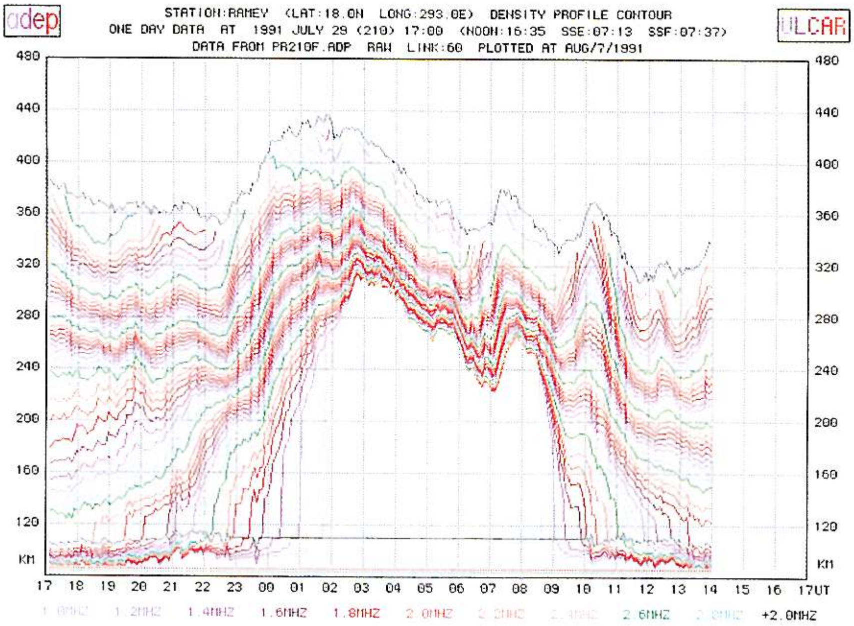

Fig. 8. True-height profile as function of time.

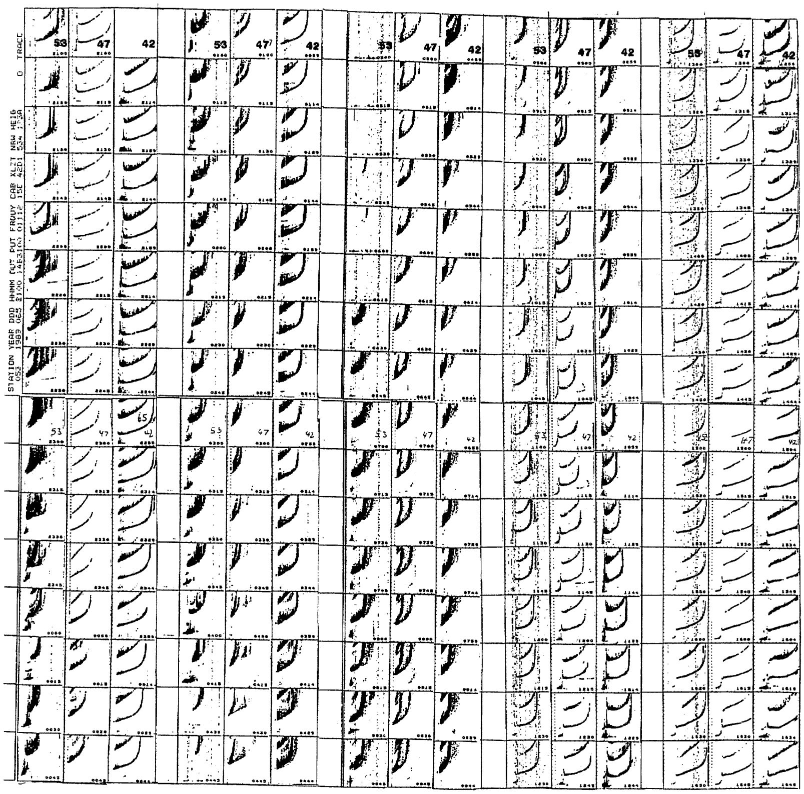

Fig. 9. Movement of high latitude through over three stations.

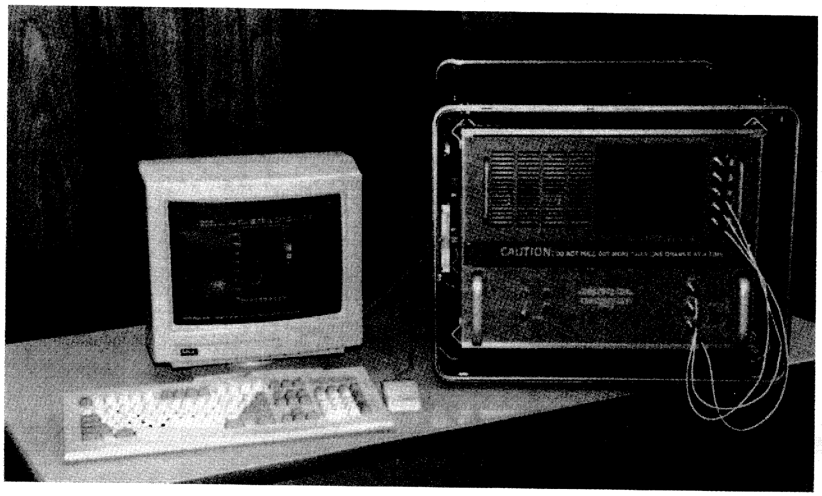

Fig. 10. Digital portable sounder.

5. Parallel developments

Some parallel developments must be mentioned although they took place less systematically. Very successful bistatic oblique links have been established with digital pulse sounders: Goose Bay, Labrador to Argentia, New Foundland, Goose Bay to Lowell, MA (fig. 11); Dourbes, Belgium to Roquetes, Spain; Roquetes to El Arenosillo, Spain. Synchronization became simpler with the advent of inexpensive GPS receivers. It is, however, obvious that the principle of frequency variation, now called «chirp», is basically preferable for oblique sounding when simultaneous vertical soundings are not required and local interferers do not saturate the receiver input. Chirp can use almost 100% duty cycle for the transmitter and can with the same signal/noise ratio and the same transmitter power make faster ionograms with better range resolution. In the DPS pulse sounders the range resolution has been improved by

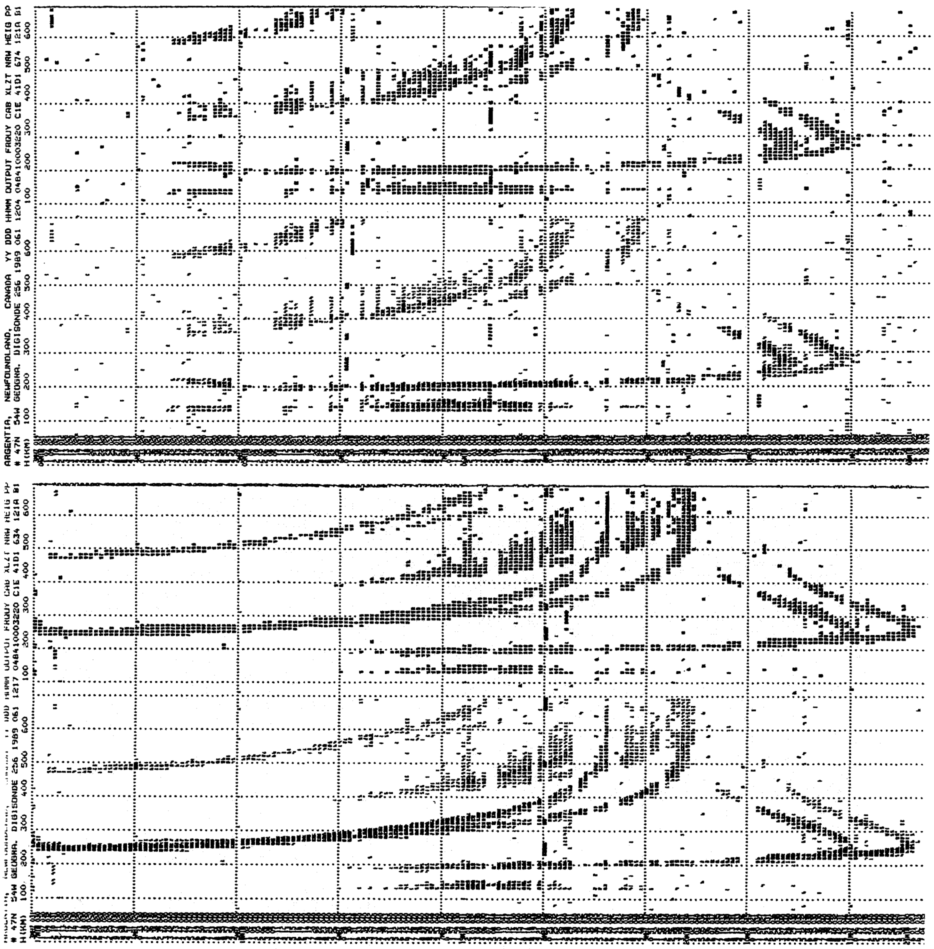

Fig. 11. Sequence of bistatic ionograms between Goose Bay and Argentia, Canada; amplitude and status (Doppler and polarization).

wider bandwidth and smaller transmitter chip length. The phase sounder (Hammer and Bourne, 1976) as well as the Precision Group Height scheme (measuring the phase change with frequency) is practically limited to Radar target-like reflections, like those from the E_s layer or the minima of the ionogram trace, as fixed frequency recordings show.

6. Future ionosondes

Future ionosondes will build on these achievements and will approach the sophistication of modern scientific Radar. The low frequency (3 kHz to 3 Mhz) ionosonde for the RPI space craft will have a 768 bit long staggered pulse code with about 240 transmitter pulses and 400 spaces for reception, allowing 128 samples for each of 128 or more ranges simultaneously. This will reduce sounding time by a factor of 6 and allow measurement of a much wider Doppler spectrum. Increased speed and small size (fig. 12) will also be important for a topside sounder. Ground based sounders can use this scheme too and might be equipped with 4 IF channels to receive simultaneously all four frequencies of a smoothed two-hump transmitter pulse built-up from four square wave pulses of signals 25 kHz apart. A nonlinear spectrum analysis method, developed by the author, might be necessary for optimally analyzing data from the staggered pulse sequence.

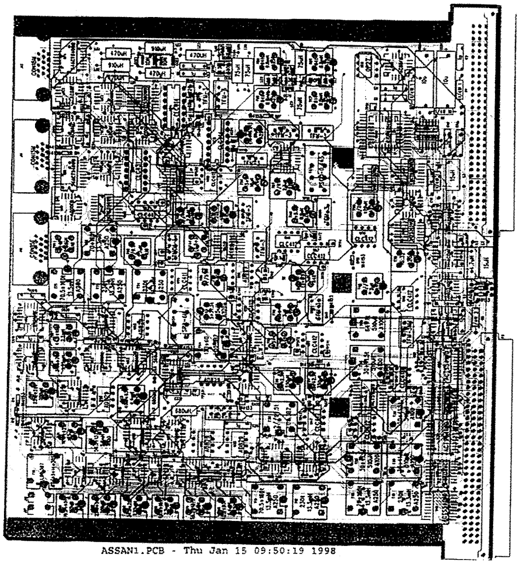

Fig. 12. Analog card #1 of RPI, comprising: receiver, oscillator and transmitter exciter.

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