Abstract: By 1930 it was already plain that electronic technology offered the best hope for future work on the acoustic speech signal. Thermionic valve development, and corresponding advances in circuit design, were opening up new possibilities, and high-quality sound recording was possible on disc or film. The new did not immediately displace the old, and laboratories often made use of incongruous blends of anachronistic technology. The kymograph, with all its failings, continued in use for speech research after the Second World War, sometimes out of necessity, but sometimes also from choice, and it even found defenders against the new technology into the 1950s. Lacerda’s chromograph needs to be studied in the general context of the development of recording oscillographs. The Lacerda chromograph certainly had advantages, but at the same time lacked the engineering refinements that might have turned it into a widely marketable device.

1 Introduction
The purpose of this paper is to furnish some background and context by giving a general idea of the capabilities of some commonly-used phonetics laboratory technology over a roughly thirty-year period chosen to coincide with the most active and original phase of Lacerda’s career. The focus will be chiefly on oscillograph systems—systems for producing records of the acoustic speech waveform or of parameters such as airflow or articulator movement—because the chromograph, for which Lacerda is best known, is a type of recording oscillograph.

Previous general surveys of relevant instrumentation in this period are [7] and [28]. Detailed accounts of recording oscillograph technology more widely are [29] and [19]. The present paper may be seen as a more technical addition to the account given in [25].

2 The electronic revolution
In very general terms, the most prominent area of technological development in this period was analog electronics, a development which was driven by the growth of military and commercial communication, by radio and television broadcasting, the cinema, and the sale of gramophone records and equipment. Until the 1960s electronic circuitry depended almost entirely on thermionic vacuum devices (British English valve, American tube, German Röhre), and the period saw both profound theoretical developments in understanding the physics of vacuum devices and great advances in manufacturing techniques [2]. Increasing sophistication of the active devices was matched by refinements in the design of the circuits which incorporated them.

By 1930 many countries had radio broadcasting stations; radio had become a popular hobby, informed by numerous technical magazines. There was already a radio and audio industry, marketing not only radio receivers, but loudspeakers, gramophone pickups, and countless components and accessories.

It was plain that this burgeoning electronic technology offered the best hope for future work on the acoustic speech signal. It was to take much longer for research on speech production to
benefit from the electronic revolution. Stetson’s influential *Motor phonetics* of 1928 [33], which relies on the mechanical kymograph, was reissued in 1951 and continued to be cited into the 1960s. Writing in 1957, Gunnar Fant declared that although it was ‘ready for retirement’, the kymograph ‘might still find some use for physiological recordings’ [7: 290]. Between 1930 and 1960 the great hope for future work on speech production was the refinement of X-ray studies, particularly of X-ray movies. That enterprise received a direct boost from vacuum tube technology in the 1950s with the development of the (analog) image intensifier, which permitted X-ray filming with much lower radiation exposure.

The latter part of the period under consideration saw also the widespread adoption of magnetic tape recording. This became important not only for the collection and preservation of speech samples (for example in dialectology) but also as an experimental and signal-processing tool in its own right. Repeated and speeded-up reproduction of a magnetic recording underlies the mode of operation of the original speech spectrograph, for example, while various kinds of ‘speech stretcher’ using magnetic tape recording were developed as aids to auditory analysis [6: 37–42], [28: 91–102].

Figure 1. Schematic plan of apparatus.

**Figure 1.** Block diagram showing components of the electroacoustic method of analysis [30: 2]

3  **Old and new**

From about 1930 we begin see explicit references to ‘old’ and ‘new’ approaches in phonetics. A 1934 paper in the journal *Nature* says ‘In experimental phonetics the older mechanical methods still predominate’ and contrasts ‘the new electrical methods of speech recording and reproduction’ [1]. The new approach is often characterised as ‘electroacoustic’. By contrast the old method is commonly referred to as the ‘graphic’ method; of course, the kymograph is meant. The term ‘graphic’ can be traced back to Marey [26] and was retained by others [33], [13].

3.1  **The electroacoustic method**

The electroacoustic method refers to the combination of a microphone (or electrical pickup from a gramophone record), a valve amplifier, and an oscillograph of the Duddell type. Figure 1
shows a contemporary block diagram of the arrangement used in the Chicago laboratory of C. E. Parmenter (1888–1982).

In Figure 2 we see what the equipment looked like in the laboratory. Only the microphone (1), audio amplifier (2), and oscillograph (entirely enclosed in a chest, 5) were commercially-available items; notice the bulky ‘breadboard’ style of construction used for the timer (3), which generated time-marker pulses to be placed alongside the oscillogram and the filter (4) (the purpose of the filter in this particular configuration appears to have been to reinforce the fundamental component which was the object of the investigation).

Figure 2. Equipment used by Parmenter and Treviño c.1932 [30].

3.2 Cost, complexity and results
Whereas a camera making a short record on a length of film mounted on a rotating drum was standard equipment for the oscillograph, the study of longer sequences, for investigations into intonation, required a different kind of camera, exposing considerable lengths of film at rates up to several metres per second in continuous motion (6 in Figure 2). Such a camera could not at this date be purchased off the shelf and had to be designed and built by sophisticated engineering and workshop facilities. Ancillary equipment, such as timers, calibration oscillators, and wave filters, also had to be built in-house. Little wonder that Parmenter and Treviño say of their method ‘It is not simple; it is laborious and expensive’ [30: 1]. It is not surprising either that the number of laboratories fully equipped this way was small. Results, however, were excellent, and permitted not only the determination of fundamental frequency, but harmonic analysis so as to determine vowel resonance frequencies and bandwidths. Figure 3 reproduces sample results from the Milan laboratory of Agostino Gemelli (1878–1959) which was equipped in a similar fashion [11], [10].
3.3 Measurement of fundamental frequency

In Figure 3, the sawtooth waveform at the top overlapping the film perforations has been marked by a second oscillograph channel fed with a 1 kHz signal so as to indicate milliseconds. Waveforms published by Parmenter and Treviño [30: 27] carry a similar time calibration. (Strangely, a time calibration channel is not included on any of the chromograms I have so far been able to examine).

The laborious task of obtaining the fundamental from the waveform is precisely the same as with the kymograph. The wave must be divided by hand into excitation periods (as in Figure 3). The length of each period must be accurately measured, and the corresponding frequency can then be calculated. A 1937 photograph of the Coimbra laboratory (Lopes, this volume, Figure 1) includes in the foreground a commercially-made example of a waveform-measuring instrument designed to ease the task. Resembling a small drawing board with sliding scales, it was first described by E. A. Meyer as early as 1911 and refined by others [28: 50–52], [14: 97], [26]. Hammarström [12] writes about the triangle tonométrique which he used in Coimbra and attributes it to Lacerda, although a later remark indicates that he was aware that it was in essentials a version of Meyer’s device [25: 94].

3.4 The oscillograph

The crucial component in the electroacoustic speech laboratory is the Duddell oscillograph—not a new device by any means, but an item which had been commercially available from 1898 onwards. It was, however, expensive, delicate (and thus easily damaged), and required both photographic processing facilities and expert technical support. By the mid 1920s, multi-channel oscillographs of this type were marketed not only by the Cambridge Instrument Company in the UK, but also by Carpentier (Paris), Siemens & Halske (Berlin), and by both General Electric and Westinghouse in the USA [16: 38]. The instrument shown in Figure 2 is a model from General Electric.

The oscillograph was, of course, a general purpose electrical measuring instrument, used for many other scientific and engineering purposes, but its excellent high-frequency response fitted it very well for the application to speech. Duddell himself published detailed oscillograms of various speech sounds as early as 1906, made with a telephone-type carbon microphone. The arrival of good-quality microphones and valve amplification greatly extended the usefulness of the oscillograph.

4 The kymograph—its disadvantages and defenders

The kymograph was a cumbersome and inconvenient instrument, and it is perhaps surprising that there is not more recorded anecdote and reminiscence about the trials and misadventures of using the kymograph for speech research. A richly documented account is provided by [21] of experiences in the teaching of medicine, another field where the kymograph was employed over a long period, and it is hard to believe that what is recounted there was not paralleled in the phonetics laboratory. Eli Fischer-Jørgensen does tell us that in Paris the kymograph used by Marguerite Durand was so antiquated that it could only be persuaded to run by emptying a
bucket of water over the drive mechanism [9]. Nevertheless she persevered in using it, and indeed produced publishable results [4]. In 1956 Marguerite Durand specifically points out that one of the advantages of the kymograph is its cheapness in use: ‘Le kymographe est l’appareil le plus en usage, à cause de la facilité et du faible prix de revient de son maniement’ (The kymograph is the most used instrument, on account of the ease and low cost of using it) [5: 156].

The contrast between the lavishly-equipped laboratories of Parmenter or Gemelli and the decrepit instrumentation available to Marguerite Durand in Paris could hardly be greater. From the 1930s great inequalities in budget and facilities must have begun to appear between laboratories in different centres. Those who had to make do with outdated equipment tried to put a brave face on things, and remained proudly loyal to what they knew, even maintaining that there were some advantages in simplicity and cheapness. This can be detected in the otherwise accurate and generous reviews of works by Gemelli and Parmenter contributed to *JIPA* by Stephen Jones (1872–1942) towards the end of his career in London [17], [18]. As late as 1959 the London linguist J. R Firth, writing in a *Festgabe* for Panconcelli-Calzia, tries to argue that the kymograph has some advantages over the (cathode-ray) oscilloscope, claiming ‘The cathode ray oscilloscope, however used, may often present too much information or indeed irrelevant information. Properly used, the kymograph is still a key instrument in any laboratory which is to serve linguistics’ [8: 35]. His remarks nicely illustrate the sometimes irrational loyalty people exhibit for the methods and tools they know and have invested in.

The kymograph had a long list of disadvantages, but they can be largely placed under two headings. One of these concerns the marking or recording system—the smoked paper, which had not only to be made—laboriously and hazardously—just before use, but also needed to be fixed by varnishing before a completed kymogram could be handled and measured. The other category of disadvantage concerns the transducers—the tambours or capsules which responded to air-pressure differences and converted them into physical movements of a marking lever. These required great dexterity to set up, had unpredictable and variable characteristics, and had never been intended for anything other than slowly-varying physiological parameters. Typically they had prominent resonances in the audio range [15] and indeed the production of kymograms with reasonable amplitudes probably depended on the deliberate and skilful exploitation of resonances.

There is some irony in the fact that the publication for which Lacerda is best known—the celebrated monograph which he published jointly with Paul Menzerath [27]—reports research which was carried out not with the chromograph of Lacerda’s own invention, but with the conventional kymograph which the chromograph was intended to replace. From this we may at least conclude that Lacerda was well practised in using the kymograph and that his desire to improve on it grew out of experience.

Lacerda gives a detailed critique of the kymograph [23: 68–78], dwelling not only on the time-consuming practical drawbacks of the device, but also highlighting more fundamental problems. He points out that the mouth curve is an unsystematic mixture of aerodynamic and acoustic registrations, that the behaviour of the system depends on the control of air venting (e.g. from the mask), and also claims that the varying thickness of soot deposited when the paper is smoked before use leads to uncontrolled variation in friction encountered by the marking stylus.

5 Lacerda’s innovations

As Lacerda—and many other inventors—pointed out, a direct ink record on plain paper is a big improvement over smoked paper. The only other real alternative—photographic recording—was much more expensive, not only from the cost of materials but because a darkroom and
processing facilities were required. But Lacerda also set out to improve the transducers, particularly to produce a device that could cope better with the bandwidth of the speech audio signal.

5.1 Electrical registration on the kymograph

Around the same time, others pursued the idea of electrical registration onto the conventional kymograph recording surface rather than photographic film. In fact electrical recording onto the kymograph wasn’t new. It is described by Rousselot, who used a carbon microphone and an electromagnetic marker, apparently of his own design. It was actually Viëtor who noted that the mouth channel of the kymograph, which had originally been intended for slowly-varying airflow and pressure indications, sometimes showed details of the acoustic speech wave. This unintended and rather unsatisfactory use of the channel became the norm. Often it was the only channel recorded, so that the kymograph came effectively to be used as an oscillograph, and attempts were made to develop tambours better able to deal with signals in the audio range. Sometimes, two tambours with different characteristics were joined in parallel to achieve better coverage. This can be seen in the photograph of Lacerda’s first polychromograph [22; 178], where two inputs (evidently mouth and larynx) are led to a total of four tambours.

The coming of valve amplification revived interest in electrical registration on the kymograph. At the first ICPhS in Amsterdam in 1932—and in the same session as Lacerda demonstrated the first polychromograph—Kurt Ketterer showed speech waveforms produced this way from gramophone records [20]. His device is a slightly-modified moving-iron loudspeaker of the day, adapted to move a marking lever rather than a loudspeaker cone. The moving-iron loudspeaker soon gave way to the moving coil pattern (which is still used today). By 1941 Heffner [13] describes adapting the more modern type of loudspeaker driver for the same purpose of moving a kymograph marker.

Heffner also describes putting a small microphone inside a kymograph mask, so as to collect simultaneous audio and airflow information, and this arrangement continued to be used for more than 20 years in those centres where partly-electrical kymograph recording continued. The last generation of publications which continued to use conventional kymography for flow and pressure registration [33] typically have an electrically-recorded audio channel alongside the channels from conventional tambours. Well into the 1950s the electrically-driven marker is widely referred to as a Ketterer-Schreiber [32; 120, 174, 181].

5.2 The chromograph in context

A large number of (partly) mechanical oscillograph systems were described over the first half of the twentieth century. They were hardly attempts to improve on the Duddell oscillograph (since that already did everything that was needed), but rather to achieve comparable results more cheaply. It was against this background that the chromograph emerged. As Lacerda himself put it ‘Wie wir wissen, ist von allen Methoden die Oszillographie die vorzüglichste; leider können sich nur wenige Forscher des Vorteils ihres Gebrauchs erfreuen; nicht nur wegen des hohen Preises solcher Einrichtung, sondern auch wegen der riesigen Unkosten, die die Aufnahmen nach diesem Verfahren dem Phonetiker verursachen würden’ (As we know, of all methods, oscillography is the best; unfortunately only a few researchers can enjoy the benefit of using it, not only on account of the high price of such equipment, but also because of the enormous running costs) [23: 108].

The chromograph is a type of inkjet oscillograph. Plainly, if a stream of ink is to be used to mark an oscillograph record, the motion of the paper supplies the x-axis or time dimension. The y-axis requires movement of the jet along a path at right angles to the paper motion. There are two ways of achieving this. Either the nozzle from which the ink is ejected can be physically steered to point in different directions, or alternatively the ink can be launched from a fixed nozzle and then deflected while in flight by bringing some or other physical force to bear upon
the ink itself. Lacerda describes devices which work both ways. The first kind of chromograph essentially reproduces the capabilities of the kymograph but without the smoke and soot. An inkjet nozzle takes the place of the marking lever, and is directed to and fro by movement of a conventional capsule membrane [22]. The Mingograph, which was to be the only widely-used inkjet oscillograph for speech research, also worked this way: it is basically a Duddell oscillograph which steers an ink nozzle in place of the regular mirror deflecting a light beam onto photographic film.

5.3 Fundamental limitations
In the 1950s a Swiss engineer Dreyfus-Graf published a series of papers dealing with the general possibilities for inkjet recorders of the type where the inket is physically steered (see [3] and references therein). His calculations indicated that as the upper frequency limit is extended, a situation is soon reached where impracticable levels of deflection energy are required. He concluded that although such devices offered great advantages in convenience and cost of operation, they were effectively limited to an upper frequency of about 500 Hz. This estimate turned out to be of the right order of magnitude. Gunnar Fant worked with the Mingograph and claimed that it was useable up to about 800 Hz [7: 326]. The solution advocated by Dreyfus-Graf was frequency division by radically slowed reproduction (as much as 20x) from a magnetic recording, which in principle could extend the range to 10 kHz.

As for the alternative approach of deflecting the inkjet during transit, a variety of physical effects were suggested and explored. The most satisfactory of these was probably electrostatic deflection, which was brought to a high degree of perfection by an engineer called Sweet in the 1960s [35]. But there is no indication that Sweet’s device got any further than the prototype, and electrostatic deflection was not one of the methods tried by Lacerda. The basis of the Lacerda chromograph is deflection of the inkjet by means of an impinging air-jet. At the time of writing no other system which worked the same way has come to light.

It is at present impossible to be certain what bandwidths were achieved with the chromograph. Hammarström claims that the system he was using in Coimbra in the 1950s had a frequency response extending to 5 kHz, although he gives no evidence to support this. Fant [7: 326] also appears to suggest that the chromograph out-performed the Mingograph but likewise gives no evidence (perhaps he relied on Hammarström’s account). It is unclear whether the two-jet system can escape the limitation identified by Dreyfus-Graf.

6 Understanding the chromograph
The chromograph took a variety of forms. Lacerda gives a classification of types of chromograph as early as 1934 [23] though that account is made somewhat difficult to follow by an unhelpful page layout and at least one wrongly-numbered footnote. Lacerda’s classification relies on three levels of sub-heading (for example A.II.b.) but this does not seem to be exhaustively followed-through.

The first level of division is between ‘mechanical’ and ‘electromechanical’. Surprisingly, this refers not to the mode of operation of the chromograph device itself, but to the form in which the input signal is supplied. There was some attraction to an entirely acoustic mode of operation, even as late as the 1930s. For a time, the chromograph offered the prospect of obtaining reasonably high-quality speech waveforms without the expense and complexity of the ‘electroacoustic’ laboratory set-up. Cost was not the only consideration. Lacerda [23: 108] indicates that in the early days electroacoustic systems gave trouble from power supply fluctuations and instability in the amplifiers.

The ‘pneumochromograph’ is one in which the ink-jet is deflected by airflow controlled by the input signal, but a further subdivision is made according to whether the airflow pulses are
simply those resulting from motion of a diaphragm within the device (this tends to produce a half-wave rectification of the signal), or whether alternatively the device is supplied with a constant stream of air which the input signal is caused to modulate.

It is not always easy to establish which form of the device was used for particular published studies. In Figure 3, though no reproduction scale is given, the apparently small size of the waveforms (when compared with the handwritten figures and the evident thickness of the lines) may suggest that they were plotted with an acoustic form of the device, where little energy was available. As the wave does not seem to exhibit rectification we may probably further infer that the chromograph which was employed was a type with a constant stream of air.

![Figure 3](image-url) Chromograms published in [24], showing division into pitch periods for fundamental frequency determination. (Millimetre scale at bottom added by the author to show page size).

The mature form of the device, as utilised by Hammarström [12] and described by him (Figure 4), accepts an electrical input signal which is made to modulate the strength of a continuously-running air-jet A, directed at the ink jet T so as to deflect it. At rest, just the right amount of air is allowed to escape steadily so as to bring the ink jet to its mid position on the zero line (between positions 1 and 2). The input signal produces to-and-fro movement of the blade L of which the tip 1 intercepts the air flow. Hammarström does not say how the electrical modulator was fabricated, although a pre-war version, described in [23: 99], was based on a commercial loudspeaker, the air-control blade being fixed to the centre of the diaphragm.

One thing that is quite clear is that the system will require very delicate adjustment and alignment, so that much training, practice and patience are likely to be needed in setting it up.²

6.1 Longevity of the chromograph

What sets the chromograph apart is that most of the other proposals for more affordable oscillograph alternatives seem to have had little use beyond their first demonstration and announcement. In most laboratories, the kymograph remained in use until it was eventually abandoned in favour of an all-electronic approach—and indeed many laboratories never owned a high-performance oscillograph but progressed directly to the sonagraph. In the post-war era the speech spectrograph quickly became the single most important laboratory instrument. For the examination of waveforms the cathode ray oscilloscope was widely available, though by no means all users had the means of photographing its traces to make them permanent. The plotting of waveforms—if attempted at all—relied on the Mingograph (also known as the Oscilomink), or, where a wider frequency response was required, a type of oscillograph which recorded directly onto special paper sensitive to ultra-violet

![Figure 4](image-url) Schematic diagram of an electrically-driven pneumochromograph [12: 31].
light [28: 55–56] without the need for chemical development.³ This eliminated the requirement for a darkroom and processing facilities, although the high cost of materials was still a factor. It would not have been feasible to use the device to collect fundamental frequency data in any quantity.

Against the background of all this change, versions of the chromograph continued in use (with some interruptions) for a total span of about 40 years and the device was used to generate a considerable body of data. The chromograph was synonymous with Lacerda’s name and became the unique selling point of the Coimbra laboratory where it was used.

6.2 The chromograph in the wider world

In 1957 the widely-read British weekly periodical The New Scientist published a news item announcing that the Swedish firm Elena was producing an inkjet oscillograph ‘said to allow frequencies of more than 1,000 cycles a second to be accurately shown’.⁴ This is the device we know as the Mingograph or Oscillomink.⁵ The news item was evidently seen by Peter Strevens (1922–1989), who had spent time in Coimbra in 1955 and was now at the University of Edinburgh. Soon afterwards, the journal published a letter from Strevens calling attention to Lacerda’s chromograph.⁶ He says that this ‘may be the first occasion on which such an oscillograph has been produced by a commercial firm but an instrument using the ink-jet method was constructed in 1932 and has since been developed to a considerable state of reliability for phonetic research’. He gives details of Lacerda’s position and laboratory, and refers to the account of the chromograph by Hammarström [12]. But of course what Strevens could not do was refer to any commercially-available version of the device, or to any patent specifications, nor even to any readily accessible technical account of it (still less a quantitative analysis of its operation). The chromograph remained something of a private secret, and was never used outside a Portuguese-speaking environment.

The chromograph would have required considerable refinement to be made into a device that might be marketed, or even for a small number of them to be installed and operated anywhere without the direct supervision of its inventor. We know little about the ink formulation that was used, for example. Hammarström mentions a dye solution, though in fact practical inks require other constituents too—at least some kind of surfactant to promote uniform wetting of the paper surface and ensure reasonable drying time. It may be wondered whether the unusually long paper path seen in photographs of the Coimbra installation, taking the form of an endless loop, might have been necessary because the ink did not dry quickly enough to allow the paper to be spooled without blotting. Certainly a much less cumbersome paper transport system would have been needed for a commercial device. The manufacture of the necessary fine glass jets would also have required standardisation, and the device would have needed some means of metering and regulating the rate of ink flow. Some surviving (unpublished) chromograms exhibit somewhat thick traces, as if through flooding of excessive ink, and Fant also notes that the chromograph was ‘not capable of producing equally fine traces as the Mingograph’ [17: 326].

Suitably engineered, the chromograph might have fitted into a suitcase; indeed the first poly-chromograph of 1932 was a compact table-top device. But in Coimbra—and later in Bahía—it assumed an almost industrial scale.⁷ It was allowed to be implausibly large and to dominate the laboratory, and perhaps its impressive size even helped to stake a claim over a lot of real estate.

7 Acknowledgements

I am grateful for valuable comments and corrections from two reviewers.

References


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1 A reviewer has drawn my attention to illustrated reports published by Gemelli as early as 1932. At the time of writing I have not had an opportunity to examine them.

2 A particular difficulty will be to ensure that deflection from the air-jet is entirely confined to the direction at right angles to the paper travel. If the inkjet is caused to move even slightly along any other path the effect will be crosstalk from the y-axis to the x-axis and consequent distortion of the waveform. In extreme cases the resulting curve may be multi-valued from apparent retrograde movement in time. Some early chromograms do perhaps exhibit this problem. Some of the curves illustrated in [23] seem to have a (physically impossible) leaning or hooked appearance (see for example those in the plate on page 93).

3 Mettas [28: 55] describes the use of a fixer for long-term preservation of the record, but this was not usual or necessary with the system used by the author in the 1970s. Oscillograms made half a century ago and since stored in darkness are still in perfect condition.

4 28 Feb 1957, page 19.

5 R. Elmqvist filed US patent 2566443 for the device in 1949 and the patent was granted in 1951. A detailed account of the operation of the Mingograph is given by Keinath [19:13].

6 March 21 1957, page 41.

7 The most extraordinary example of this is to be seen in the gigantic air compressor visible in the photograph of the Bahia laboratory. With a reservoir probably holding several hundreds of litres of air and a motor of a size to produce several horse power, it is evidently an industrial type pressed into service, and must far exceed the compressed-air requirements of the chromograph. Even more puzzling than the use of such a grotesquely over-sized unit is the fact that it is installed in the laboratory alongside the delicate chromograph itself—indeed it appears to have been given pride of place. A noisy and potentially hazardous machine, it would normally be sited well away from a working area (maybe in a cellar or separate room) and connected by an air line. One can’t help speculating that part of its purpose might have been to impress.