PHOTOMETRIC ATLAS OF THE SOLAR SPECTRUM
FROM λ 3000 TO λ 10000

I. INTRODUCTION

During the last ten years, the methods to record the solar spectrum at very high resolution have very much improved. ln our opinion, two different directions have brought essential progresses.

The first improvement concerns the quality of the instrumental profile of large grating spectrometers. Already in 1964, two of the authors of this work (L. D. and G. R.) showed the very great interest to use a grating iri a double pass arrangement, with a narrow intermediate slit. The resulting instrumental profile is reaIly limited to a narrow spectral region.
It is free from aII the satellites, periodic or not, due to the imperfections in the ruling of the grating. Thus, one of the sources of scattered light is suppressed. Besides, further corrections for the effect of the instrumental profile becomes easier. The experimental works which permitted us to show these advantages have been greatly facilitated by the availability of stabilized lasers, emitting in single mode, at different wavelengths.

More important improvements were obtained in a second direction, through the increase of the signal to noise ratio which can be reached by giving up the old method of slow scanning. J. W. Brault, at the Kitt Peak National Observatory (Tucson, Arizona, USA), studied the properties of the « atmospheric noise » always present in all the ground based observations. He showed that the amplitude of the elementary components of that noise decreases as its frequency increases. ln a given total observation time, an important gain can be obtained by shifting towards the high frequencies the domain which contains the requested information, i.e. by scanning rapidly the spectral region to be recorded. Such rapid scans are repeated, and the successive spectra are added up in order to produce the final result. Here again, the help of a new technique was necessary : it is only thanks to the development of fast and relatively cheap electronic computers, designed for real-time data acquisition, that this technique of rapid scanning became practically possible.

We thought it useful to modify the large solar spectrometer installed by the University of Liège at the International Scientific Station of the Jungfraujoch (Switzerland), to take advantage of both the double pass and the rapid scanning systems. The results obtained fully confirmed what we expected. We then decided to systematicaIly remap, for publication, the photospheric solar spectrum from λ 3000 to λ 10,000.

In submitting the result of our work to its users' criticism, we would like to pay homage to the authors of the Utrecht Atlas (*). That work remains an example for aII the observers. It has been used as a source of basic data in so many works. May this atlas be weIlcome as its worthy successor.

II.1. - *Coelostat and telescope.*

The coelostat, with its associated guiding electronics, and the telescope have been described in the near infra-red solar spectrum atlas published in 1963 (*). We refer the interested reader to that description.
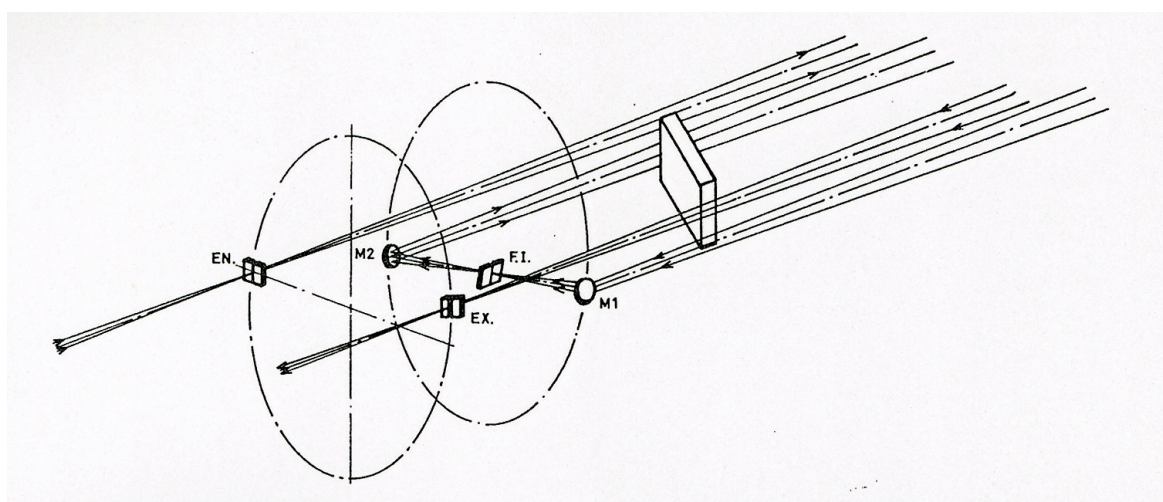
11.2. - *Monochromator.*

This accessory has also been described in the 1963 atlas. We must however mention that we now have different prisms, in LiF or fused silica, allowing us to choose the most favourable dispersion for each studied region.

II.3. - *Spectrometer.*

Again, the general characteristics of this instrument can be found in the 1963 atlas. Many important modifications have however been made in view of the present work; before a rapid description of those, we must mention that, this time, the spectrometer optics worked under a pressure of about one mm of mercury in order to avoid the perturbing effects from convective motions of air in the optical path.

II.3-1. - *Double pass.*

The optical arrangement of an Ebert-Fastie spectrometer is particularly easy to modify in order to work in double pass. A small plane mirror M1 sends the incoming beam of the first pass on a slit located behind the grating. The width and the position of this intermediate slit can be modified, by remote control, from an external control panel. The light passing through the intermediate slit F.I is sent back to the main mirror and to the grating by means of a second small flat mirror M2, just below the beam entering the spectrometer. The exit

slit cornes in EX, at the converging point of the rays coming back from the second pass, just above M1. A shutter, also under remote control, can interrupt the optical path, behind the intermediate slit. ln this way, we can measure the zero position of each record. Under these conditions, the scattered light passing through the exit slit and coming, either from diffusions by nonperfect optical surfaces or from undesirable reflections in the instrument, remains present when the zero position is recorded. Thus, it is not included in the measurement of the signal from that zero value.

II.3-2. - *Rapid scanning.*

The.rotation mechanism of the grating is essentially still the same as the one described in the atlas of 1963. We rnust recall that "the fast motion" is obtained by turning the platform supporting the grating about a vertical axis positioned by precision ball-bearings. The "slow motion" is produced by a sliding nut on a precision screw pulling a thin ribbon of steel rolling onto an arm fixed to the grating axis. The constant tension is maintained by a counterweight system. A rapid scanning system has however been added. The ribbon is now fixed to the platform by means of a lever. The "slow motion " having brought the grating to a given incidence angle, a back and forth oscillation of the lever then produces a scan on both sides of a mean position. The lever oscillation (at constant angular speed) is obtained from the linear motion of a piston moving in a cylinder, by means of a metallic strip rolled onto a portion of a cylinder fixed to the lever. For each scan, the piston is displaced at a constant speed, in a way producing an increase of the incidence angle on the grating. A complete scan lasts 50 seconds and corresponds to a rotation of 15'50". The return is made rapidly, in roughly one second. Two important accessories are attached to the piston. First, a " position transducer" which gives an electrical voltage varying linearly during the motion of this piston, with an accuracy of about 2 %. Second, a cube-corner trihedral reflector placed in one arm of a two-beam interferometer. This interferometer is illuminated by a monochromatic He-Ne laser beam. Its transmission varies periodically when the piston moves. A phototransistor converts the optical fringes in an electrical signal, amplified and then clipped. One rising edge of that signal thus appears each time the piston has been displaced by a distance equal to half the wavelength of the laser line, i.e. each time the incidence angle on the grating increases by 0.024". As we shall see hereafter, these rising edges will command the successive readouts of the spectrometer output signal.

11.3-3. - *Ratio recording.*

A very thin glass plate is installed behind the spectrometer entrance slit, at an angle of 45°. It reflects about five percent of the incident light to a diffuser located in front of a photomultiplier. The output signal from this detector gives, at each moment, a measurement of the total quantity of energy entering the spectrometer, after filtering by the monochromator.

lIA. - *Detectors and associated electronics.*

For the observations covering the region λ 4300-λ 6200, commercial (but selected) photo multiplier tubes EMI 9558QA and EMI 9659AM have been used. At longer wavelengths

we have chosen the new RCA tubes C 31034A and C 310340. ln the ultra-violet, we have adopted a twenty-stage photomultiplier made under the direction of A. Lallemand at the « Laboratoire de Physique Astronomique de l'Observatoire de Paris ». This tube has an Sb-Cs photocathode (response similar to that of an S5) ; equipped with a very thin glass window, it is sensitive down to 2400 angströms.

An electronic microammeter, with fast response, (Keithley type 417), used normally on its full scale 3.10^{-8} ampère range, provides an electrical voltage proportional to the output current of the detector. This voltage is low-pass filtered, and then slightly amplified in order to make the best use of the range from 0 to 10 volt of the analog to digital converter of the computer.

A memory oscilloscope displays this signal in the Y axis. The X sweep is obtained by means of a saw~tooth voltage coming from the above mentioned position transducer (11.3-2.). Thus, the spectrum corresponding to each scan is drawn on the oscilloscope screen. With the practice, this stable visualization of the covered spectral region has appeared extremely useful, not only when the operator must bring the grating exactly in the mean desired position, but also during the observations: thanks to the memory ability of the scope we may, at any time, check whether aIl the scans are well superimposed.

III. ELECTRONIC HANDLING OF THE DATA

III.1. - *Computer and peripherals.*

A Honeywell DDP-224 electronic computer is installed at the Jungfraujoch laboratory. It is a processor specially designed for real time control and data acquisition, but with excellent capabilities as a general purpose computer. Here are shortly its principal characteristics. The core memory has 16K words of 24 bits, with a read-write cycle of 1.9 microseconds; it also includes a hardware floating point option so that the execution time for the corresponding instructions is very short. The available peripherals are: an input-output typewriter - a line printer - paper tape reader and punch - digital graph plotter - three magnetic tape units - an additional memory of 524,000 words, on fixed head discs, mean access time 10 milliseconds - one analog to digital converter (binary output with a precision of 14 bits plus sign and a conversion time of 20 microseconds). A multiplexer allows, by program, to connect any of its 32 possible analog inputs to .the converter.

III.2. - *Data acquisition program.*

During the observations, the spectrometer is essentially under the control of the computer. Only the choice of the region to record, the correct adjustement of the monochromator and the checking of the position of the intermediate slit remain under the responsability of the observer.

The computer reads the date and the time from a digital clock, prints the time and the computed air-mass. It then closes the shutter behind the intermediate slit and determines the zero value as a mean of 6000 measurements made under these conditions, and gives the return order to the scanning system. Then starts the recording procedure.

Each measurement, as we have already said, is triggered by the signal coming from the interferometer which controls the grating rotation. This signal produces the switching from the main program to a "measure routine", and gives the multiplexer and the A-to-D converter the necessary orders for the successive readouts (at 20 microseconds interval) of the output signal and of the reference signal measured at the entrance of the spectrometer. It takes the ratio of these two values, stores the result of this division in memory and then sends the computer back to the main program.

During each scan, roughly 800 measurements are made per second. The main program performs a low pass numerical filtering of the data, after which the number of points kept is divided by 8, thus bringing the rate down to about 100 per second. A scan normally contains 5000 points after filtering and it ends by order of the computer. During the returns of the piston to the origin of its successive scans, those blocks of 5000 points are stored on the disc, one after the other. When the computer reaches the number of scans requested, it stops the recording process, reads the time, computes the new air-mass, closes the shutter and measures the zero position again. It then reads, from the disc, the spectrum corresponding to the first scan and searches for the sharpest absorption line in that record. Then, it makes the summation of all the successive scans, by looking for the shift in abscissa which gives the best fit with the first spectrum by correlation in a narrow spectral range near the chosen line. For 50 scans of 5000 points each (which have taken a little less than 45 minutes), the DDP-224 roughly needs 25 seconds to make the addition. The result is transferred on magnetic tape with other useful information (wavelength of the beginning of the record, order, date, time at the beginning and end of record, zero positions, mean air-mass, slit widths, etc ...) then the computer calls the observers for new instructions.

III.3. - *Further data handling.*

We do not plan to describe here all the programs allowing to read data from magnetic tapes, to copy them, to sort them, to make the index of a tape, to search for a given region and to draw it on the graph plotter, to add, with the best possible fit, two or more records, etc...

We shall only insist on the few programs which have been determinant for the preparation of the present atlas.

The records are first treated by a numerical low-pass filtering program where the band-width is automatically adapted to the local conditions: for example, the filtering is less important in the vicinity of the atmospheric lines, as these are particularly sharp.

A human decision is then required : the position of the local continuum, i.e. the level which, after reduction, will correspond to 100 % of the intensity scale, must be chosen on each record and defined in a sufficient number of points. The exact wavelength and the position of one line per plate must also be given to the computer. On the basis of these data, and of a table of exact positions of photospheric lines (*), a program successively

handles aIl the records made in a given order of the grating. It « straightens » the spectra in order to have a horizontal continuum, fits together the different records, determines the wavelength scale to obtain the best fit with the table and, finaIly, resamples the tracing at two milliangstroms intervals. The spectral intensities are then written on magnetic tape, in blocks of 500 points, each corresponding exactly to one angstrom and preceeded by shorter blocks, containing various useful technical informations.

A last program makes the final drawing of the spectra in the adopted form for the present atlas.

IlIA. - *Instrumental profile.*

After a long hesitation and numerous discussions, we have decided not to correct our data for the effect of the apparatus function. For anybody wishing to apply such a correction, we publish the instrumental profile of our spectrometer, recorded in the different orders of the grating.

An ionised krypton laser, in the cavity of which a suitable Fabry-Perot etalon is inserted to select single mode operation, has been used as a monochromatic source for each. of these observations. These records have been taken under the exact conditions of the solar observations, we mean in rapid scanning, with addition of many different tracings and, of course, with the same slit widths.

IV. DESCRIPTION OF THE TRACINGS

A linear wavelength scale has been chosen, corresponding to 50 mm per angstrom. On the other hand, the DDP-224 computed and marked out the wavenumber scale during the drawing process itself(*).

As a rule, each plate covers 10 angstroms, with an overlap of 1 angstrom between two successive records. A few tracings have been drawn on a smaller wavelength scale to show particularly broad lines over a sufficiently large extent on a single plate. Whenever useful, two tracings are produced, the first corresponding to a normal intensity scale, from 0 to 100 percent, the second spreading « full scale » the section from 80 to 100 percent, to allow precise measurements of faint lines.

No attempt has been made to define the exact position of the continuum. As mentioned (IlI.3.), we have just straightened all the records in order to offer an atlas of photospheric lines which should be easy to use.

The wavelength scale directly gives the photospheric lines positions measured in air, corrected for the Doppler shift corresponding to the displacement of the Earth relative to the Sun. The corrections have also been applied to the telluric lines. The positions of the latter are thus approximate and can therefore not be used as such for very high precision molecular spectroscopy work. We have tried, above all, to put at the disposaI of the scientific community an atlas of photospheric lines, accepting as a result to give up a large part of the available information concerning the telluric absorptions.

(*) The Edlén's formula *(J.O.S.A.* 43, 339, 1953) has been used to obtain vacuum wavenumbers from wavelengths in air.

Whenever possible, we have selected, amongst all the records made, those in which the telluric lines were the weakest.

Our plates being practically always means of observations made at different dates, the relative intensities of the atmospheric lines have a meaning only if they are measured in narrow spectral regions corresponding to identical conditions of observation. Small vertical marks, drawn just above the spectrum, indicate the limits of the regions within which all the atmospheric absorption conditions remained constant.

V. ACKNOWLEDGMENTS

(*) At present working with the Belgian Burroughs Company.

Original Babcock grating : 600 lines per mm

ruled area 202 X 130 mm

Limits of the orders :

2991 to 3314.998 : 9th order
3315 to 3584.998 : 8th order

Bausch and Lomb grating : type 35-53-32-45

300 lines per mm
ruIed area 256 X 128 mm
blaze angle : 63°26'.

Limits of the orders :

3585 to 3762.998 : 16th order
3763 to 4005.998 : 15th order
4006 to 4293.998 : 14th order
4294 to 4649.998 : 13th order
4650 to 4998.998 : 12th order
4999 to 5499.998 : llth order
5500 to 6107.998 : 10th order
6108 to 6876.998 : 9th order
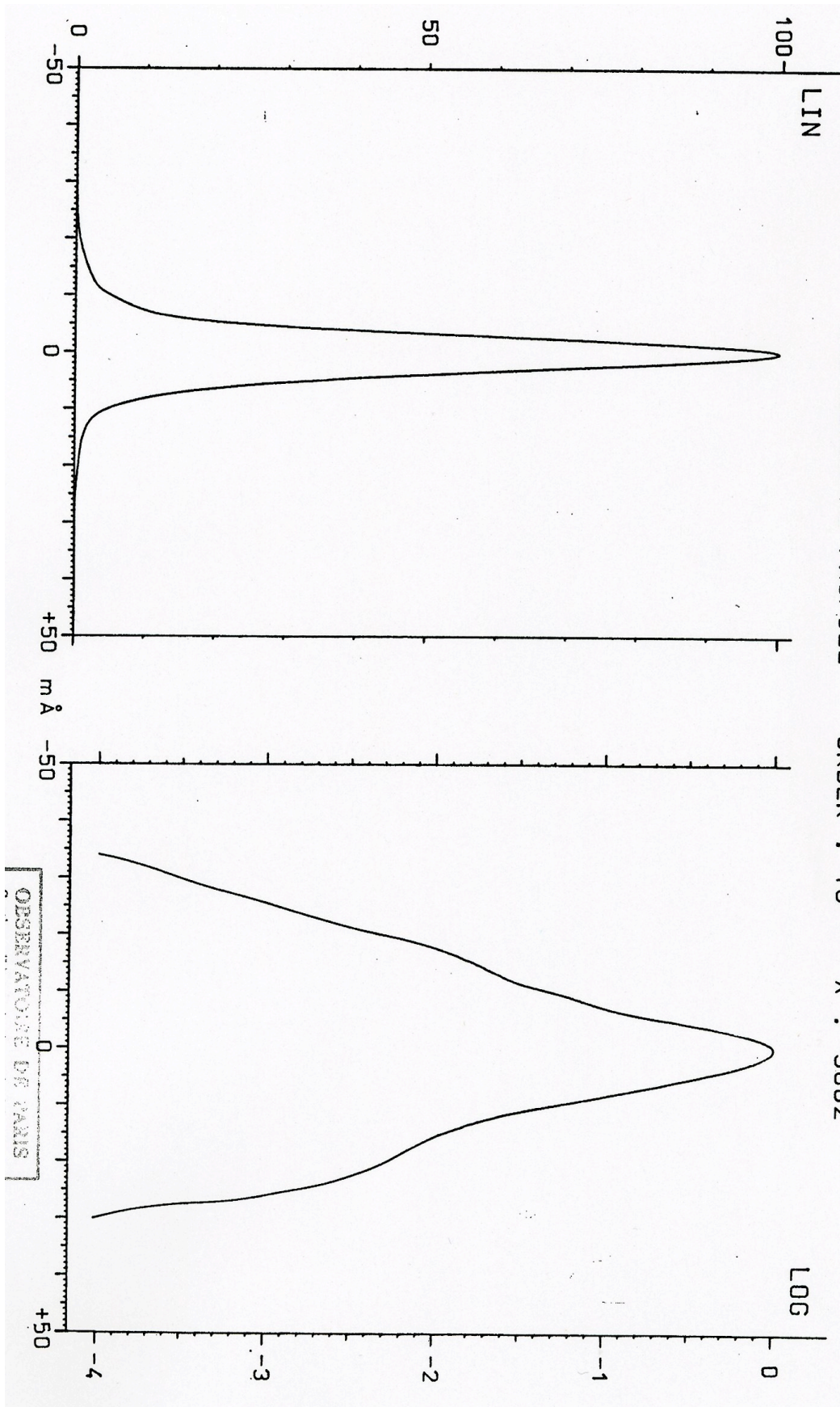6877 to 7770.99S : 8th order
7771 to 8695.998 : 7th order
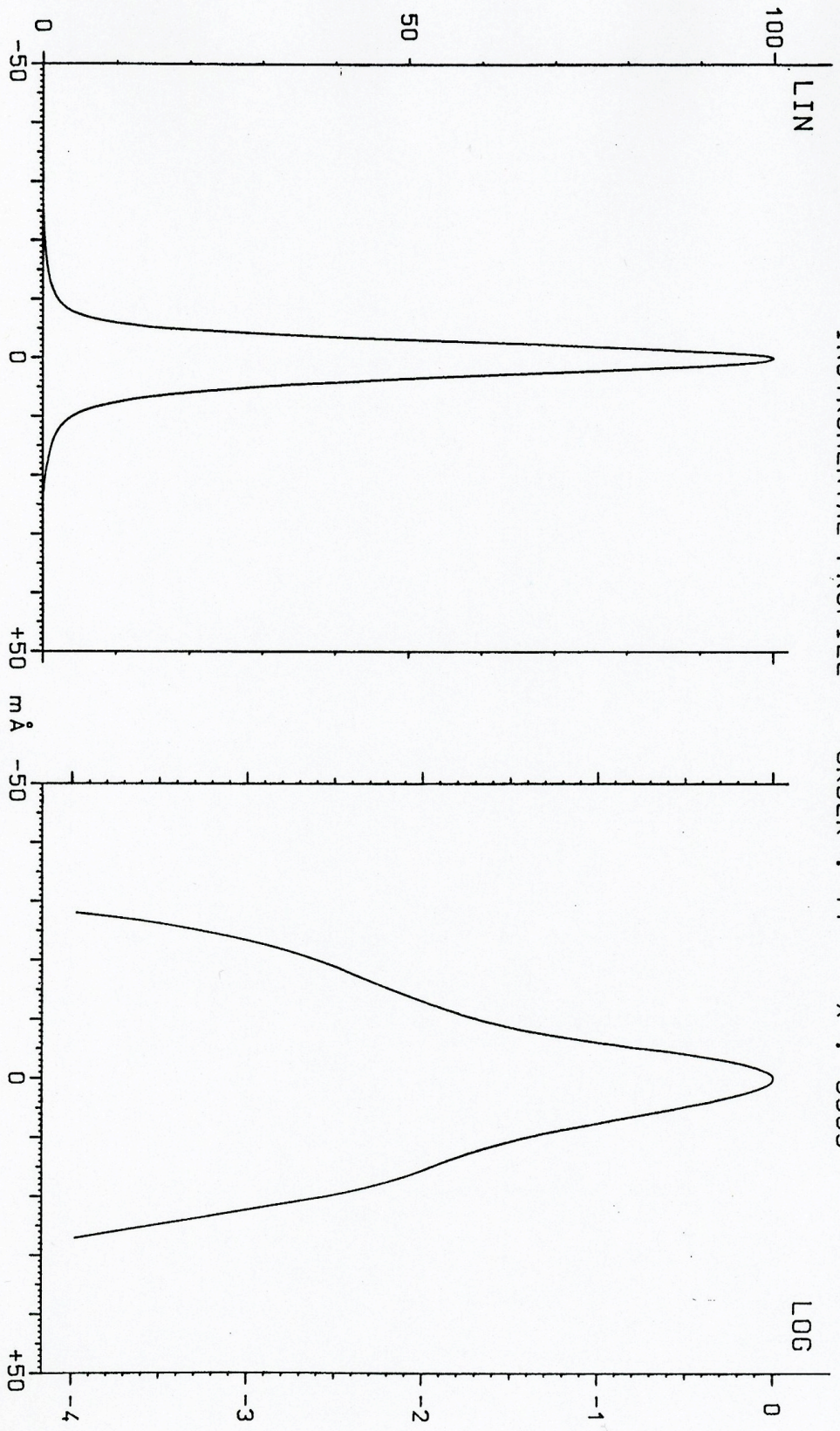8696 to 10,002.998: 6th order

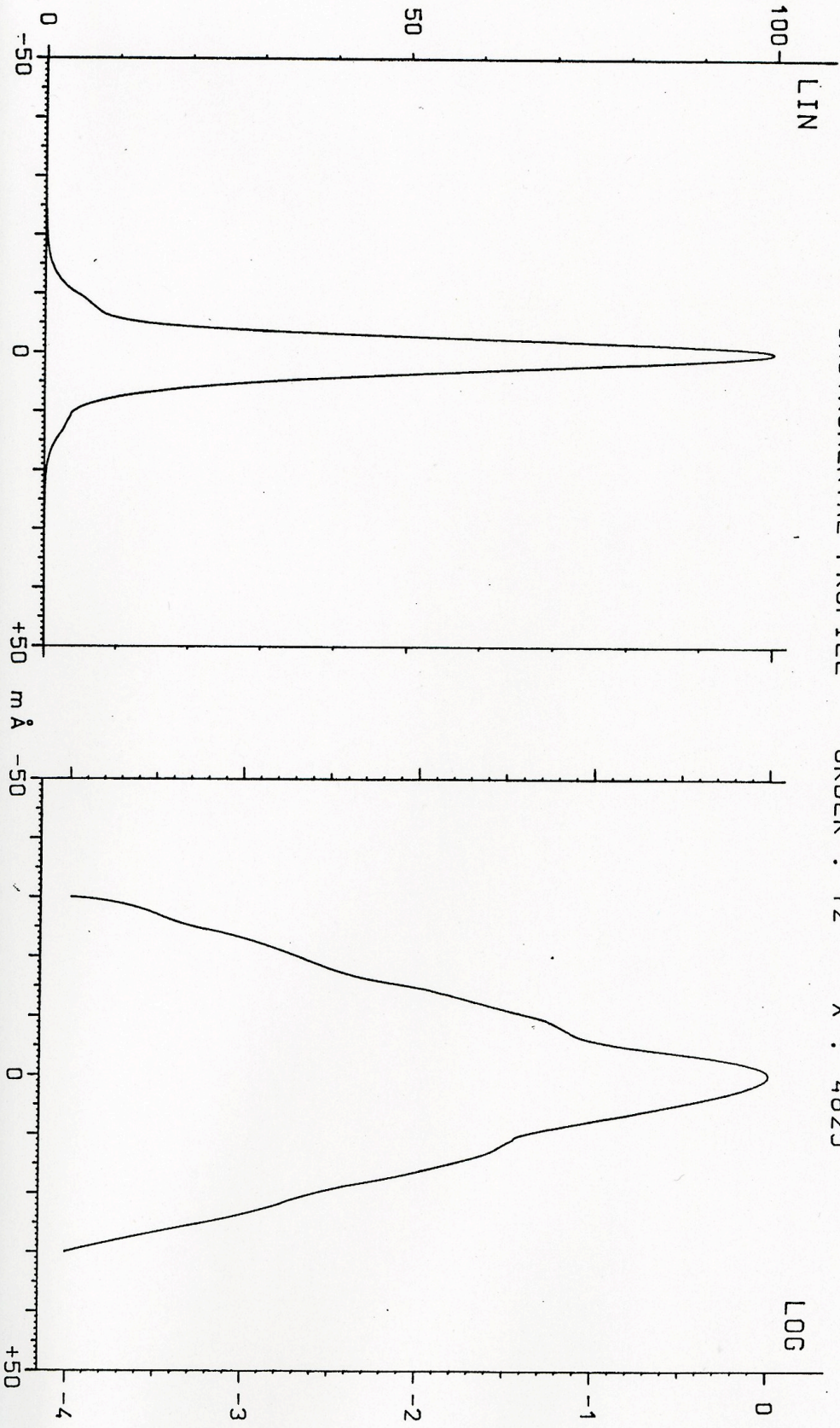INSTRUMENTAL PROFILE   ORDER : 10   λ : 5682

INSTRUMENTAL PROFILE   ORDER : 11   λ : 5309

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INSTRUMENTAL PROFILE   ORDER : 12   λ : 4825

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