The Great
Hewlett Packard

by Giovanni Becattini

The non-plus-ultra in electronic instrumentation

For all the engineers of my generation, Hewlett-Packard, or simply “HP”, was the non-plus-ultra in electronic instrumentation. Only for oscilloscopes, some of us preferred Tektronix.

HP was founded by Bill Hewlett and David Packard in 1935. The company started in a garage in Palo Alto and became one of the biggest and most respected electronic company in the world.

In this book, we wish to talk about the golden-age HP equipment we most loved, and to to tribute great women and men who made possible this unbelievable cultural explosion which marked so much our engineer’s life for ever, even before the commercial success,

We do not pretend having written a rigorous and thorough treatise; we simply wanted to create a photo-album, with historical and technical notes, to contribute in some way to the preservation of these classical instruments and, at the same time, of an immense capital of our history.



Giovanni (*Gianni*) **Becattini,** born in Florence, Italy, in 1951, is a graduated electronic engineer and a pioneer entrepreneur.

Aged sixteen he started a cooperation with *CQ Elettronica* the most important Italian magazine for amateur electronics. In 1973, he started the design of a computer based on the first 8080 samples available in Italy. In 1975 he presented the first Italian microcomputer project and founded *General Processor* (formerly *Micropi*) the first company in Italy producing computers for personal use. In 1998 he founded *AEP Ticketing Solutions*, today a Modaxo company.

Author of several books and publications, he still holds the role of AEP board member.

Giovanni Becattini
The Great
Hewlett-Packard

7/2024 edition



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The Great Hewlett-Packard

Giovanni Becattini

Introduction

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Giovanni Becattini, said “Gianni”

8640B Signal Generator

To my wife
and my family

5335A Universal Counter

181A Storage Oscilloscope

180A Oscilloscope

Recently Added

7/2024 edition: several corrections and additions - the following equipment has been added:

- 5335A Universal Counter
- 180A Oscilloscope
- 181A Storage Oscilloscope
- 1825A Dual Time Base
- 1806A Dual Differential Amplifier

3325A Function Generator

410C Voltmeters

8012B Pulse Generator

Previous Additions

4/2024 edition: added equipment:

- 8165A Function Generator
- 8065A Pulse Generator

2/2024 edition: besides minor enhancements, the following equipment has been added:

- 3325A Function Generator
- 8012B Pulse Generator
- 410C Voltmeter section has been fully revised and extended



Hewlett-Packard

The company we talk about in this book was founded in a one-car garage in Palo Alto by Bill Hewlett and David Packard in 1939, and initially produced a line of electronic test and measurement equipment. They won their first big contract in 1938 to provide the HP 200A, a low distortion frequency oscillator for Walt Disney's production of the animated film Fantasia, which allowed Hewlett and Packard to formally establish the Hewlett-Packard Company on July 2, 1939. The company grew into a multinational corporation widely respected for its products.

In the years, HP become the leader of instruments for the scientific, business, and industrial markets, producing every kind of apparatuses that became synonymous of top technology and quality. Some of them, like the 8640B signal generator or the 8568B spectrum analyzer are still today so spectacular that one could stay hours just watching their internals.

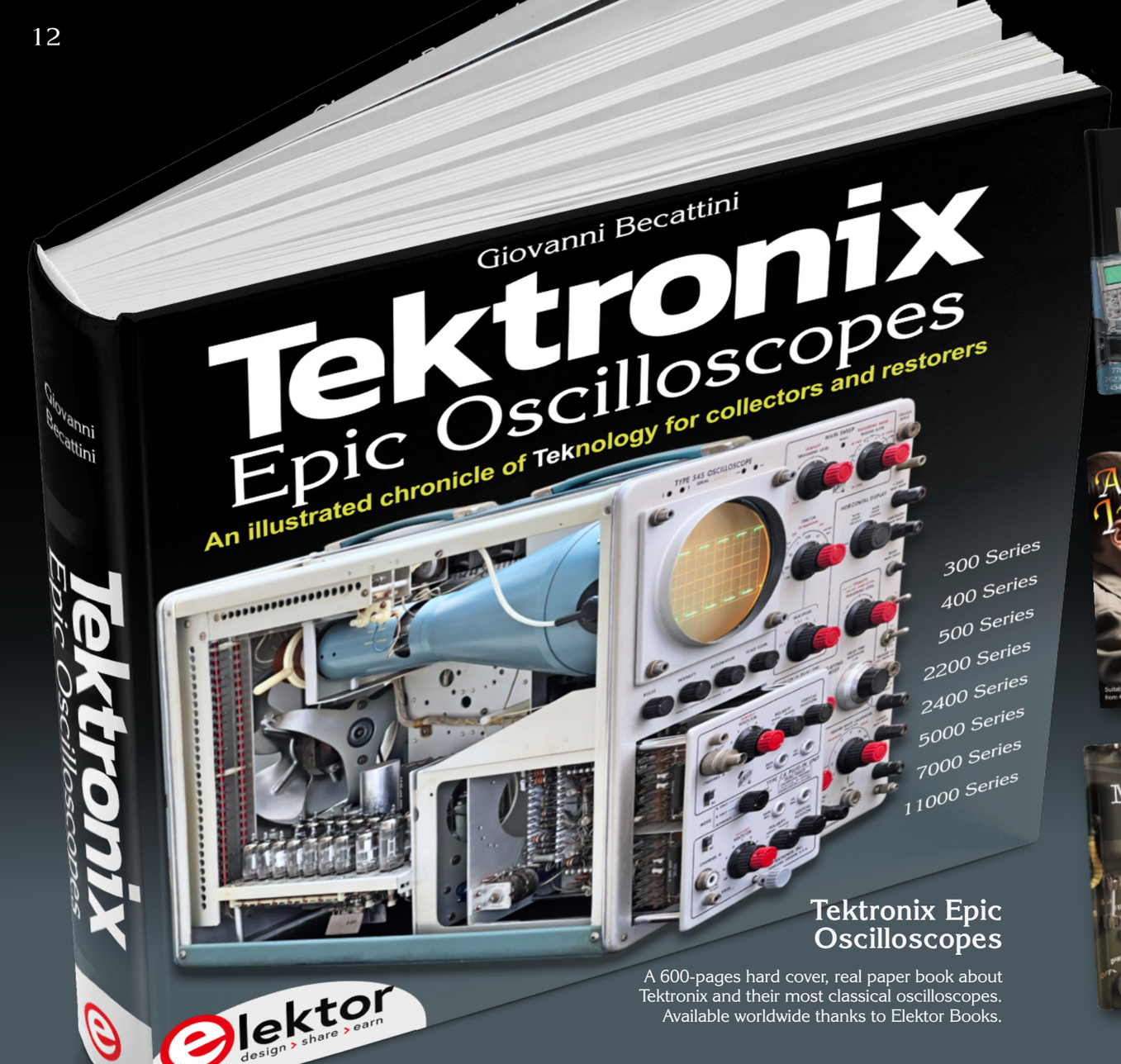
In 1972, HP introduced the HP-35, the world's first handheld scientific electronic calculator, who joined the successful desktop “calculators” 9000-Series, inspired to Olivetti Programma 101. We talk of all this in this book.

In 1999, HP spun off its electronic and bio-analytical test and measurement instruments business into Agilent Technologies (later Keysight), while HP remained only in IT sector, especially for PCs and printers. I ask myself if that brand change has been one of those incomprehensible decisions that only the heartless finance operators can make, like that which had sunk Olivetti many years before, as we describe in these pages.

For these reasons, in this book we will talk about the wonderful instruments of when HP still used to be our beloved Hewlett-Packard.

On the left, the garage at 367-369 Addison Avenue in Palo Alto, California where all started in 1939. Photo edited from BrokenSphere - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=10479277

Giovanni Becattini Book Series



Tektronix Epic Oscilloscopes

A 600-pages hard cover, real paper book about Tektronix and their most classical oscilloscopes. Available worldwide thanks to Elektor Books.



Tektronix, the 7000 Series

A 740-pages in-depth look at the most classical Tektronix 7000-Series oscilloscopes: models, technologies and restoration techniques.



Tektronix Restorer's Notebook

A valuable help for the vintage oscilloscopes restorer, with repair stories and component layouts for some classic equipment.



Adventures with Instruments

A book dedicated to those charming instruments neither from Tektronix nor Hewlett-Packard.



Tektronix Epic Oscilloscopes Supplement

A "live-update" of the Tektronix Oscilloscopes book from Elektor Books, with new models, data and articles.



Military surplus equipment

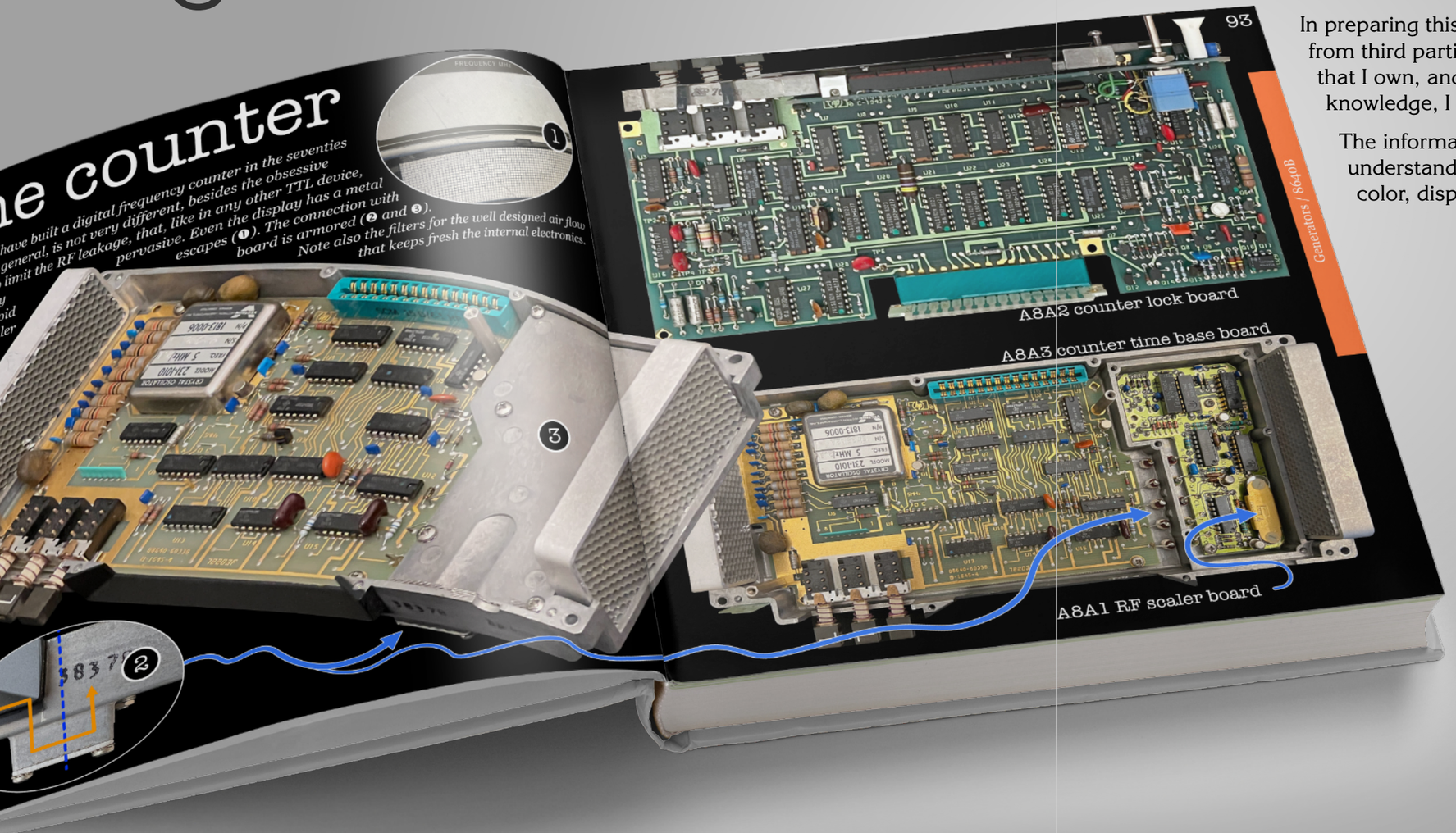
A 164-pages review of more than 30 famous military receivers, transmitters and instruments, with tons of beautiful photos.



The Great Hewlett-Packard

A 1029-pages review of many classical instruments from the fifties to the nineties by the great Hewlett-Packard: spectrum analyzers, generators, oscilloscopes, voltmeters, frequency meter, up to the handheld calculators and the Series-80 computers.

Organization of this book



In preparing this book, I didn't want to just collect and reproduce material from third parties. Rather, I did my best to talk mainly about equipment that I own, and about things that I could test. Together with my existing knowledge, I did extensive Internet research and photo editing.

The information contained here is huge, so, to make the things more understandable, I divided the book in main sections, identified by a color, displayed on the right side of each right page.

- Voltmeters
- Signal Sources
- Oscilloscopes
- Counters
- Spectrum Analyzers
- Calculators
- Computers
- HP-IB (GP-IB IEEE-488)

NOTICE: I don't claim any historical rigor, I am not an expert of this matter. Even though I am an electronics professional, in this case I work as a simple enthusiast, with limited means and a home laboratory. If I wrote something wrong, or infringed somebody else's rights, please write me and I will amend consequently.

PLEASE LINK ME: If you like, I will be grate if you link its download page (http://www.k100.biz/parade.htm).

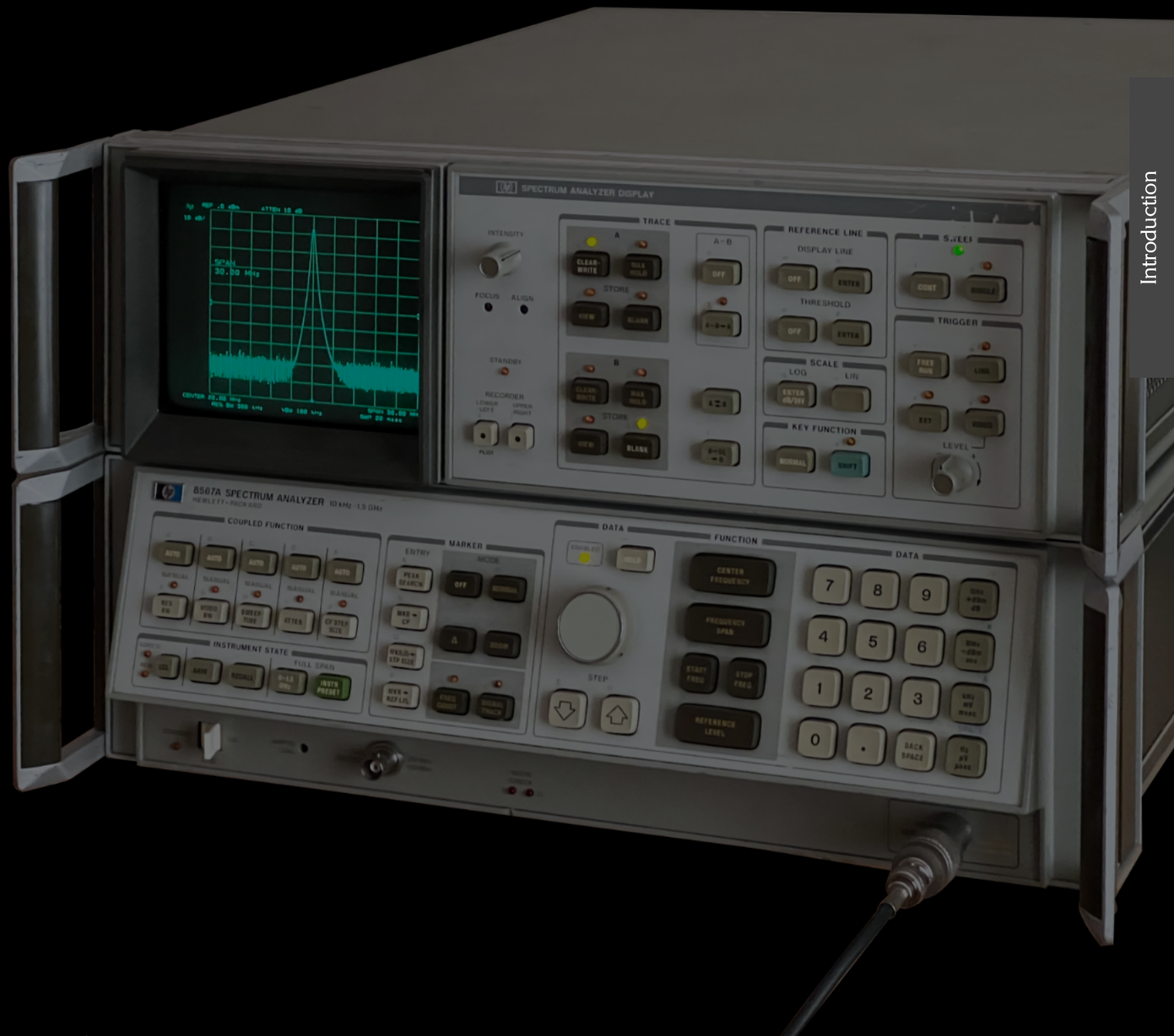
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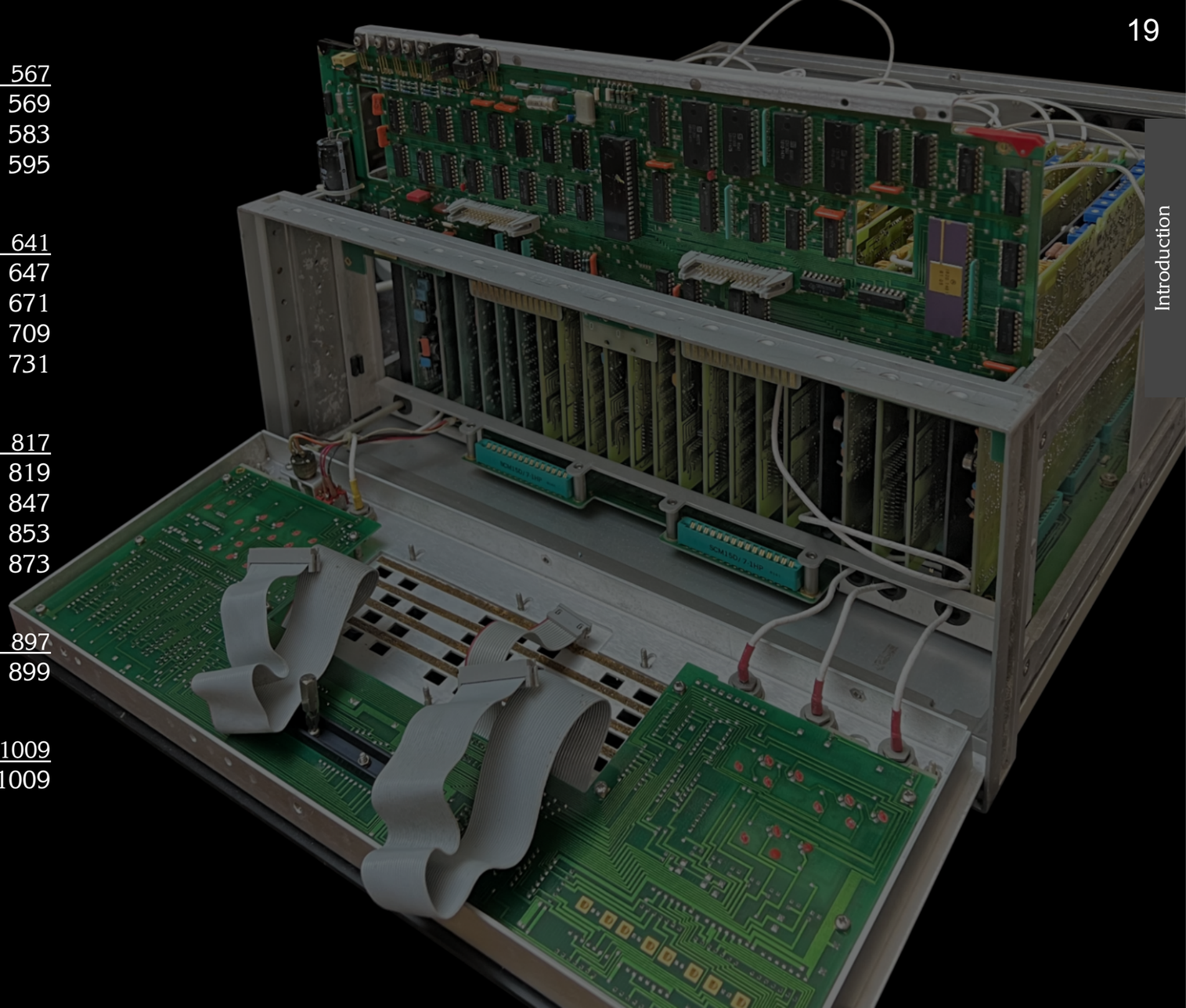
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- An interface bus for all 1009



Voltmeters

Subsection

400H vacuum tube voltmeter

An AC only but very precise voltmeter

HP400H vacuum tube voltmeter

The HP Model 400 vacuum tube voltmeter is an accurate and sensitive average-responding RMS calibrated voltmeter which will measure AC voltages from 0.001 volt full scale to 300 volts full scale over a frequency range of 10 cycles to 4 megacycles. It has an input impedance of 10 megohms, effectively preventing disturbance to circuits under test. The distinctive features of this voltmeter make it valuable for measuring gain, network response, and output level with speed and accuracy. The wide (at the time) frequency range makes it suitable for audio, RF and video measurements.

The HP400H was part of a line of three instruments that included Model 400D, H and L, being H the best version and, at his time, probably one of the best on the market. It uses as many as 9 tubes, and is capable measuring voltages down to 100 μV with 10 Mohm/15 pF input impedance, up to 4 MHz frequency.

My HP400H is in mint conditions and still today works wonderfully.

Why a vacuum tube voltmeter

In the fifties, who could not afford a high-impedance vacuum-tube voltmeter, had necessarily to make use of an analog multimeter, which, having no electronic amplifier, used the energy from the circuit under measure to move the hand of the instrument, altering, with its reduced input impedance, the operation of the circuit itself.

Practically, it is like adding a resistance in parallel to the circuit. Its value is determined by an important parameter of the multimeter: “the ohms/volt”, to be multiplied by the selected full scale value. For example, a 5,000 ohm/V multimeter, set to “10V”, has a resistance of 10 x 5,000 = 50,000 ohm, a too low value for a tube circuit (a vacuum tube voltmeter has from 10 to 50 Mohm input resistance).



1953



Applications

The sensitivity of this voltmeter is sufficient in many instances to measure hum and noise level directly and as an audio level meter. It can used also as a high-gain 4 MHz amplifier to give increased sensitivity to oscilloscopes, bridges, and other equipment requiring additional sensitivity.

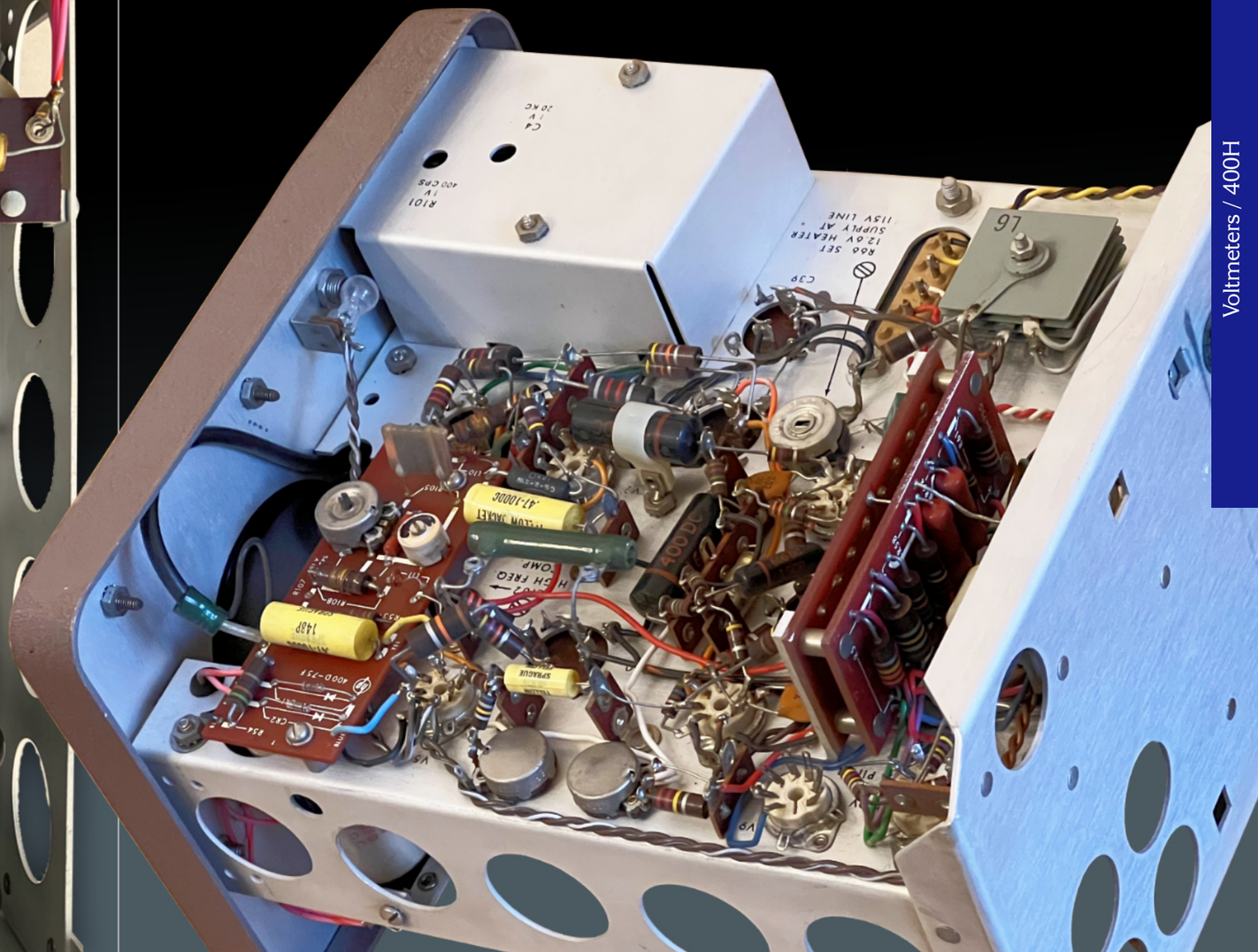
Specifications

- **Voltage range**: O. 1 millivolt to 300 volts. Twelve ranges selected with front panel switch. Full scale readings of:
  - 0. 001 0.100 10.00
  - 0.003 0.300 30.00
  - 0.010 1.000 100.00
  - 0.030 3.000 300.00
- **Decibel range**: -72 to + 52 db, in 12 ranges.
- **Frequency range**: 10 Hz to 4 MHz
- **Accuracy**: at nominal line voltage +10%. Overall accuracy is within:
  - +1% of full scale, 50 Hz to 500 kHz;
  - ‡2% of full scale, 20 Hz to 1 MHz;
  - ‡3% of full scale, 20 Hz to 2 MHz;
  - ‡5% of full scale, 10 Hz to 4 MHz.
- **Long term stability**: reduction in Gm of amplifier tubes to 75% of nominal value results in error of less than 0.5%, 20 Hz to1I MHz.
- **Calibration**: reads rms value of sine wave. Voltage indication proportional to average value of applied wave. Linear voltage scales 0 to 3.0 and 0 to 1.0; dB scale, -12 dB to+2dB, based on 0 dBm= 1 mW in 600 ohm; 10 dB intervals between ranges.
- **Input impedance**: 10 MΩ shunted by 15 pF on ranges 1. 0 volt to 300 volts; 25 pF on ranges 0.001 V to 0.3 V.
- **Amplifier**: output terminals are provided so voltmeter can be used to amplify small signals or to monitor waveforms under test with an oscilloscope. Output approximately 0. 15 volt RMS on all ranges with full-scale meter deflection. Amplifier frequency response same as that of voltmeter. Internal impedance approximately 50 ohms over entire frequency range.

Analog pointer instruments

The pointer of old analog instruments had advantages respect to modern digital multimeters. For example, when aligning a receiver, it is much easier and faster to look at the hand for the peak, instead of having to mentally decode the fast upgrading numerical display, which is often rather confusing.





Voltmeters

Subsection

410C voltmeter

Far to be a simple multimeter, it was a valuable instrument and remained in the catalog for more that 23 years.



1963

Yet Another Analog Multimeter?

Don't judge hastily

It is rather easy, today, to make the mistake of hastily judging old stuff. In this case, the temptation is to rank the HP410C as an "old analog multimeter", but it was (and partly is) instead a very valuable instrument, with superior specifications and a great commercial success. The 410C was introduced in 1963, and remained in catalog until 1986 (23 years!). Its price was originally of 425 USD (with the AC probe), equivalent today to 4,224 USD. Not for everybody…

A new jewel

HP voltmeters have always been valued for their accuracy, for the wide range of measurements, and for their reliability - in short, for their all-around performance. With the introduction of the 410C in 1963, these instruments included now a new multi-function voltmeter designed to make measurements in both tube and transistor work. The general usefulness of this new model was justified saying that its high current sensitivity permitted to measure minute currents such as leakage currents in semiconductor diodes and transistors, currents that most transistor test sets could not measure, at the time.

What it does

The HP410C has been designed to measure the four quantities most often measured in typical bench work: **DC voltage**, **DC current**, **resistance**, and **AC voltage**. It measures positive or negative DC voltages from 1 millivolt to 1,500 volts and has an input resistance which has been made very high to permit measurement in virtually any circumstance: 100 Mohm on the upper ranges and 10 Mohm on the three most sensitive ranges.

The instrument will also measure positive or negative DC currents from 150 mA down to 0.1 μA. In fact, by using the three most sensitive voltage ranges as current ranges, DC currents down to 0.1 nA (0.1×10^{-9} ampere) can be measured.

The impedance of the meter for these nano-ampere measurements, is, of course, the 10 megohms of the instrument as a voltmeter on these ranges, but this value is usually permissible since the resulting voltage drop is small. This high current sensitivity makes it a simple matter to measure the leakage currents mentioned earlier.

AC measurements

As to AC voltage, the voltmeter will measure over a very wide frequency and voltage range by using the optional 11036A detachable probe, that we will see later.

With this probe AC voltages can be measured from 20 Hz to well above 700 MHz at levels from 0.1 V to 300 V.

Resistance measurements

To complete its multi-function role, the instrument measured a wide range of resistances. Seven resistance ranges are provided, permitting measurements from 1 ohm to 500 Mohm.

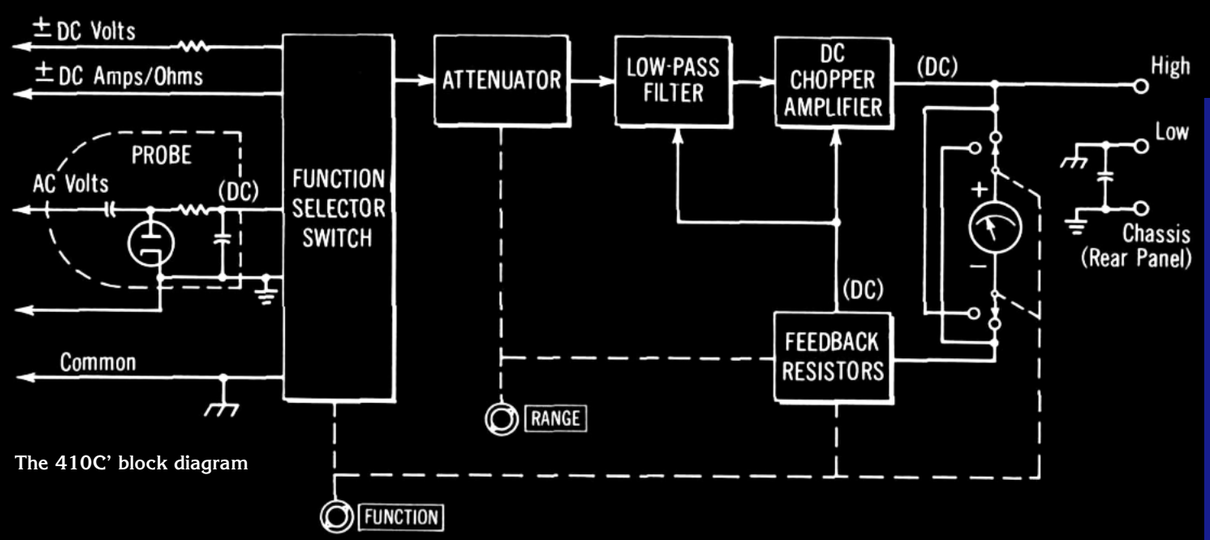
Floating inputs

The instrument includes a number of other design features that are valuable to those making circuit measurements. For one, the DC measuring circuitry is floating and can be used up to 400 V from ground. This point must not be forgotten when you repair its power supply, as we will see later.

Stability

The stability of the instrument is such that no panel zero control is provided for DC measurements. An AC zero control is provided but it merely compensates for warm-up changes in the contact potential of the AC probe's rectifier diode and in any event is generally used only on the most sensitive AC ranges. The heater voltage for the diode is rectified and regulated so that no use is normally required of the AC zero control if a few minutes' warm-up is allowed. The amplifier has a high input impedance and an exceptionally low drift rate, being specified as less than 0.5% of full scale **per year** at constant temperature. The negligible drift rate and low noise (less than 0.5% of full scale on any range) allows the most sensitive de voltage range to be 15 mV full scale and practical measurements to be made to below a millivolt.

The "new" unit's indicating meter was selected to be of the taut-band-suspension type. This type of suspension avoids bearing problems, since the meter deflection occurs through torsion of a metal strip or band and no conventional moving-pivot bearings are used. As a result the meter has high repeatability and has proved eminently satisfactory for general use. Each indicating meter is individually-calibrated on the HP meter calibrator and checked to have of itself better than ¼% tracking error.



The 410C' block diagram



Measurements

Small currents measurement

The voltmeter measures DC current by sensing the voltage drop across internal precision shunt resistors. Sensitivity is such that currents of less than 1.5 microamps can be measured with a shunt resistor of only 9 kΩ on the most sensitive current range (the maximum current range is 150 mA full-scale with a 0.3 ohm internal shunt).

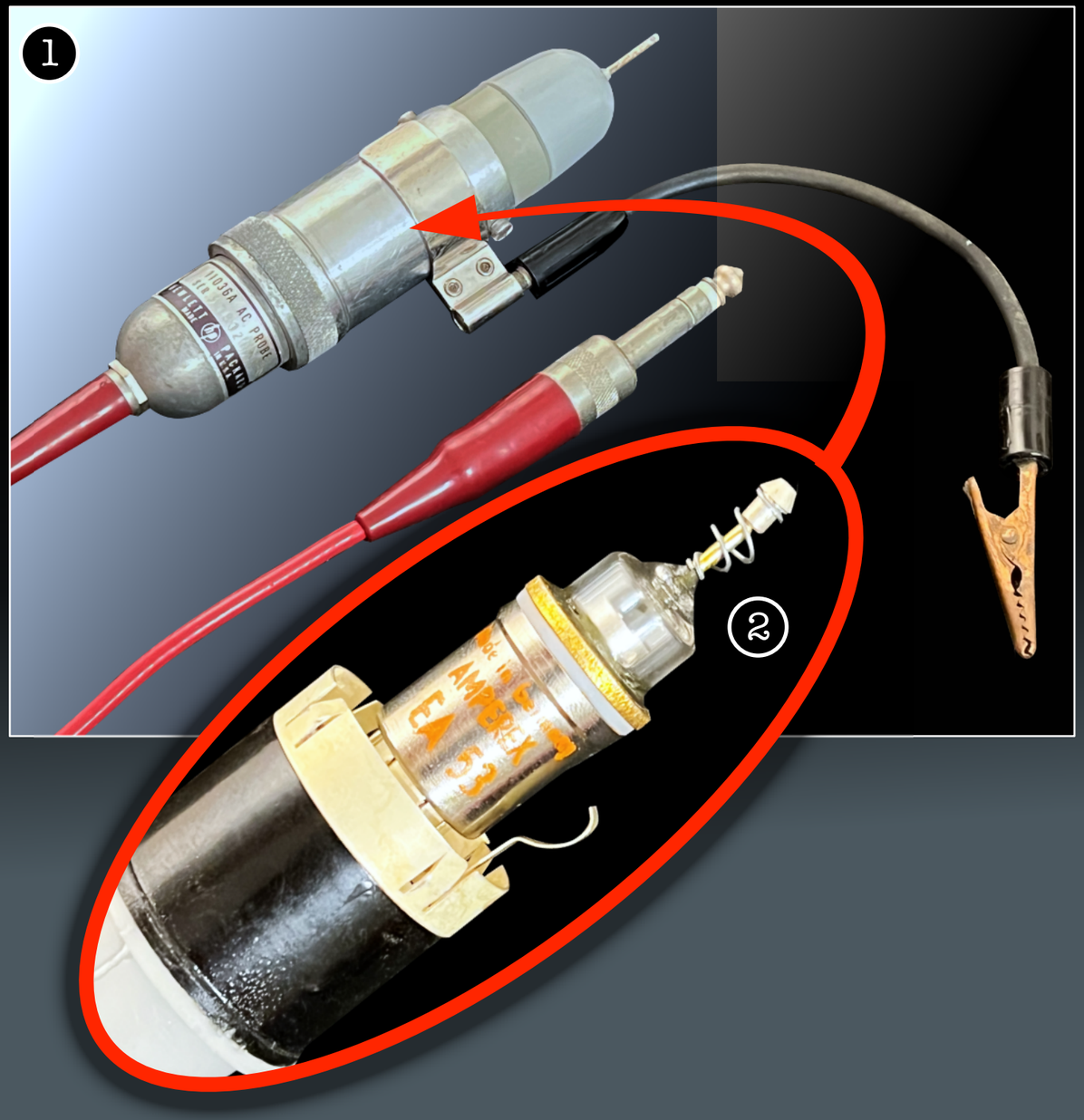
Measuring ultra low currents

I never thought that, but you can measure even smaller currents by use of the three most sensitive voltage ranges, measuring the voltage across the instrument's input impedance (10 Mohm). In this fashion, currents as low as 0.15 nA can be measured.

AC measurements

As already noted, to measure AC voltages the 410C required the optional 11036A detachable probe. With it, the 410C measures AC voltages with 3% accuracy over the range 100 Hz to 100 MHz (10% from 20 Hz to 700 MHz). High input resistance of 10 megohms and capacitance of only 1.5 pF minimize loading of the circuit under test.

The probe has a rectifying diode which converts the DC meter into a peak-responding AC voltmeter. With the probe, the instrument accurately measures sine wave signals having frequencies as high as 700 MHz, and it can be used for comparison measurements up to 3 GHz. An AC zero control is included for suppression of the thermionic diode contact potential.



❶ The optional 11036A AC probe allowed to reach 700-MHz measurements.
❷ Inside the probe, a vacuum rectifier diode is included. Appreciate its professional construction and how it is easier today to use solid state diodes…

Documentation

Which 410C?

Starting to work on this splendid instrument, I soon discovered that two different models with the same name of 410C existed. They are functionally equivalent, but physically different in the amplifier section. The first type was introduced in 1963 and was described in the 5/1963 issue of HP Journal. As we are going to see, it uses a chopper amplifier; the other type was introduced years later (1981?), and uses a common operational amplifier.

My units

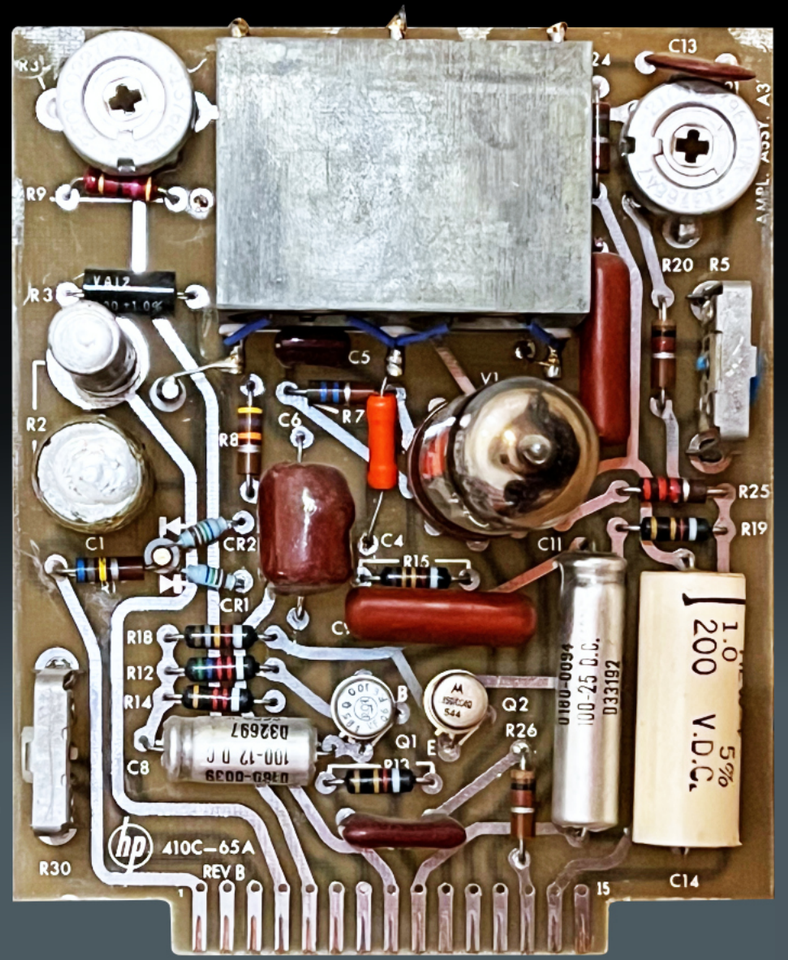
The instruments described in these pages come from my friend Francesco Sartorello, whom I never stop thanking, and are both of the first type, which, useless to say, I prefer for their fascinating chopper amplifier, which we will try to describe in details.

The manuals

I could find the following manuals for the 410C:

- OPERATING AND SERVICE MANUAL - MODEL 410C ELECTRONIC VOLTMETER
  - HP part No. 00410-90005
  - Date: 1963 (printed September 1968)
  - Serials prefixed: 807, with Appendix C, Manual Backdating Changes adapts this manual to Serials prefixed: 311, 328, 339, 433, 532, and 550
  - Note: another copy of it, printed in 1965, is available. The source is nothing less… the US Central Intelligence Service!
- HEWLETT-PACKARD ELECTRONIC VOLTMETER MODEL 410C
  - TM 11-6625-1614-15 Department of the Army
  - Date: 1967
- OPERATING AND SERVICE MANUAL - MODEL 410C ELECTRONIC VOLTMETER
  - HP part No. 00410-90007
  - Date: August 1969 (printed May 1974)
  - Serials prefixed: 0982A, with Appendix C, Manual Backdating Changes adapts this manual to Serials prefixed: 311, 328, 339, 433, 532, 550, 807, 844, 952 and 982

- OPERATING AND SERVICE MANUAL - MODEL 410C ELECTRONIC VOLTMETER
  - HP part No. 00410-90009
  - Date: 1981 (printed March 1981)
  - Serials Numbers: 0982A22339 and above (the chopper amplifier has been replaced by an integrated operational amplifier); for those instruments with serial numbers 0982A22338 and below, refer to Manual Part No. 00410-90007



A6 Amplifier Board

The A6 Amplifier Board, in its original chopper version.

It was replaced in the first eighties with a simpler one, based on an integrated operational amplifier.

Officially, the product was considered the same, and the 410C name was not modified.

Construction

The instrument is housed in a typical HP modular cabinet occupying 1/3 of a standard 7 inch high rack-mounting combining case, and is composed by three printed-circuit boards, a novelty at the time:

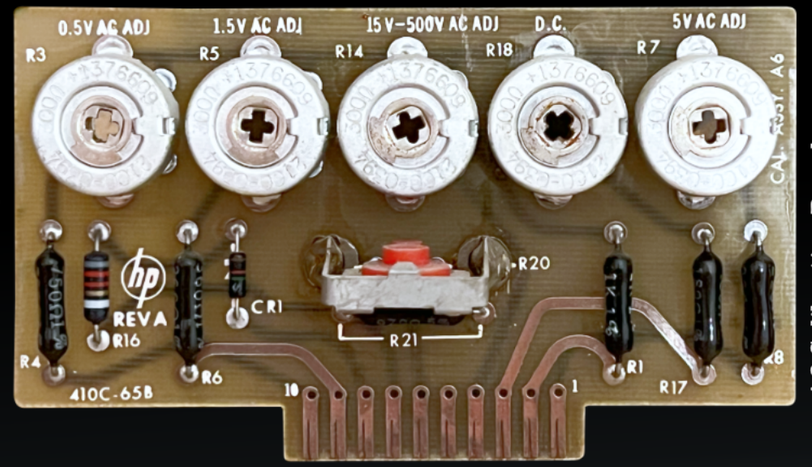
- A3 Amplifier Board;
- A7 Power Supply Board, which holds the connector for the A3 Board as well;
- A6 Calibration Board, with only some resistive trimmers.

The rest is built the old fashioned way. Material are of very good quality, with ceramic switches, still perfectly working with no false contacts, and precision wire resistors. The galvanic treatments were well done, keeping the device immune from corrosion.

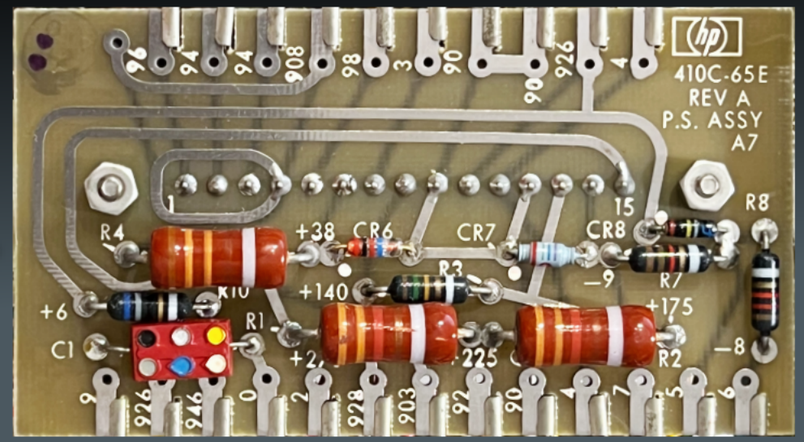
The 410C weighs less than 3.7 kg. and may be used on the bench, with the tilt-up bail, or slipped into the combining case for rack use.

I don't like very much the probes directly connected to the instrument without any connector (except for AC). I can see the reasons for such a choice, but it is not very practical.





A6 Calibration Board



A7 Power Supply Board

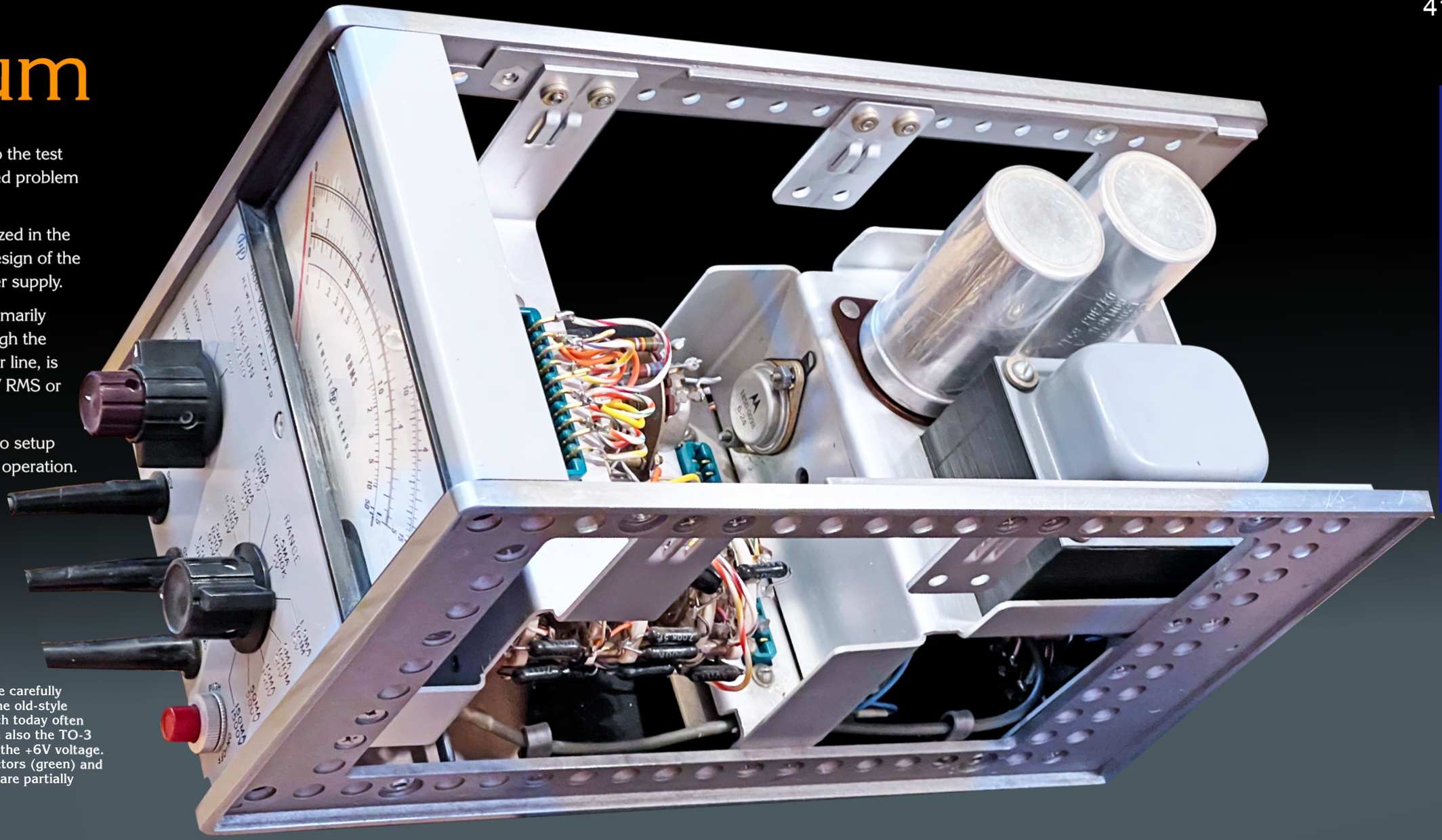
AC Hum

Injection of mains AC hum into the test circuit is a frequently overlooked problem with floating DC instruments.

This problem has been minimized in the 410C by careful attention to design of the shielded transformer and power supply.

Hum injection, which arises primarily from capacitive coupling through the power transformer to the power line, is held typically to less than 2 mV RMS or 10^{-7} A RMS.

An internal adjustment allows to setup the instrument for 50 or 60 Hz operation.



In the photo you can see the carefully shielded transformer, and the old-style electrolytic capacitors, which today often require to be replaced. Note also the TO-3 transistor, used to stabilize the +6V voltage. Also the board edge connectors (green) and the precision wire resistors are partially visible in this photo.

The Circuit

Hybrid technology

In the sixties the first transistors became available but the designers felt not yet confident to rely only on semiconductors, so often resorted to mix both technologies in hybrid solutions. The 410C follows this road, and, according to HP, "combined the best advantages of tubes and transistors". One section of a dual-triode tube economically provided high input impedance with a low noise figure; the other section served as the output cathode-follower. Two transistors provide high gain, the overall loop gain being 46 dB at DC.

Output connectors

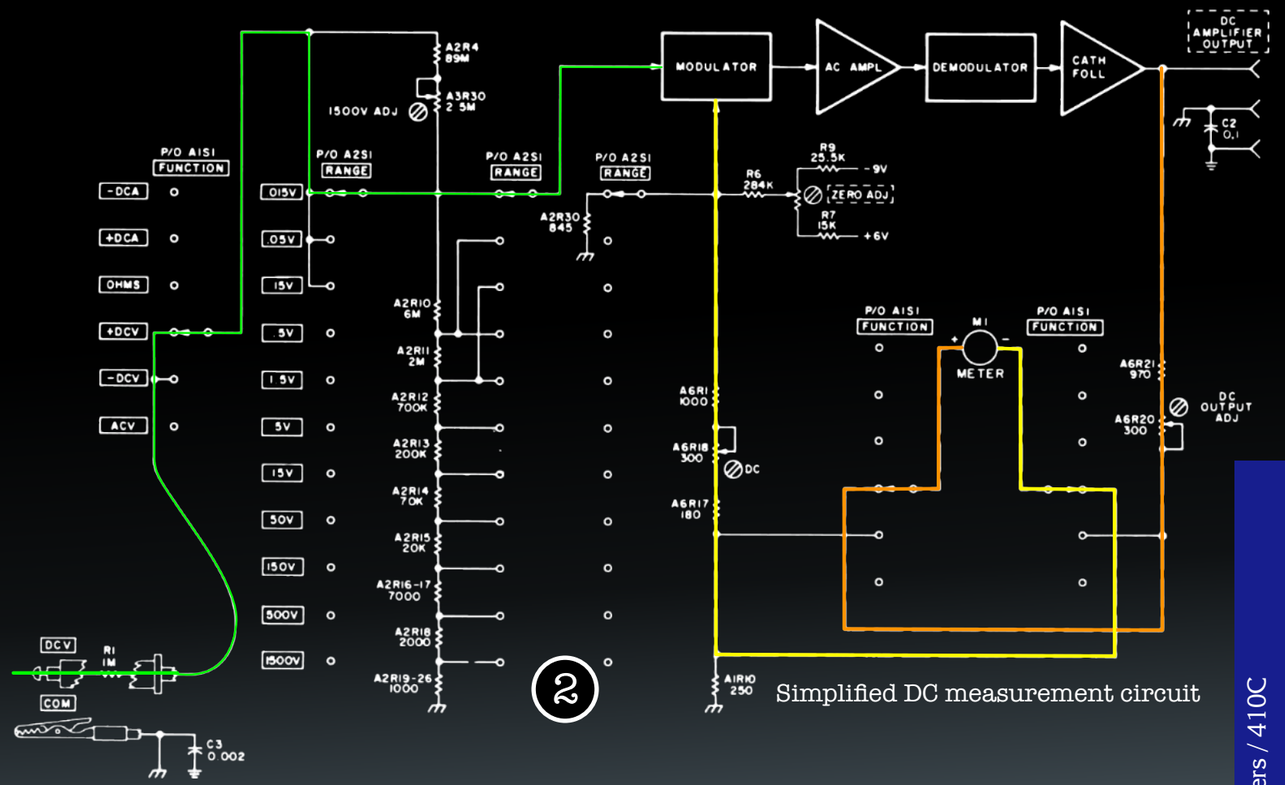
The overall usefulness of the 410C has been enhanced by providing output terminals on the 410C rear panel, so that any of the four types of measurements can be recorded on a DC recorder or so that the instrument can be used as a DC voltage or current amplifier. Overall instrument voltage gain (in the most sensitive range) from input probe to output connector is 100. The DC amplifier connects



❶ 410C's rear panel. Note that the voltmeter's circuit is floating respect to the metal frame. The floating ground is connected to the central red terminal, while the black one is the frame ground. Thanks to the chopper amplifier, when the circuit is correctly operating, the ZERO ADJ. trimmer should be tuned only once for ever.

❷ The simplified circuit in the DC measurement mode. In green the main signal path; in orange and yellow, the feedback to the chopper amplifier, as described next.

❶ Basic chopper amplifier block diagram.



Simplified DC measurement circuit

to output terminals at the rear of the instrument, supplying a voltage proportional to meter deflection (1.5 V full scale). Negative feedback reduces the output impedance to less than 3 ohms so that up to 1 mA can be taken from this output without affecting accuracy. The instrument also may be used as a narrow-band amplifier (or attenuator) with voltage gains from 100 down to 10^{-3}. Frequency of the amplifier is 0.5 Hz at the -3 dB point.

DC measurement circuit

Like in all multimeters, the basic measurement is the DC voltage; the others are in someway a derivative of it. As you can see here above, the input circuit is very simple and easy to follow. Practically, a simple voltage divider.

Chopper Amplifier

A chopper… wow!

The 410C is a very interesting device, also from the circuit point of view. A rather simple circuit, with very exciting performance, mainly due to the **chopper amplifier**. I remember I studied it when I was in university and then I completely forgot it until now. This is a wonderful opportunity to study this peculiar amplifier a little deeper.

The requirement

To deal with small signals that change slowly, we need a **DC-coupled** amplifier, with its own complexities and drawbacks. While it is possible to boost the gain on a direct current system, these modifications often increase signal noise and decrease the stability of the signal. A possible alternative to traditional amplifiers is the chopper amplifier, a very interesting circuit that we are going to describe now.

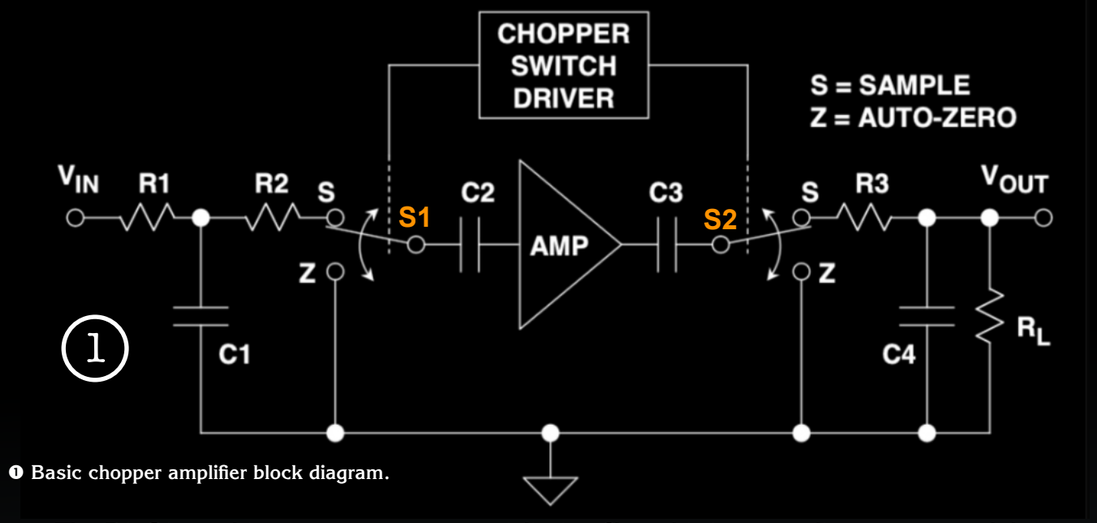
What is a Chopper Amplifier?

A chopper amplifier is an electric circuit that converts a DC (or slow changing) voltage into AC, more precisely into a rectangular wave which has the same amplitude of the signal itself, and which is rather easy to boost.

A basic chopper amplifier circuit is shown in figure 1. There are two possible states: **auto-zero** and **sampling**, depending on two synchronous switches on the input and the output of the amplifier:

- when the switches are in the "Z" (auto-zero) position, capacitors C2 and C3 are charged to the amplifier input and output offset voltage, respectively.
- when the switches are in the "S" (sample) position, Vin is connected to Vout through the path comprised of R1, R2, C2, the amplifier, C3, and R3.

The frequency of the switching is called **chopping frequency** and is usually between a few tens Hz and several kHz (85 or100 Hz in the 410C, depending on the mains AC frequency of 50 or 60 Hz respectively).



❶ Basic chopper amplifier block diagram.

The R1-C1 combination serves as an antialiasing filter; this is a sampling system, and the input frequency must be much less than one-half the chopping frequency in order to prevent errors. In the case of a voltmeter like this, we can assume that Vin is stable.

The amplified signal is then sent across a low-pass filter (R3-C4) that rebuild the original signal.

It is also assumed that after a steady state condition is reached, there is only a minimal amount of charge transferred during the switching cycles. The output capacitor, C4, and the load, RL, must be chosen such that there is minimal Vout droop during the auto-zero cycle.

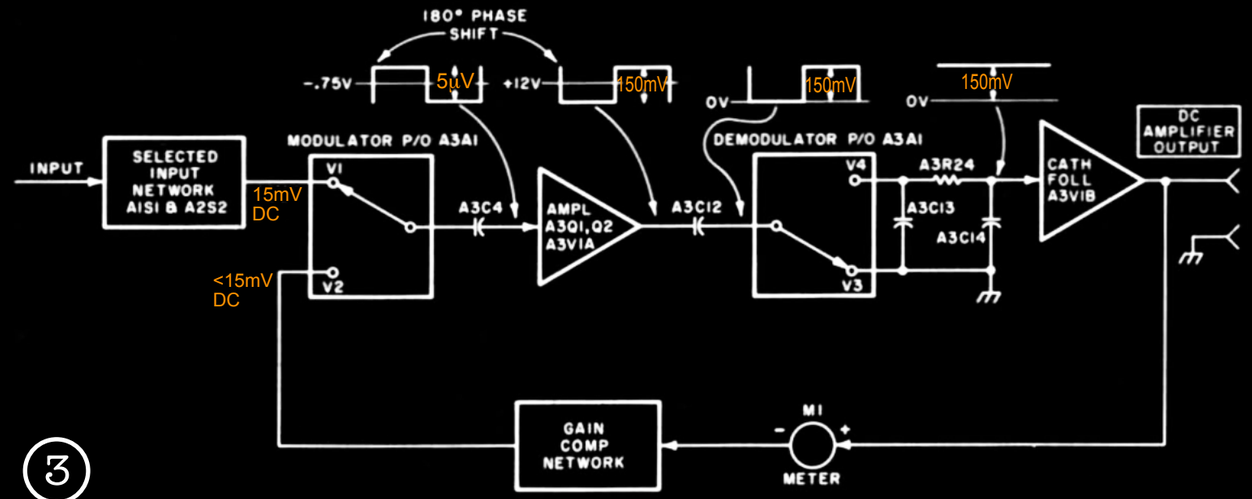
410C's chopper amplifier

In the 410C, the chopping action is performed by four non-mechanical **photoconductors**, which have low resistance when illuminated and high when dark.

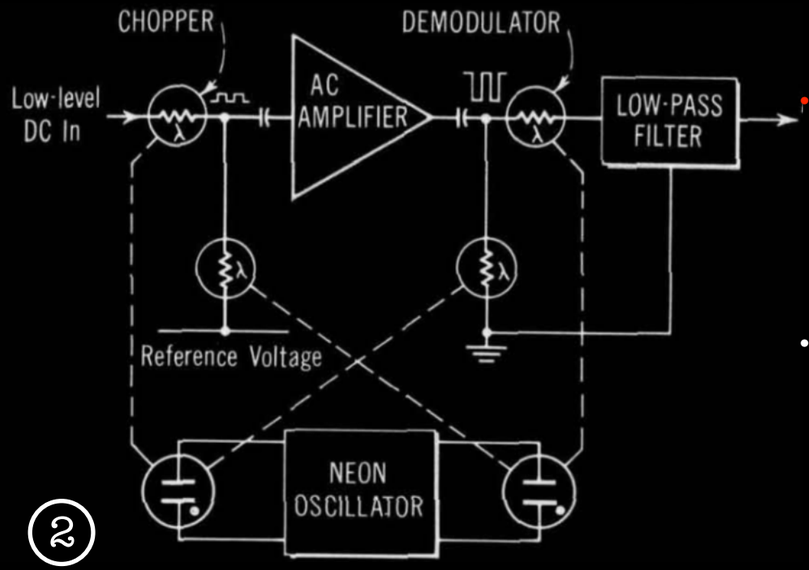
They are connected as shown on diagram ❷ on the next page. The two neon lamps compose a relaxation oscillator and illuminate alternately the photoconductor pairs.

The circuit is slightly different from the base chopper, because:

- the switches are **differently phased**, because when S1 is in S position, S2 in in Z position. This just because the amplified signal to the input of the demodulator-chopper is 180° out of phase with the output of the modulator; So, the substance remains unchanged. No contact noise is



3



2

generated by this type of chopping action and the circuitry is arranged so that offset voltages are negligible;

- however, S2 does not close exactly to ground but to a voltage that can be preset by A3R21 (BIAS ADJ.) from 0 to about -9V. The manual does not give information about this trimmer….
- switch S1 **does not close to ground** but to a part of the output signal. The signal to S1-S is 15 mV for the full-scale voltmeter output. In this case, the input to S1-Z is not zero, but 15 mV less 5 uV, significantly reducing the swing in the rectangular wave sent thru the AC amplifier, and incrementing the DC feedback around the amplifier.

Thus, the chopped signal inputted to the amplifier has an amplitude of only 5 uV, which becomes 150 mV after amplification.

Figure 3 shows the mechanical equivalent of the 410C's chopper amplifier, while photo 4 shows the "important" photoconductors assembly, made-up by a piece of die-cast and machined aluminum.

The effective amplifier is composed by a 12AT7 dual triode and two germanium transistors, replaced later by silicon ones.

❷ The 410C's chopper amplifier logic block diagram from HP Journal No. 5 1963 where the 410C is described.

❸ The 410C chopper mechanical-equivalent amplifier's block diagram.

❹ The photoconductors assembly, two on each side, four total. The neon lamps stays in the middle.



4

Restoration

Still very appreciated

Looking at eBay ads, you can understand that the 410C was very popular, and that many units had been sold; still today is highly appreciated and sought after.

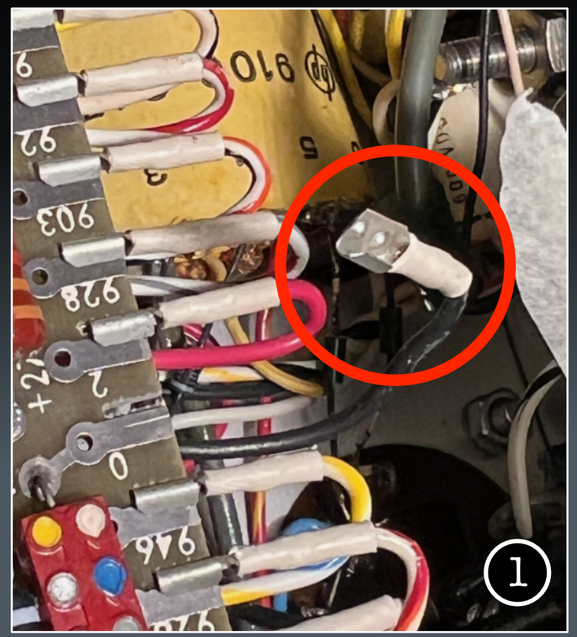
Simple but complex

I must admit that I spent a lot of time on my two babies. The “rough” repairs were relatively easy, but then it took me a fair amount of effort to understand how the circuit really worked. The second unit, almost identical to the first and near in the serial number; only knobs are different. I report here below the summary of my experience.

Broken contacts

Besides recapping (see next page), which I consider now a job routine, I had two “unusual” problems, which caused great instability (see the photos):

- in the first 410C, a self-desoldered junction on a terminal of a rotary switch (opposite page);
- in the second one, a joint to the Power Supply Board was broken, but it seemed to be good, just looking at it (here on the right).





❶ Connections to the Power Supply Board are made by mean of small Faston-like connectors, which insert directly on the board. One of them was broken, but on the back side, so it was not easy to see.

❷ A strange fault. I lost a lot of time trying to understand a very annoying instability in the reading. Then I discovered that a soldered joint lost all the soldering material. Fixed it, the HP410C returned stable, ready to be calibrated.

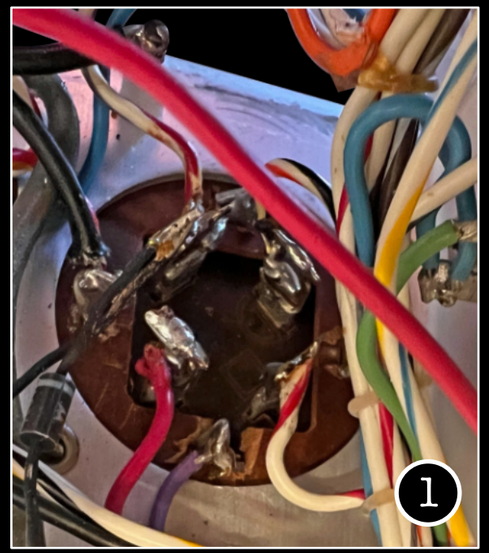
Recapping

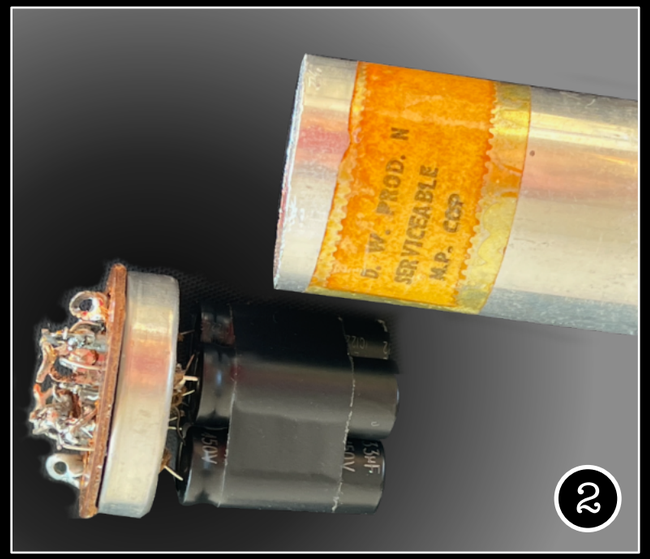
Often, the overall cause of a faulty instrument is a capacitor, and also in this case the rule was confirmed. The first HP410C required to change C5, the high-voltage level filter, and the second C6, the one for the low voltage.

I am sure you can understand me if I like to keep also the original look of the equipment, when possible also inside the housing; so in both cases I decided to dismount the old cans, to saw them, and to allocate inside the new capacitors.

The old capacitors were mounted with rivets, so I had to drill them, and then replace with screws and nuts. A routine job, I would say.

❶ The bottom side of the capacitor C5 which lost all its capacity.
❷ ❸ I cut the can with a saw, emptied its content and installed four modern capacitors. Then I closed again the can with technical adhesive tape,





Repairs

❶ Voltages on A7 Power Supply Board.
❷ Waveforms in overdrive conditions, as described in text.

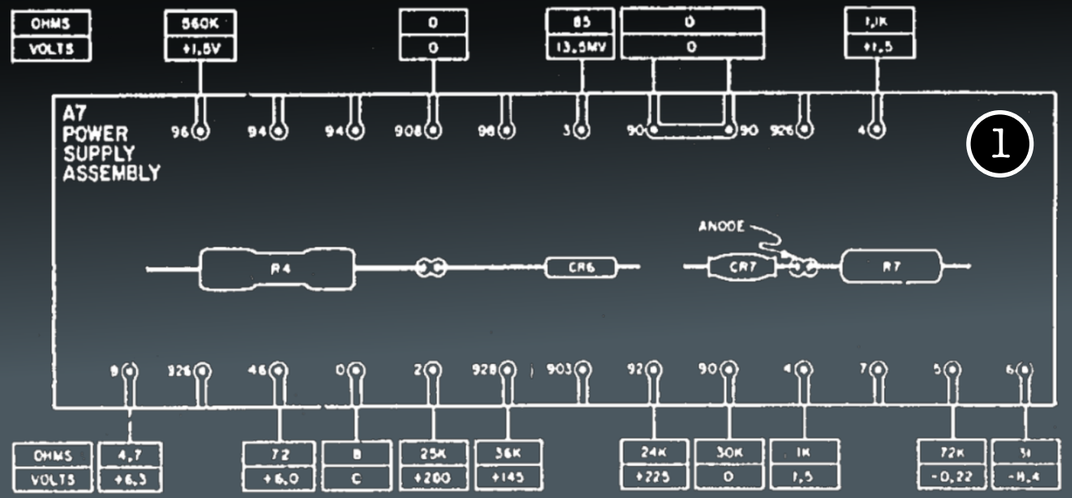
I defined the above described repairs as “routine jobs”. Let’s see now the most complex parts of a possible restoration.

Voltages first

The manual clearly specifies the power supply voltages. I found very useful the drawing below, with the voltages on the A7 Power Supply Board terminals. Before going on, all these voltages must be OK. Check also the ripple, which can mean a faulty filter capacitor when excessive.

Overdrive test

This test is very important to find possible malfunctions, and is based on giving an input voltage to the voltmeter sensibly greater than the full-scale value: a DC voltage of 0.5 V, in the 0.15 V range. This because, as we saw, some voltages in the chopper amplifier are so low that they cannot be easily measured.



The diagrams on the right is extracted by the military version of the manual (TM 11-6625-1614-15) and is more complete than the others, having also the DC levels and the time values.

Don’t forget to use at least a **10 Mohm** oscilloscope probe or you risk in some cases seeing nothing.

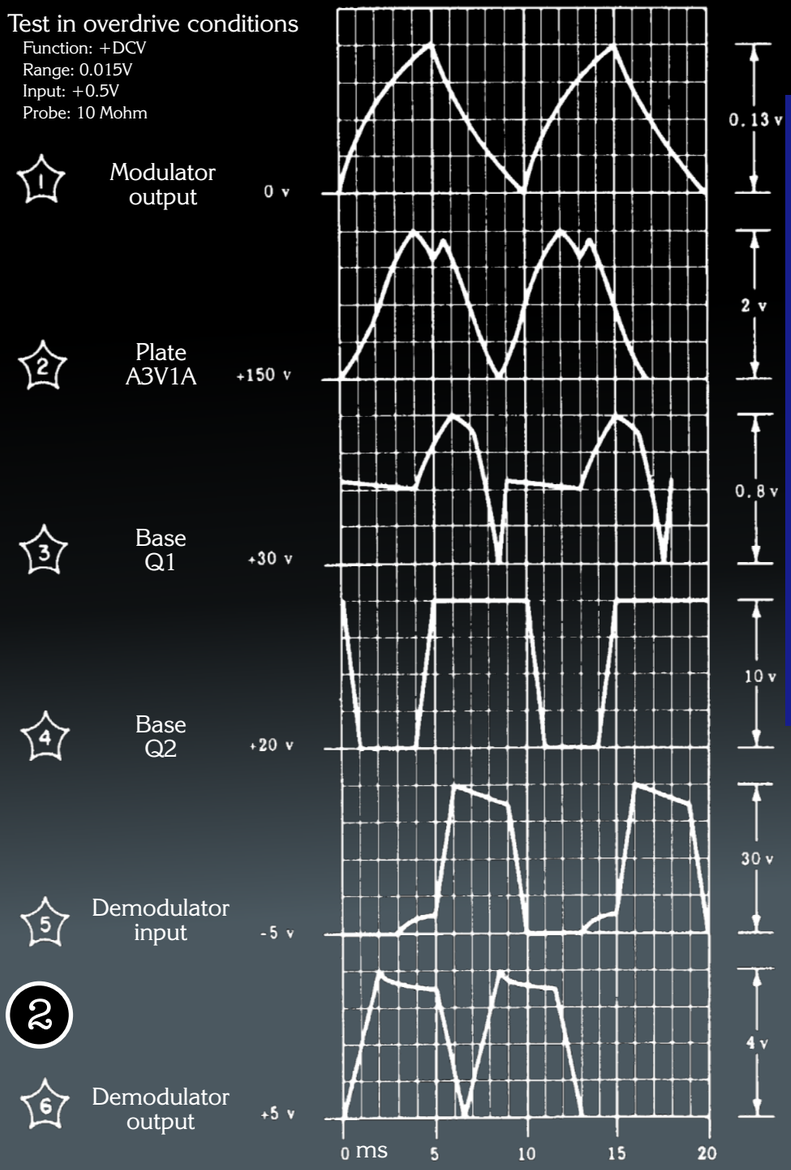
Zero instability

This overdrive test allowed me to find a problem in my second unit. Its problem was an instability in the zero value.

The test revealed that the modulator output (waveform 1) was lower than expected, although the voltmeter worked however rather well.

After a fair amount of work, my suspicions concentrated on CR1 and CR2 diodes, which I suppose to be there as a photoconductor protection.

I tried to remove them, and, without them, the zero was absolutely stable. I tried to replace them with two 1N5819, the only I had at hand, but the problem returned.



After other days of test, I got again convinced that those diodes were the culprits. I tried again: with the diodes, the output modulator was very low and the zero was unstable. Without the diodes, all went smoothly. This time I replaced the original diodes with two 1N4148s and… I won!

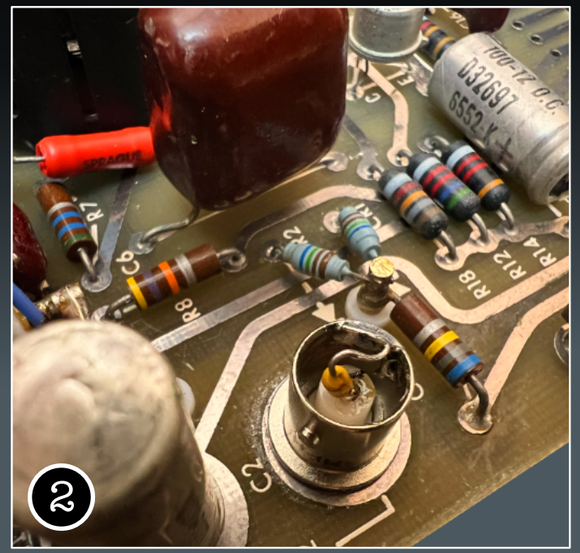
C1 and C2 self-criticism

In the previous edition of these notes, I suggested to replace C1 and C2 poly capacitors on the amplifier boards. It was not a good advice. These capacitors are very peculiar and had been changed more times in the 410C history, probably a sign of their critical function.

I believe that …a capacitor is always a capacitor, but in this case the peculiarity is probably not in the capacitor itself but in their shielding. One of them was missing (my fault, I lost it) and replaced it with a surrogated version, created with a BNC panel connector, as shown in the photo. It seems to work rather well, and even approaching the hand, the needle does not move.

❶ The original C1 and C2 Styracon B capacitors.
❷ The rebuilt capacitor inside a BNC connector.
The two brothers. Finally the zero setting is stable! Note the different knobs, both are original, as you can see seeking the Internet HP410C images. The left ones seem to be newer, but that unit has a serial number 39 units lower than the other.







A Bit History



The Model 400A, the first HP Vacuum Tube Voltmeter was designed by Dave Packard in 1942. It could measure AC voltages as small as 5 mV and as high as 300 V, simply and directly without any precautions, over a frequency range of 10 Hz to 1 MHz.

In 1946, the HP410A was introduced, HP's first high frequency electronic voltmeter and the grandfather of our 410C. Convenient for laboratory and production-line use, it could measure AC voltage from 20 Hz to 700 MHz, DC voltage at 100 Mohm input impedance, and resistance from 0.2 ohm to 500 Mohm. For making AC measurements a special low-capacitance probe was employed which incorporated a new diode developed by Eimac for this instrument. Input capacitance was only 1.3 pF; input resistance was 6 Mohm below 10 MHz, less at higher frequencies owing to dielectric losses. On AC the meter read 1 V full scale to 300 V full scale in 6 ranges. DC measurements could be made from 1 V full scale to 1,000 V full scale in 7 ranges.

Four years later, the 410B (image above) arrives. In the new design, better long-time stability was achieved and the circuit was made simpler. Other advances included elimination of dry cells from the ohmmeter circuit and the use of a more stable DC amplifier with fewer tube types. The Model 410A was discontinued and orders for it were filled with the new model at no increase in price.

❶ The 1950 HP410B let us foresee the future 410C, which however will arrive after 13 years. The general concept is the same and also the AC probe looks similar.

❷ The 1953 HP400H vacuum tube AC voltmeter, a very professional instrument.

❸ The 1963 HP410C.

❹ The 1973 HP3403C is the relatively modern digital version of the voltmeter. It cannot measure current neither resistance. We are going to describe it in the next subsection.

Three voltmeters' generations together

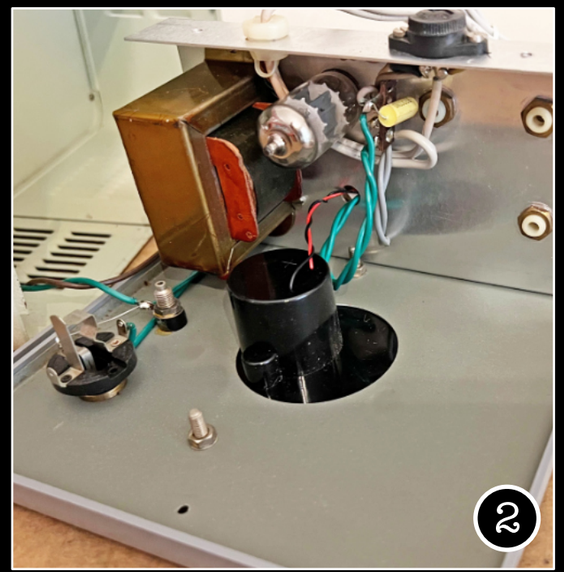


Impossible comparisons

Here in Italy we used to be clever at computers. For example, Olivetti invented the Programma 101, very similar to the future HP 9800 Series. But in the instrumentation field we never had a strong tradition. Most Italian instruments were designed for radio and television repairers, so were low-cost and low-quality. Chinaglia was an important company in this area; in 1968 introduced the electronic voltmeter you can see here, a modest instrument not very stable neither precise, based on a single tube and few passives. I don't know its street price, but it was probably only a fraction of the 410C. On the other hand, for this poor Italian market, we had a good production of passive volt/ohmmeters and of very good milliamperometers, probably among the best.

❶ The simple electronics of the Chinaglia VTVM 1001 electronic voltmeter. The switches are in bakelite. ❷ The top side was even poorer... ❸ The VTVM 1001 near the HP410C; the look was modest but the indicator was good, not only from outside. ❹ In background on the big photo, the 410C internals, the switch is in ceramic.









Voltmeters' orgy

To close this ample chatting on the 410C, I propose you other military electronic voltmeters.

TS-375/U voltmeter: constant input resistance of 30 MOhm. It can be used directly from 40Hz to 50kHz (10kHz to 150MHz using with its active probe).

TS-505 /U general purpose AC and DC VTVM and ohmmeter. Completely watertight, the input resistance is 20 M ohm (50 M on 1,000 V range).

Read more about them on my free book "Surplus photo parade".





1977

AN/USM-413

The U.S. Air Force AN/USM-413 is a military AC RMS-responding voltmeter and amplifier that conforms to OSHA (Occupational Safety and Health Administration) and industry safety requirements for operation in hazardous locations and hostile environments. It is definitely off-topic, except it's a voltmeter, but Francesco gave it to me, and it is too beautiful to resist including it here.

The meter is the military version of the industrial Ballantine 9601A instrument. The instrument was developed for testing electronic and electrical equipment in an uncontrolled flight line environment where service usage demands explosion proof performance in heavy gasoline vapor atmospheres. The voltmeter is constructed to promote the safety of operating and maintenance personnel. It is an ideal instrument for many heavy duty industrial applications where maximum protection for both the operator, the environment and the meter are primary requisites.

The AN/USM-413 covers six decade ranges from 5 millivolts to 500 volts full scale over a bandwidth from 10Hz to beyond IMHz. It can measure waveforms with the kind of distortion commonly encountered in industrial testing without change in its basic accuracy of ‡3% of reading. The meter is also usable as a wide-band precision amplifier providing six 20dB steps of gain over an absolute range of 124 dB total.

Operation in completely unsheltered environments is reliable and fast. The AN/USM-413 is immediately usable under any combination of operational and environmental conditions called out by MIL-T-21200 for Class 2 equipment. Temperature coefficient of accuracy is less than 10.05%/°C from 40°C to +15°C and from +35°C to +55°C. You can use it with confidence out of doors in the arctic or in hot steel mills. Its explosion proof qualities are assured by full compliance to the stringent explosive atmosphere tests of MIL-STD-810B,Method 511, Procedure 1.

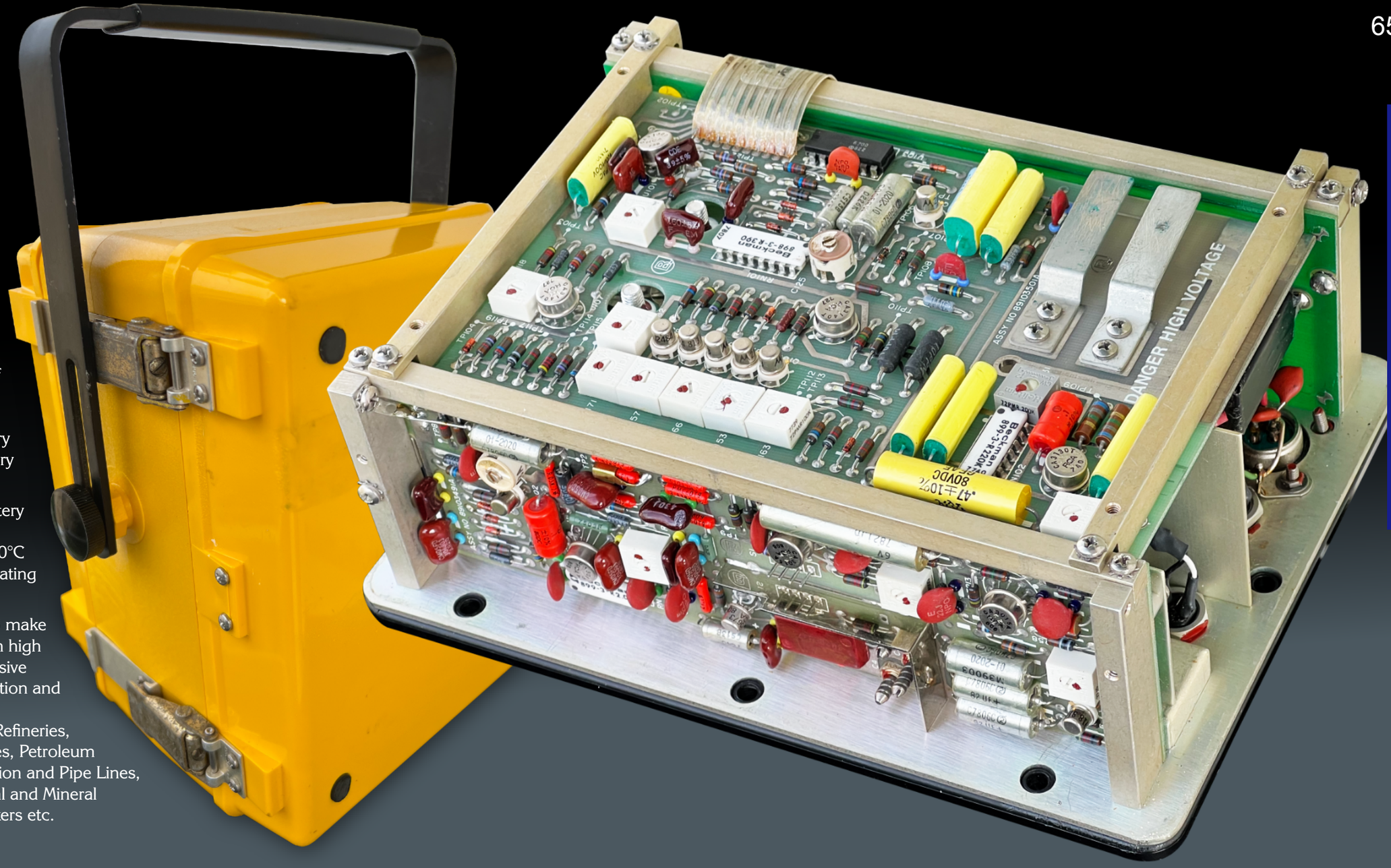
Further safety provisions for the user result from the AN/USM-413's capability of operating without damage while floating off-ground to ‡500 volts peak. Additionally the unit is internally protected against input overloads to 1500 volts on all ranges above 5 volts and to 500 volts on all lower ranges. The instrument will recover from an overload within 10 seconds. You can use it with confidence on power lines, on top of poles or in manholes.

The tough, shock resistant, flame retardant thick-walled LEXAN case is metallized internally to provide conformance with the EMI characteristics of MIL-STD-461 for Class C1 equipment. The case is gasketed at the front panel and all shafts, making it rain proof, dust proof, and salt-fog resistant, and switches are sealed. A gasketed front cover includes a storage compartment for probes and ac power cable.

A piggyback battery pack is built into a separate compartment in a gasketed cover secured to the rear of the meter case, completely isolating the batteries to avoid damage to internal circuitry in the event of battery leakage. The unit meets severe military shock and vibration specs.

An important feature when using battery power is the availability of 8-hours of continuous use in temperature from 0°C to 55°C and a full 4-hours when operating at -40°C.

Al characteristics of the AN/USM-413 make it the safest instrument to use in such high risk plants and applications as: Explosive Atmospheres, Mining, Power Distribution and Generation, Railroad Switchyards, Electroplating, Processing Mills and Refineries, Pumping Stations, Airfield Flight Lines, Petroleum Processing, Tank Farms,Gas Production and Pipe Lines, Flour and Food Processing, Chemical and Mineral Processing, Marine LPG and Oil Tankers etc.



Voltmeters

Subsection
3403C true RMS meter

A small but wonderful instrument

HP 3403C true RMS voltmeter

The Hewlett-Packard Model 3403C True RMS Voltmeter makes AC voltage measurements on six ranges of 10 mV to 1000 V full range, with over-range capability of up to 190% of range except as limited by maximum allowable input voltage. In addition, the Model 3403C makes DC voltage and DC + AC measurements on five ranges. It was introduced in 1973, to unify the previous, short-lived 3403A and 3403B, from 1972, and remained in catalog until 1983.

RMS value

In general, the RMS value of an AC voltage or current is defined as the value which has the same heating effect of DC current or voltage of the same magnitude.

True RMS

The “true” adjective seems rather funny to me, but has its reasons. The RMS value of a **sinusoidal wave** can be evaluated mathematically from its peak-to-peak value with the formula Vrms = Vpp * 0.35. Some instruments measure the peak-to-peak value and the apply this formula to calculate the RMS value.

But what does it happen if the value is not sinusoidal, e.g., a rectangular wave? These instruments, simply, give a wrong value. So, the term “true” is basically a commercial indication that can be translated in “my instrument tells you the true value, not like my competitors’ ones that give you wrong results”.

The 3403C

The 3403C was in 1977 the last edition of an AC voltmeter generation and belongs to the “true HP” era of fantastic instruments, that I find wonderful not only for their functions but also for their construction, incredibly genial and perfect in every detail, perhaps even better than Tektronix.



1973

Help on line

Today pressing a key and getting the manual is almost common to every type of electronic device. At the time, it was not easy or possible, and thus they used some foldable sheet with synthetic information (we have already found something like that in the 7854 Tektronix oscilloscope).

In this case, the 3403C has an extractable plastic sheet with useful information about the instrument characteristics.

It reports as well the zero dBm voltage value for the most common load values (600, 75 and 50 ohm) that I normally forget and that every time I need to search again on the Internet.



Specifications

Input impedance - below 10 MHz:

- 1 ÷1000 V ranges: 10 MΩ ±10%, 19 pF;
- 0.01 and 0.1V ranges: 20 MΩ ±10%, 16pF.

At higher frequencies, the input impedance is not accurately represented by the above description. When measuring these signals, a termination should be used at the 3403C input equal to the characteristic impedance of the signal source. The impedance of the cable used should also match the source impedance. This is necessary to minimize the loading effect of mismatched impedances and standing waves. In these conditions, the maximum input loading error goes from 1 to 20% (see the table in the photo).

Voltage measurement accuracy: 0.2÷0.3% at frequency below 20 MHz. 5÷10% above. See the tables in the photo for a more precise indication.

Warm-up time: to obtain readings within the specified measurement accuracy, turn the instrument on and allow to warm up for at least 15 minutes.

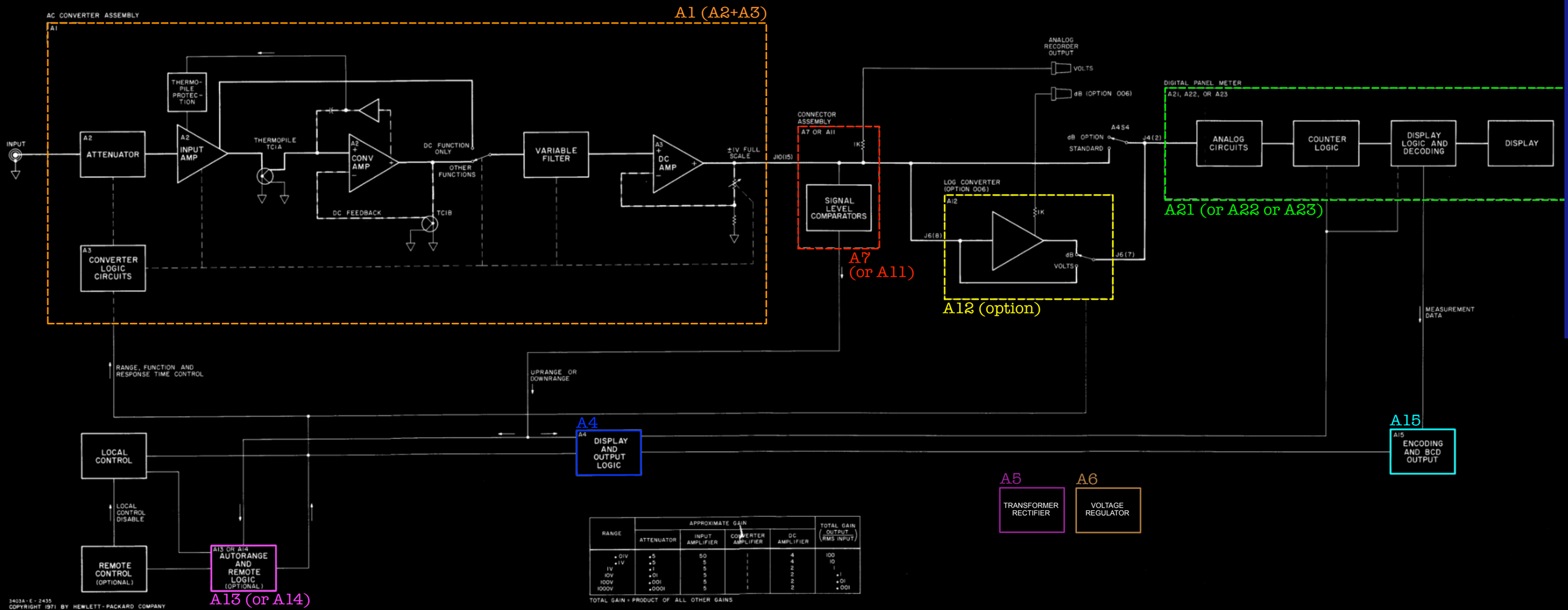
Response time: 1 s (fast), 10 s (slow).

Reading rate: 4/s (fast), 2/s (slow).

Maximum input voltage:

- high to low: 1000 V rms, 1500 V peak or 10^8 V Hz on any range.
- maximum dc in ac function: ‡ 500 V dc.
- low to chassis: ‡ 500 V peak, when floated with special banana jack-to-BNC adapter.

3403C block diagram



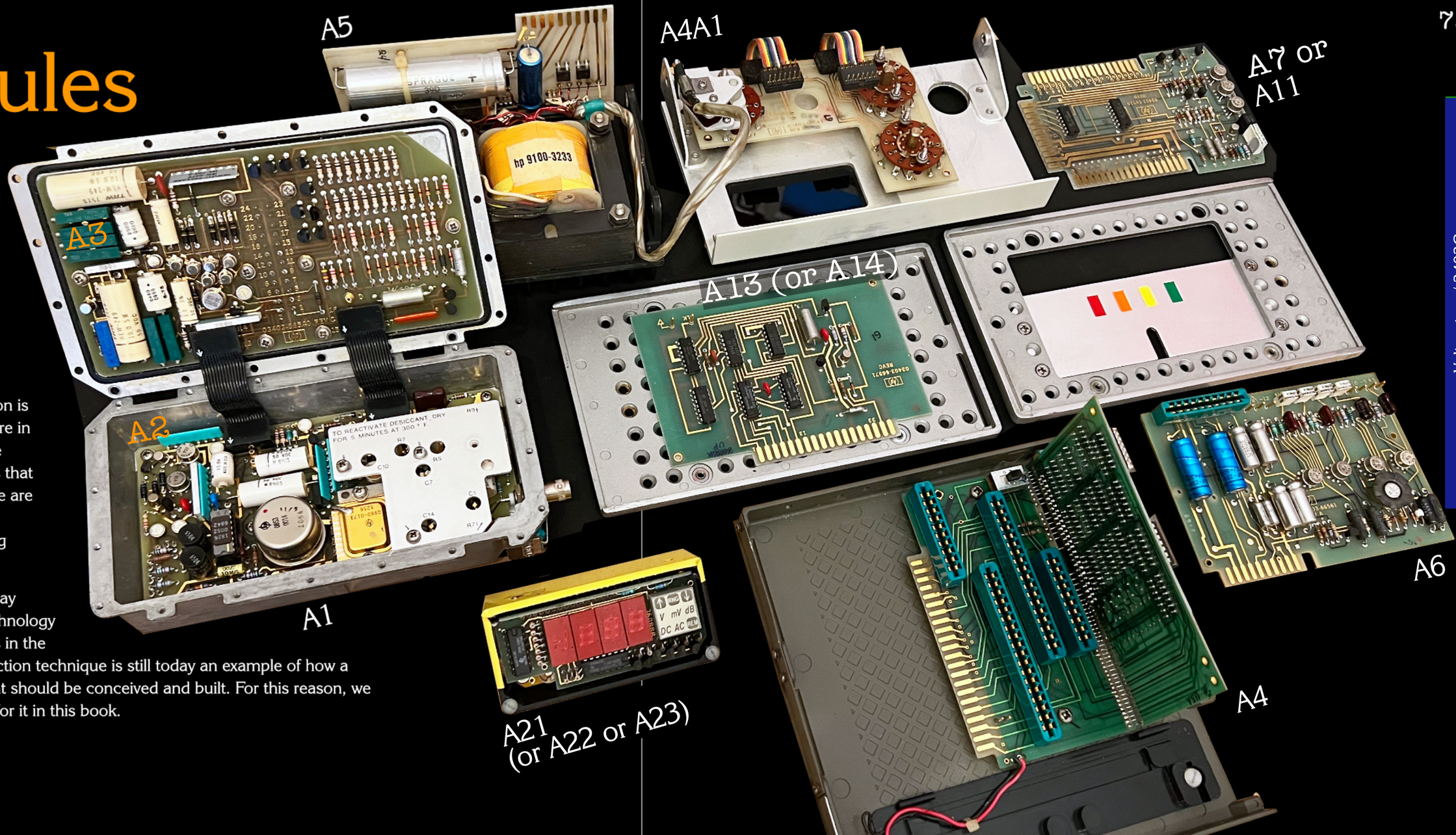
RANGE	APPROXIMATE GAIN				TOTAL GAIN (OUTPUT / RMS INPUT)
	ATTENUATOR	INPUT AMPLIFIER	CONVERTER AMPLIFIER	DC AMPLIFIER	
.01V	.5	50	1	4	100
.1V	.5	5	1	4	10
1V	.1	5	1	2	1
10V	.01	5	1	2	.1
100V	.001	5	1	2	.01
1000V	.0001	5	1	2	.001

TOTAL GAIN = PRODUCT OF ALL OTHER GAINS

Figure 7-2. Block Diagram.
7-3/7-4

Voltmeters / 3403C

Modules



The 3403C construction is extremely modular. Here in the photo, you can see almost all the modules that compose it and that we are going to present in the photos on the following pages.

The 3403 circuit is today definitely obsolete: technology has made great strides in the years. But the construction technique is still today an example of how a professional instrument should be conceived and built. For this reason, we reserved much space for it in this book.

Edge connectors

The base module is the one where all the other modules are mounted. The metal base is obtained with die-cast aluminum, on which the carrier board is mounted, to host edge connected daughter boards, a solution very common in the seventies.

An edge connector is the portion of a printed circuit board (PCB) consisting of traces leading to the edge of the board that are intended to plug into a matching socket. The edge connector is a money-saving device because it only requires a single discrete female connector (the male connector is formed out of the edge of the PCB), and they also tend to be fairly robust and durable [from Wikipedia]. However, the edge connectors were often plated with gold, to be durable, and, in the years, the increasing gold cost reduced their convenience.

The vertical A4 display interface board, with so many soldered connections, is instead rather unusual.



Building it up

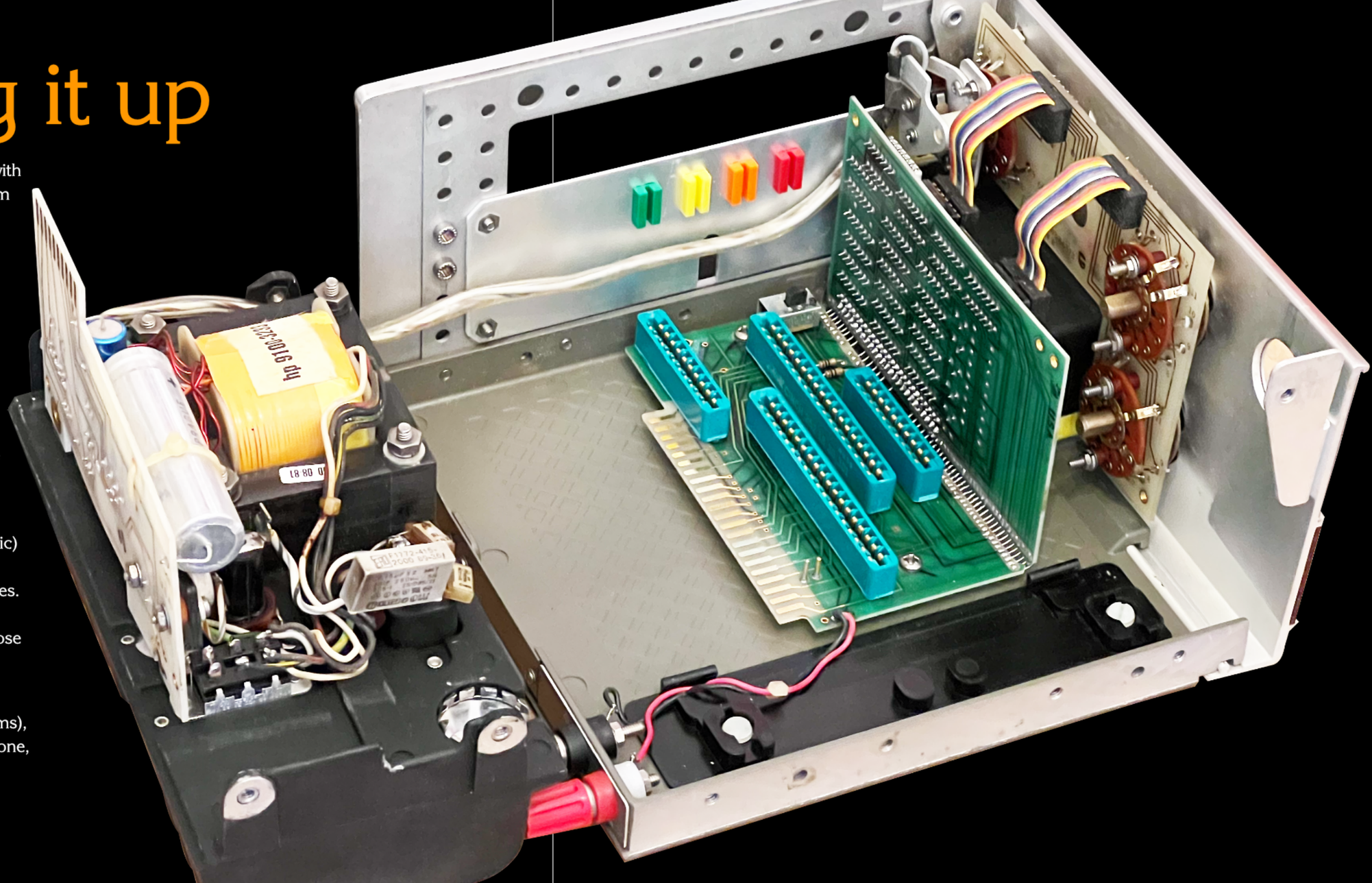
Here we can see the 3403C build up, with some other modules which start to form the complete voltmeter. Here, we have added the traditional transformer module and the front panel module, that includes the display.

The side metal plate is again die-cast, while the front parts are extrusions.

The capacitors present on the line connector receptacle, well visible in the photo are not present in the 1973 schematic diagram, and were probably added at a later time.

The small ones are of the same pestilential RIFA type (transparent plastic) that we have met more times in the Tektronix oscilloscopes reparation stories. They seem to belong only to two categories: those that exploded and those that are going to explode.

Confirm this rule, one of them was exploded (but without apparent problems), so I replaced both and also the bigger one, which didn't look too healthy.



No eye on costs

The **A1 AC converter assembly** is a key module of the 3403C and includes the input attenuator. Is is another masterpiece: an armored aluminum die-cast that can be opened like a treasure chest and that contains the A2 and A3 boards. Inside, the magic components that can measure the mythical true RMS.

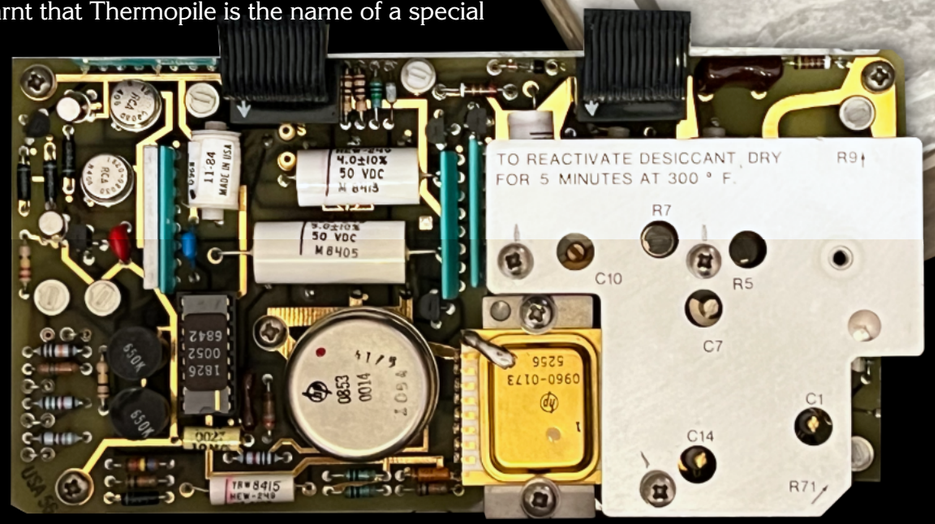
The thermopile

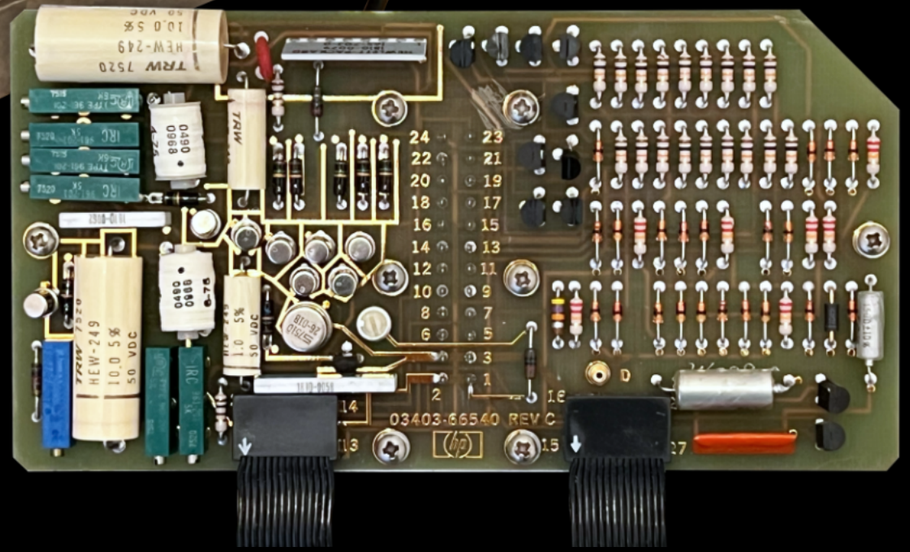
For what I knew, Thermopylae is the site of the battle between the Greek forces (including Spartans, Thebans and Thespians) and the invading Persian forces, fought in 480 BC.

Today, I learnt that Thermopile is the name of a special component used in the 3403C to evaluate the "true RMS" value, measuring the power dissipated in a load. A specially designed dual thermocouple called a **thermopile** is used in the Converter Amplifier. Each half of the thermopile consists of 30 thermocouples in series, resulting in high sensitivity. The low thermal mass of the thin-film construction permits rapid response to input signal changes.

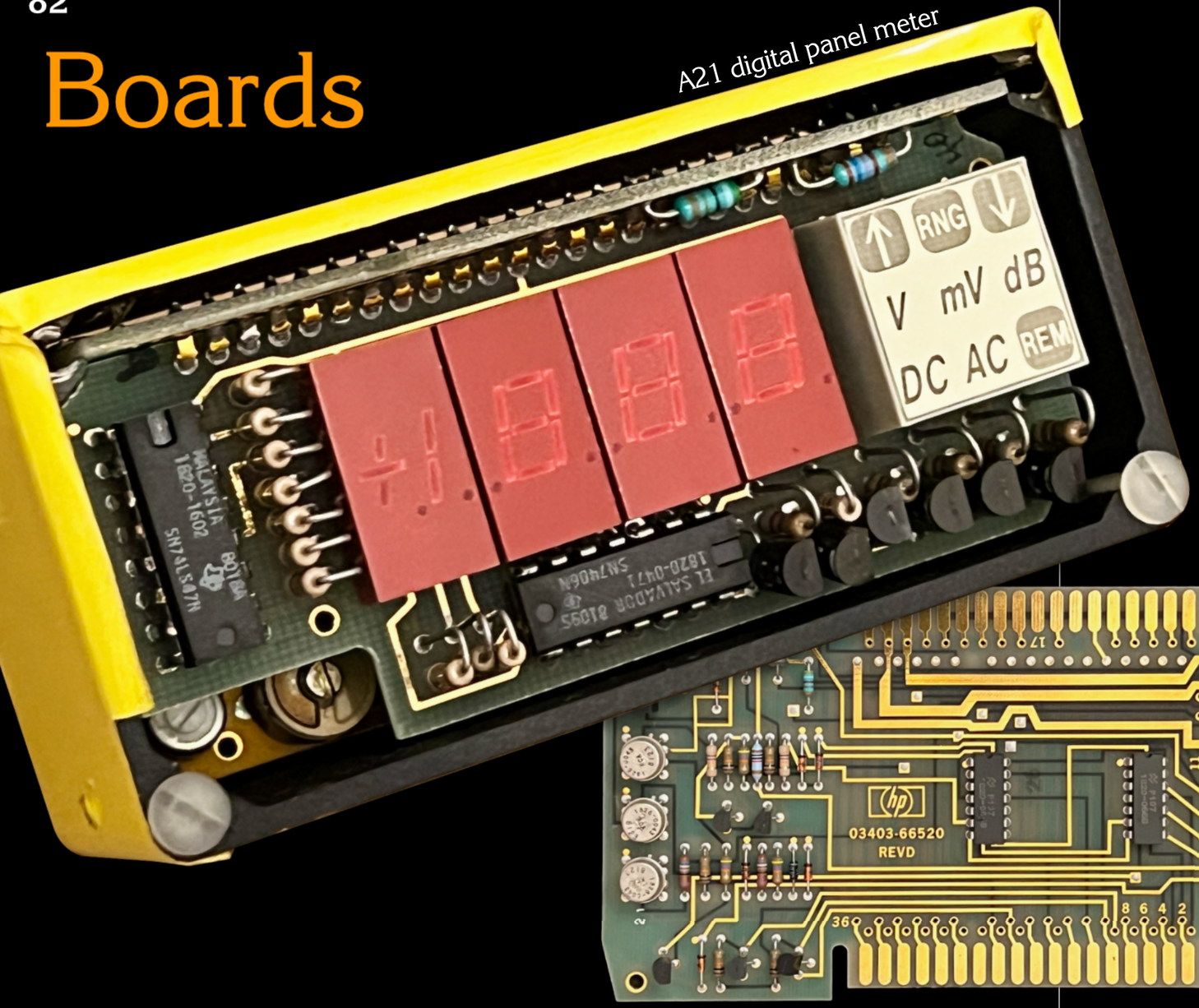
One half of the dual thermocouple converts the AC to DC, and the other half is used in the DC feedback loop of the Converter Amplifier. Since a thermocouple is a non-linear device (output proportional to power input), the feedback offsets the non-linearity of the input to the amplifier, resulting in a linear DC output.





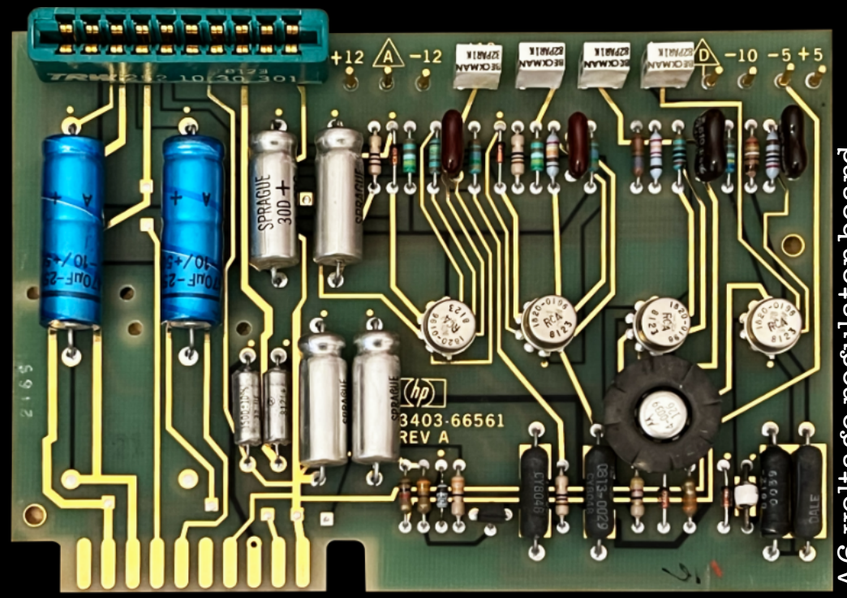


Boards

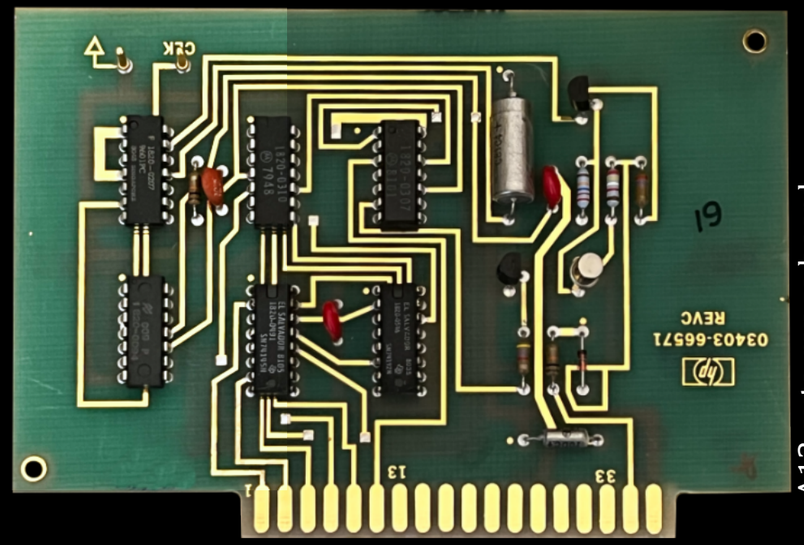


A21 digital panel meter

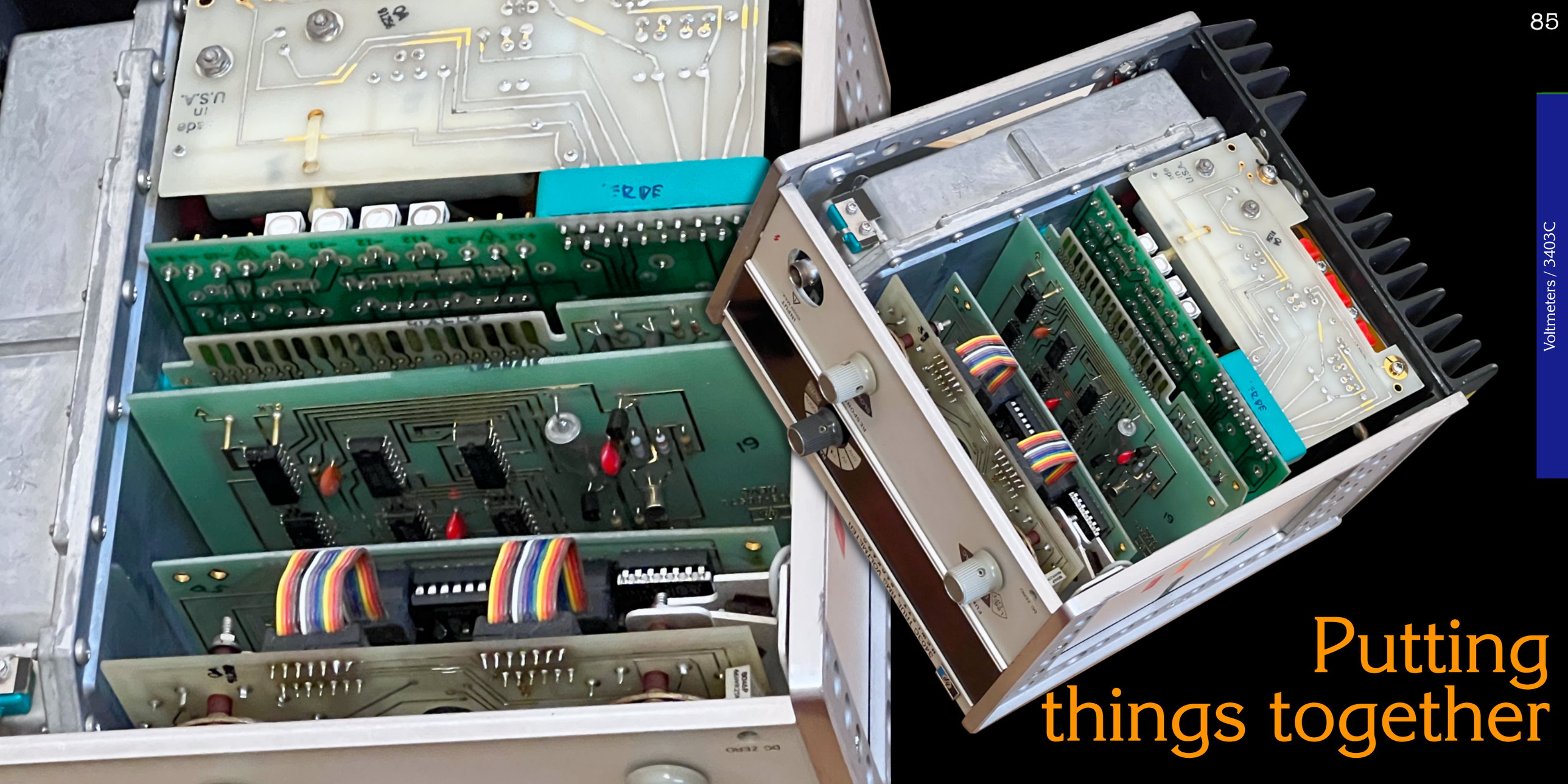
A7 connector assembly board



A6 voltage regulator board



A13 auto-range board



Putting things together

300 μV in twenty years

My 3403C seems to be from the first part of 1980. Perhaps someone has calibrated it in the years: I could find some signs of the typical sticks that calibration laboratories apply (I hate them, because removing them is normally very time-consuming). The fact is that it is still rather precise, for what I could see. I have not reference instruments, and the most precise is probably the Picotest waveform generator that you can see in the photo, fully digital, that in most cases agrees with the 3403C values.

Very interesting is also the comparison with the 3403C's ancestor HP400H that I described in the "Surplus photo-parade" book that you can download from my web site and that I am going to add to this book also. In this case as well, the read values are similar enough, with only 300 μV of difference after 20 years. The HP400H was a reputable tube instrument, very professional in its age, that still today I often use. In front of the 3403C, it can only measure AC values, with a bandwidth of only 6 MHz. But with the charm of tubes….





Signal Sources

Subsection
An Introduction



Signal Sources

Signal Sources

When you work on a new circuit, or just want to test an old one, you often would like to have a certain kind of signal as a stimulus to check how the circuit behaves. Hewlett-Packard produced a large number of **Signal Sources** for laboratory or production use.

Understanding Old Equipment

Before affording the technical description of some HP Signal Sources, let's talk of them in general and introduce some base concepts which will help us understand them better.

Of course, over the years, technical requirements have evolved, and what was a starship in the seventies could not be enough for an amateur today. Anyway, we describe in this book instruments that were great in their time and that, in many cases, are capable to perform very well still today.

Like for Playboy girls, you must not look at these instruments as they are today, but with the eyes of their time, and the following notes try to give you the proper yardstick of evaluation. The matter is very wide; we will limit to most obvious annotations.

1972

The 8640B, one of the most fascinating Signal Generators ever. It offered high spectral purity, even when producing FM signals. Ahead of its time, it was based on a cavity oscillator and a superb construction that you could remain watching for hours. A timeless great classic, highly valued even now.

Source Categories

Basic Types

Signal Sources have been described by various names; 1976 HP catalog discussed their nomenclature, depending on their design and intended use. Most Signal Sources can be considered to be part of the following main categories:

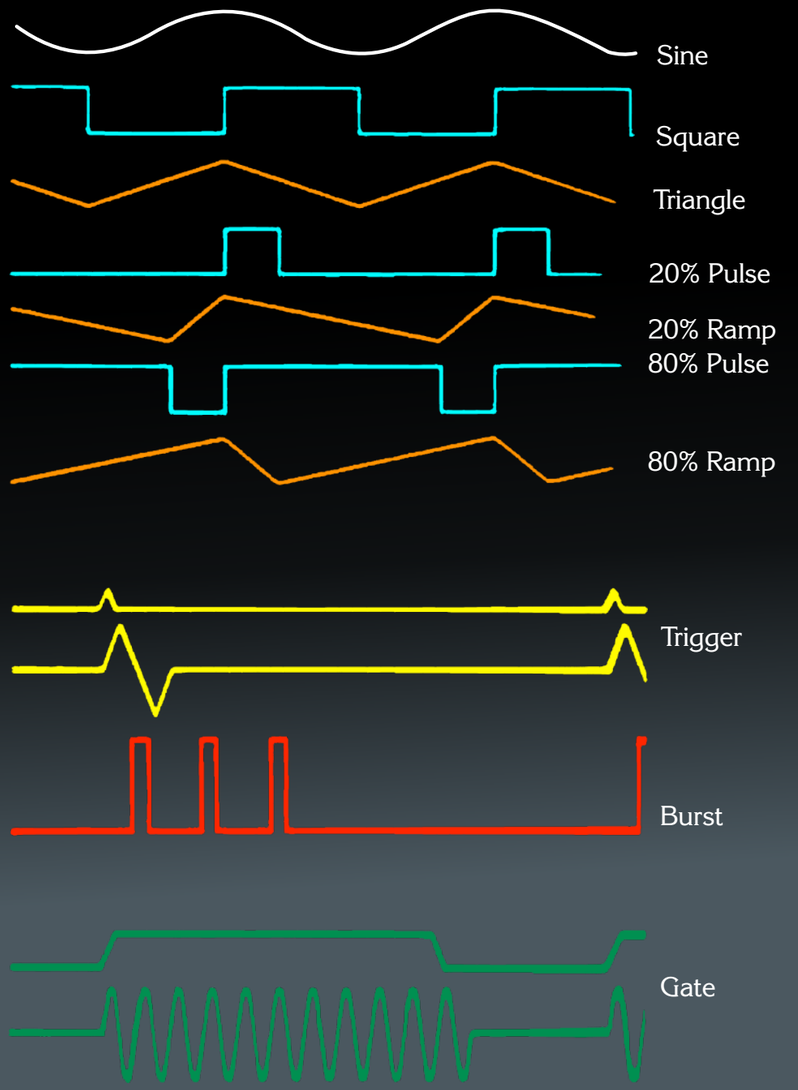
- **pulse generators;**
- **oscillators;**
- **signal generators;**
- **function generators**.

Waveforms

Signal Sources typically produce waveforms like:

- **sine waves**, like those produced by rotating generators; practically the projection of a point rotating on a circumference;
- **rectangular waves**, ideally a repeated switch between two different values;
- **ramps**, a linearly increasing voltage;
- **triangular waves**, a linear ramp followed by a symmetrical negative slope.

Today we have arbitrary function generators, i.e. instruments capable of producing almost any kind of waveform, but, in the period of time we are discussing, it was highly appreciated the possibility to combine in some way the above basic types to obtain also “strange” waveforms.



The waveforms produced by the 8165A Function Generator. Note, in front of a traditional function generator, the addition of **bursts** and **20-80% duty cycles**, a way to extend the typical application capability of the instrument.

Trigger and **gate** modes came from previous generation models. Trigger mode allowed the production of a single pulse, even if sinusoidal, and heavily influenced the circuit design. Also gate mode was not trivial, because it was not a simple AND of a free running oscillator with a control signal, having to start exactly with a new pulse and end exactly after a whole pulse.

Those were the reasons why most of these instruments used a capacitor-charge ramp as an oscillator, as we are going to analyze in details when discussing the presented models.

Unicuique Suum

Ancient Romans used to say with these words “to each his own” (if Latin heavily left its traces in Germany, guess in Italy…). In this case, the ancient Roman wisdom is relative to Signal Source categories, mainly differentiated by target applications.

Pulse Generators

A **pulse generator** is an electronic equipment generally used to produce rectangular pulses. In consequence, their main parameters are:

- pulse repetition rate (frequency);
- pulse duration (width);
- pulse amplitude (height);
- pulse leading and trailing edge slant (slope).

Oscillators

The name **test oscillator** was used to describe an oscillator having a calibrated attenuator and output monitor, typically for low frequency sine waves.

Signal Generators

The term **signal generator** was reserved for an oscillator with modulation capability, typically for RF use.

Function Generators

The name **function generator** was reserved to a signal generator delivering a choice of different waveforms with frequencies adjustable over a wide range. Function generators produce sine, triangle, square wave, saw-tooth waves, pulses. sweep. and modulation.



The 8000-Series Pulse Generators from a dedicated catalog, probably from the mid-seventies.



8015A Pulse Generator

1975 The 1975 8015A, a model from the many which composed the old 8000-Series, from which our travel in Hewlett-Packard Signal Sources starts. It was entirely based on discrete transistors and its qualities were not exceptional, even if it offered many possibilities to generate different waveforms.

Specifications

We give in the following some notes about Signal Sources specifications.

Frequency Range

One of the obvious key specifications for any Signal Source is the frequency range it covers. According to HP, in selecting an oscillator or function generator, the user was most interested in its frequency coverage, and their question to be answered here was, "Will the instrument supply both the **lowest and highest frequencies** of interest for anticipated tests?" Lowest frequency limits are probably most interesting for pulse generators, while top limits are for signal generators.

Frequency Accuracy

Accuracy measures how close results are to the true or known value. **Precision**, on the other hand, measures how close results are to one another.

I find them are funny terms, because are rather different from most people' common speech, where:

- we use the term *precision* instead of the correct term *accuracy*;
- we use the term *stability* (or *repeatability*) instead of the correct term *precision*.

In a Signal Source, *accuracy* is when I set it for 10234 Hz and I really get that value. I can consider it *precise* if I set to 10234 Hz and it remain stable on its value, whichever it really is.

Accuracy and precision of an Signal Source are important and a target for any project. We will see some different technical solutions proposed by HP and their (relevant) differences. Not all of them are obvious or predictable. Many factors influence these parameters, like, for example, temperature and ageing.

In this point, accuracy & precision, we could include **dial resolution**, and in general its implementation.

Frequency standards

In frequency synthesizers, frequency is determined by a **frequency standard** used within the generator. In addition, most of them offer the possibility to use also an external reference, typically running at 10 MHz. Modern TCXOs (Temperature Controlled Crystal Oscillators) can be used as external references to increase accuracy & precision in an inexpensive way. You can buy these devices from Amazon for few euros.

Frequency Stability (Precision)

Frequency stability of an oscillator determines the ability of an instrument to maintain a selected frequency over a period of time. Component aging, power-supply variations and temperature changes all affect stability. Carefully chosen components, such as precision resistors and capacitors in the frequency-determining networks contribute to long-term stability.

In our little travel in HP Signal Sources, we will see the evolution in the frequency generation scheme.

Signal Purity

All Signal Sources produce some level of spurious signals. Levels of harmonics and spurious signals are normally quoted in terms of decibels relative to the carrier (dBc). Generally speaking, free analog oscillators have lower levels of spurious signals than those based on frequency synthesis, like PLLs.

Phase noise

We will afford this matter with Spectrum Analyzers. Phase noise is in frequency domain what we call jitter in time domain, i.e. phase instability of the signal. Like signal purity, phase noise is greater in synthesized Signal Sources, because the basic PLL correct oscillator phase to keep the frequency locked. Fractional-N PLLs sensibly reduces this problem, thanks to a “smooth” phase adjustment (e.g., like done in the 3325A). Phase noise levels are measured in terms of dBc / Hz.



8012B Pulse Generator

1975

The 8012B is another of the mid-seventies Hewlett-Packard product line. It offered many of the 8015A possibilities in half the space. Its construction was slightly better than its bigger brother.

8165A Programmable Signal Source



1978

In 1978 HP started innovating the Signal Source line by introducing new programmable microprocessor based instruments. One of the first of them was this 8165A. Among its novelties, the Phase Locked Loop frequency generator which offered a stability unknown on the previous models.

Output Level

Another important Signal Sources' specification is their output level (power or voltage). Some tests require large amounts of power into low-impedance loads (typically 50Ω), while others merely require sufficient voltage output into high-impedance loads.

For most RF signal generators, the power output specification is defined in dBm, i.e. dB relative to one milliwatt; for function and pulse generators, it is more often defined in amplitude level, i.e., in volt. Best models offer both.

Note that, with a 50Ω load, the power increases rather quickly: 10 V require 2W power, 20 V should require 8W.

RF generators have their top output power between 10 and 20 dBm (10 to 100 mW), while function/pulse generators may offer 10 V/50Ω or 20 V/1kΩ.

Power accuracy

For many test scenarios it is necessary for the output of the signal generator to be accurately known. This is because the response of the unit under test is most likely to vary according to the signal generator level. In some circumstances it is likely that the response may be very sensitive to the signal generator level. As a result the signal generator level accuracy specification is of great importance.

Modulation

In order that many tests can be undertaken, it is necessary in many instances that the signal can be modulated. Although more recently many types of modulation are required, in "our" Signal Sources AM and FM can be possibly present, and not always both. Sometimes they were offered as an option. Even if present, often they required the use of an external signal generator as modulating signal.

Pulse Parameters

Pulse generators offers as a rule the possibility to change repetition rate, amplitude and pulse width. Best models offer also the adjustment of leading and trailing edges, i.e., rise and fall time, and the delay respect to a trigger pulse. Other can generate not only single pulses but also bursts of counted pulses.

Pulse Parameters Accuracy

As obvious, the accuracy and the granularity (resolution) of parameters adjustment is relevant. We will see that some models offer only a “rough” control, while others allow to define the pulses with extreme precision.

Sweep

The sweep function allows a Signal Source to create a waveform with varying frequency and a constant amplitude. The equipment allows to select start and stop frequencies and the sweep time. The variation can be linear or logarithmic. Some models offer the possibility to choose between them.

Sweep generators are commonly used to test the frequency response of electronic circuits like filters or amplifiers.

An output is normally provided with a ramp voltage proportional to the emitted frequency to control the scan of an oscilloscope with which you can plot the output response of the circuit.

The models based on a VCO (Voltage Controller Oscillator) offer the dual possibility to control the generator frequency with an external ramp generator.

Temperature Range

In those years, temperature was a problem, probably more than today. HP used to declare 0-50°C operating range, with no derating factor between 20-40°C. For me used to automotive devices, it seems a dream, but laboratories were not generally in the middle of the steppe.

Microprocessor Not/Yes

Today it is no longer an option, but in the 70-80s microprocessor presence made the difference.

Microprocessor control promoted highly accurate pulses. Parameters could be directly entered via the instrument's keyboard, and displayed on LED displays. The “soft” vernier controls gave a fine adjust capability to "tweak-in" any pulse parameter, and you could increment or decrement the selected parameter either in single steps or at speed.

8160A Programmable Pulse Generator



1979 — One year later, in 1979, the new 8160A was introduced. It was an extremely precise (and expensive) instrument, much different from the other models here described, probably destined to semiconductor industry for device qualification.

Error detection by the microprocessor further simplified pulse setup by solving the old problem of incompatible settings. Should pulse width exceed pulse period, for example, the microprocessor could indicate a TIMING error. All possible mis-settings were detected and the type of error was indicated to aid rapid correction.

Parameter Storage

Microprocessors introduced a new problem/opportunity. Previously, setups were stored in the knobs themselves, but now? Complete parameter and mode information for many independent instrument set-ups had to be stored, to avoid manual resetting every time the instrument was switched on.

Also waveforms could be stored and recalled either manually or via the HP-IB.

By utilizing a single command to recall an entire instrument set-up, men hours could be saved. In simple repetitive testing applications, storage of test waveforms gave a high degree of user convenience without an external controller.

HP-IB Programming

I tend to forget this point, which was instead very important. Old instruments could not easily be remotely controlled. Microprocessor control over all interface functions made remote programming as easy and straight-forward as manual control, and each of our instruments could so become part of complex automatic systems.

The instruments employed keystroke programming so that data entry via the HP-IB was an exact simulation of manual entry. Bus commands for each front panel key simply replaced manual keystrokes.

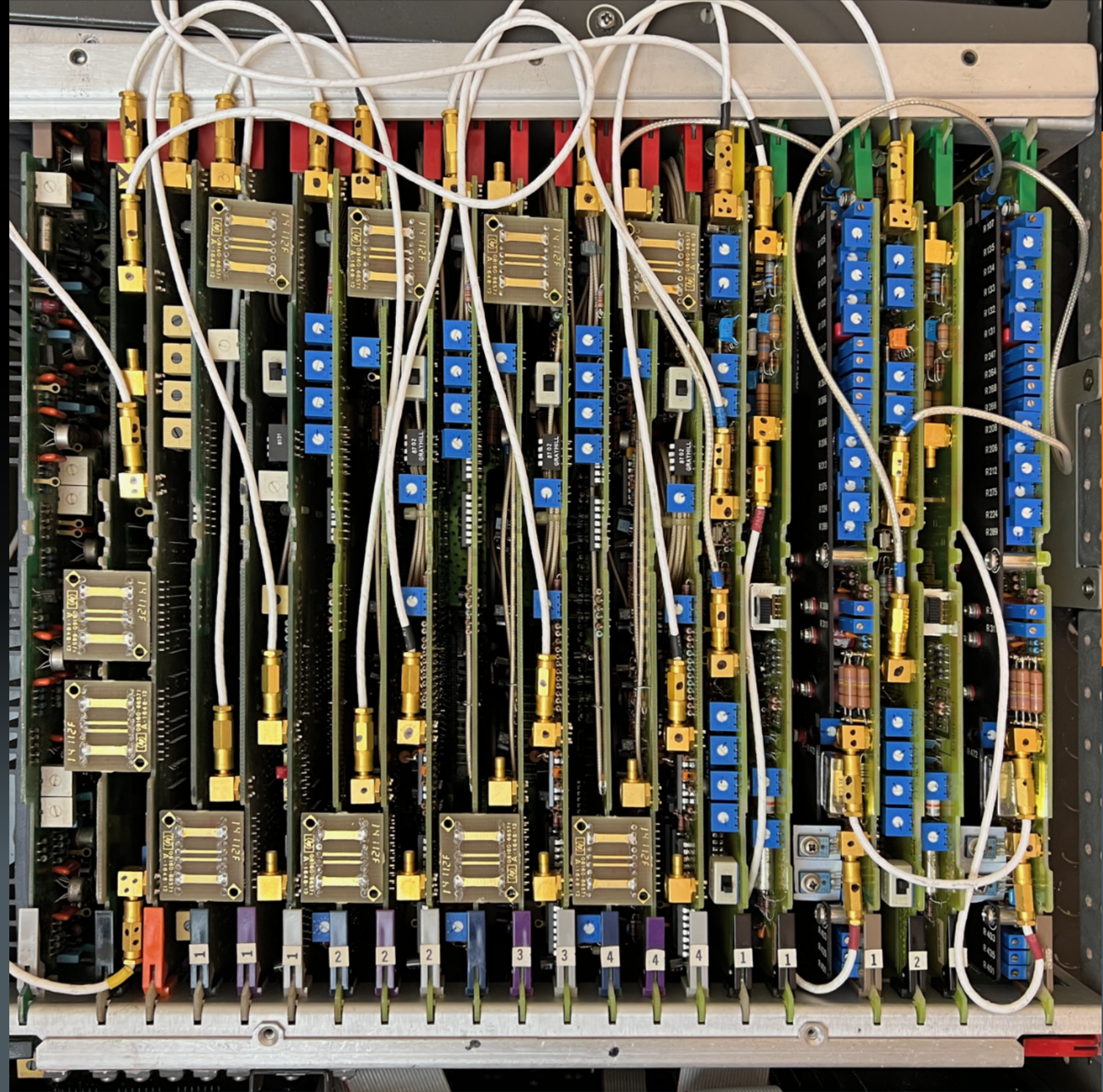


Photo: splendid landscapes were offered by the best HP instruments, were gold was used without saving. I heard that gold-scrapers contribute to the extinction of our beloved. Just like scraping “La Gioconda” for the paint…

The Years of Change

3325A Synthesizer / Function Generator



1979 With the 3325 we are entering in the modern era: the 3325A's engine uses the new Fractional-N PLL, which offers a reduced phase noise and the possibility to define values with up to 11 significant digits.

1977

In 1977, I was starting to produce my first Z-80 based microcomputers, sold also as kits, with some success, and my instruments were three: oscilloscope, oscilloscope and oscilloscope (a Tektronix 545). In reality, I had also a digital counter and a digital pulse generator, both home built, but I never contemplated the opportunity to buy a function generator. The money was scarce and we had to make do…

1977 HP Signal Sources

At the same time I was playing with the first microprocessors, HP was printing its 1977 catalog, which surely I proudly received, where the offer for Signal Sources was abundant, but not very exciting. As we will see talking about the not-by-me-beloved 8015A and 8012B, most of **pulse generators** were still analog and discrete transistor based. Things weren't much better on the **oscillators/function generators** front, albeit the first frequency synthesizers were already present, but still rather old fashioned.

Well different was the offer of **signal generators**, where the mythical, 1972 **8640B** was still reigning, probably one of the most appreciated HP instruments ever.

The Years of Change

At HP, however, people didn't sit idle, and in 1978 catalog two "nouvelle vague" instruments, the first of a long series, make their appearance on the scene: the **3335A Automatic Synthesizer** and the **8165A Programmable Signal Source**, listed in both the Pulse Generators and the Oscillator & Function Generators sections.

They will be followed by other extraordinary models, like the **8160A Precision Pulse Generator**, one of the most expensive ever, or the innovative **3325A Function Generator**, based on Fractional-N synthesizer, as we are soon going to see.

Signal Sources

Subsection
8640B Signal Generator

A true classic masterpiece in signal generation

HP 8640B signal generator

A religion?

The 8640B is not a normal RF signal generator but is more **like a religion**, to which my friend **Francesco Sartorello** (a great surplus expert whom I introduced you in my first book on surplus equipment) initiated me, entrusting to me two of these fantastic instruments. It's automatic: just open one of them, look at its interiors, and the magic flux will infect you also.

The 8640B is a radio frequency signal generator present in Hewlett Packard catalog from 1973 to 1991, when it was priced at the astronomic figure of 14,600$, as shown in the table on the next page, not ashamed but pride of being not synthesized. It was more than 32,500$ today, without any option.

General specifications

The 8640B covers the frequency range 500 kHz to 512 MHz, extendable to 1024 MHz with an internal doubler (Option 002). Using the HP 11710B Down Converter, the HP 8640B frequency range can be extended down to 10 kHz. An optional internal audio oscillator (Option 001) has a frequency range of 20 Hz to 600 kHz.

The 8640B has an output level range of +19 to-145 dBm (2V to 0.013 μV) which is calibrated, metered, and leveled to within +0.5 dB across the full frequency range of the instrument. The output is protected against up to 50W of reverse power (with Option 003).

1972

Modulators

The 8640B also has AM, FM, and pulse modulation for a wide range of receiver test applications.

In the phase locked mode, FM capability and spectral purity are maintained while providing FM rates from 50 Hz to 250 kHz.

Spectrally pure

The most appreciated 8640B quality is its spectrally pure output signals, due to the full analog design and the heavy, die-cast modules' construction.

The noise of the HP 8640B is extremely low beyond 10 kHz offsets. At a 20 kHz offset from the carrier, SSB phase noise is <-130 dBc at 450 MHz and <-122 dBc at 550 MHz. Broadband noise floor is better than -140 dBc/Hz.

Phase-lock stability

I always beware of analog generators; yes, they may have a pure output signal but their stability is always very relative. In this case we follow the Italian proverb "having your wife drunk, and the barrel still full", i.e. a win-win condition. The 8640B is an analog signal generator but with the stability of a synthesized one. Just press a key, and it phase locks to the RF output frequency of the crystal timebase used in the counter.

Resulting in drift that is better than 5x10-8/hr, while still maintaining its native spectral purity. The 8640B can also be locked to an external 5 MHz standard, possibly increasing the stability even more.

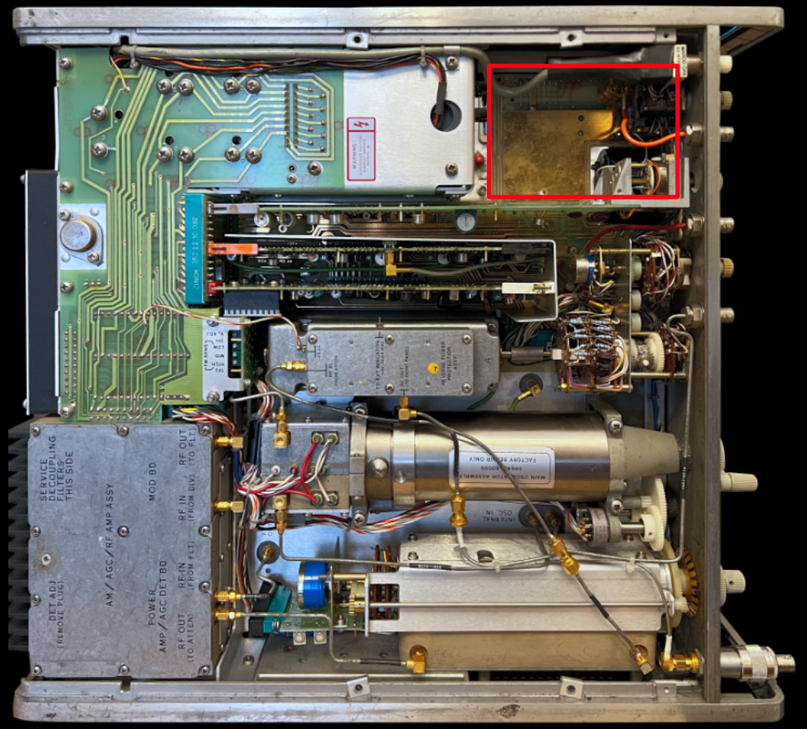
By the way: an 8640A existed, without this the digital display and the PLL feature.

1991 price list	
8640B Signal Generator	**$14,600**
Opt 001 20 Hz - 600 kHz internal audio oscillator	+$600
Opt 002 Internal doubler 512 - 1024 MHz	+$1,255
Opt 003 Reverse power protection	+$455
Opt 908 Rack mount kit (5060-8740)	+$39
Opt 910 Additional operation and calibration manuals (08640-90208) and two service manuals (08640-90215).	+$350
Opt 915 Add service manual (08640-902)5)	+$155
Opt W30 Extended repair service.	+$315
Opt W32 Calibration service.	+$3,260

More than professional

It seems that Francesco is always knowing what can unleash my electronic passions, and also in this case he was right. In the beginning, I was not totally convinced of this SG and was simply… curious.

Even without all the qualities that above said figures say, you can't help but falling in love with this masterpiece in electronics, as soon as you remove the bottom cover, just with 4 screws. A magic word of die-cast aluminum sealed modules, encrusted with small gold stars (the RF connectors) opens to you, as shown here and in the following pages.



The picture here on the right is not just the same reported few pages forward. It depicts a 1974 8640B without the Option 001, i.e., the low frequency variable oscillator, that stays, when present, in the area in red. There are many other differences, like the switch block with the gears, about in the center of the front panel, but we will discuss these differences later.

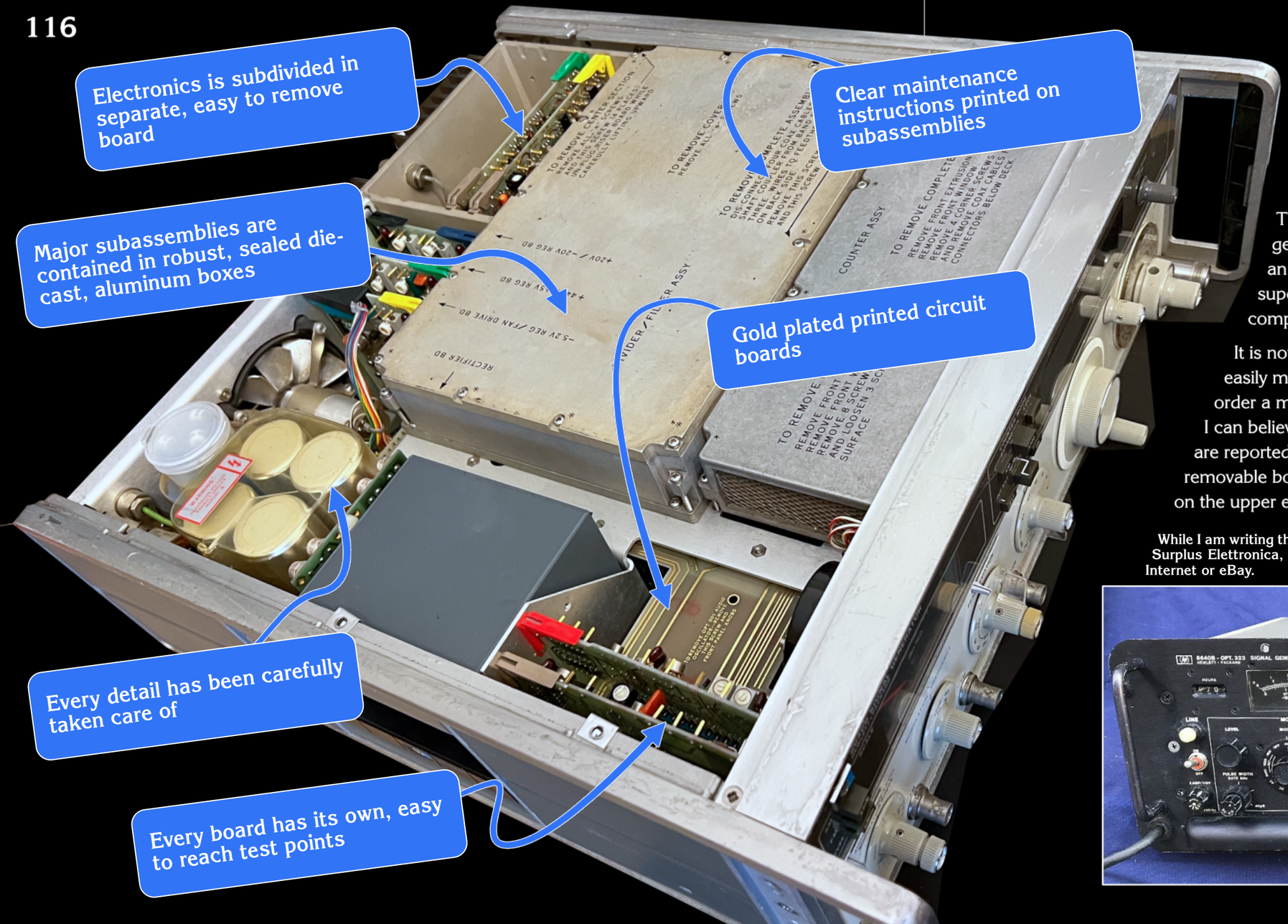
Designed to be serviced

The chassis carries two pieces of test equipment: a signal generator and a frequency counter combined together to give you an accurate readout of output frequency, very useful and far superior to similar equipment, where a separate counter or complicated reference procedures are needed.

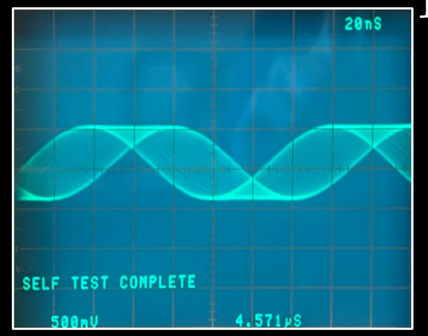
It is not common to find an instrument so perfectly designed to be easily maintained. Francesco told me that when the Army decided to order a military signal generator, very few modifications were required and I can believe that. In addition to the modular structure, clear instructions are reported on each sub-assembly. Most of the electronics is contained in removable boards, and each of them has its own test points, easily accessible on the upper edge of the board itself, and so the adjustment trimmers.

While I am writing these notes, an 8640B Opt. 323 (aka AN/USM 323) is available at Radio Surplus Elettronica, one of the best Italian surplus shops. You can find them easily on the Internet or eBay.





8640B
The circuit



Amplitude and frequency modulation at the same time from the HP 8640B, viewed on a Tektronix 7854 oscilloscope.

The HP 8640B is subdivided in three main sections:

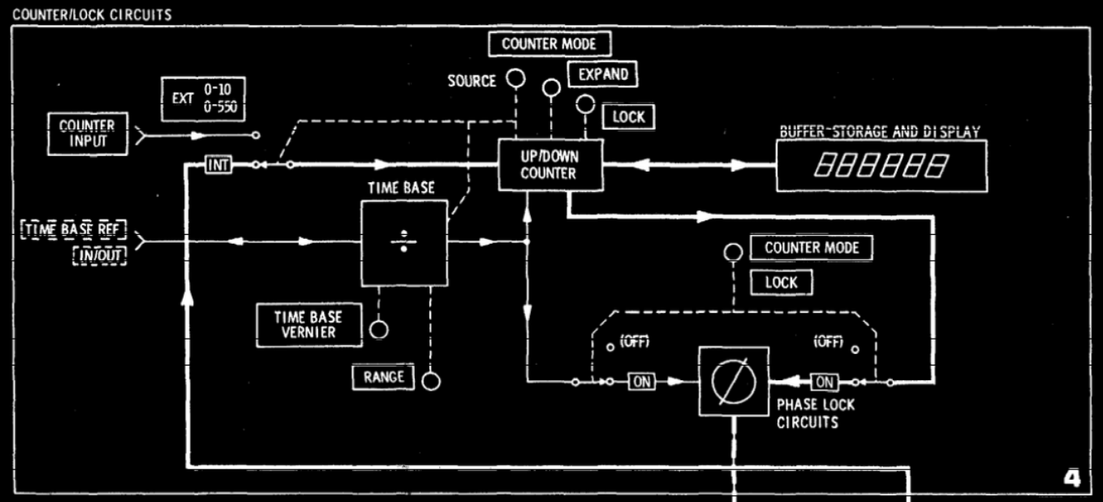
- the RF oscillator with the FM circuits;
- the output amplifier, with the AGC and the AM circuits;
- the frequency counter, that can also be used independently.

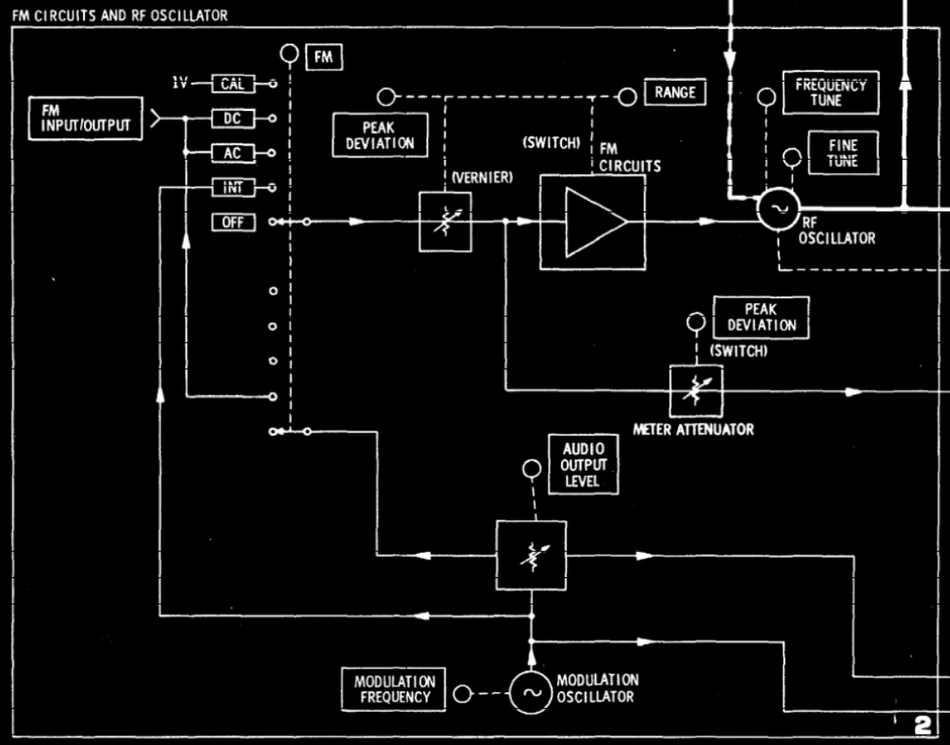
The basic 8640B covers the range 500KHz to 512MHz (plus a little extra for the benefit of overlapping ranges) but could be extended (in the factory) to additionally cover the range 512 to 1024MHz. The range switch has the 512-1024 MHz position and the display shows the right figures turning the frequency knob, but without the option, the frequency remains the same as in the 256-512 MHz band.

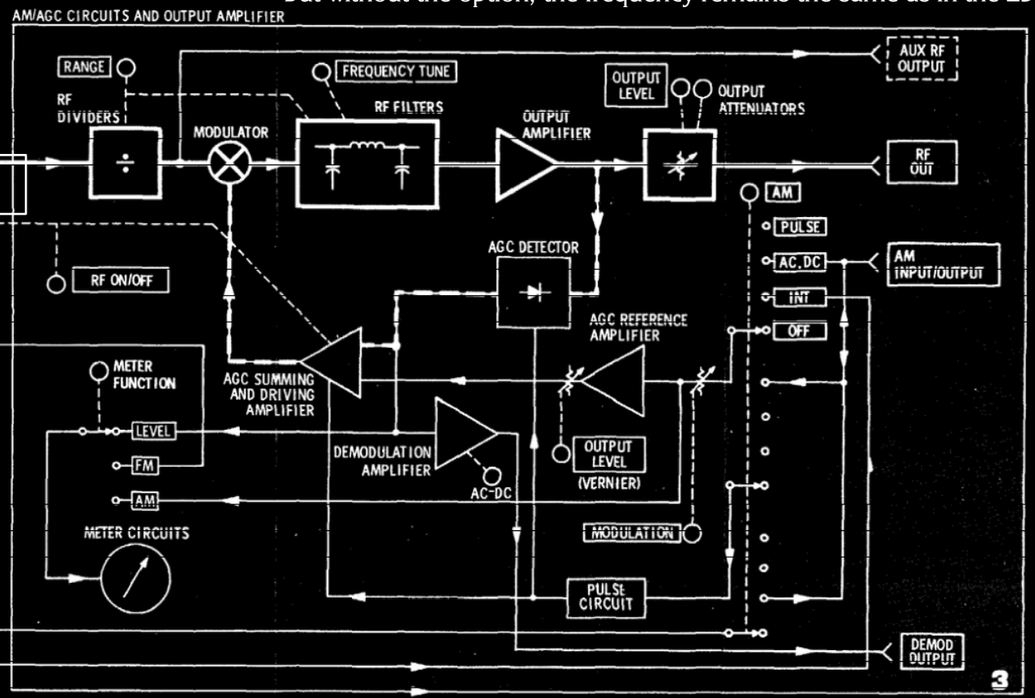
The 8640B is namely analog (i.e., not synthesized) but relies however on a digital circuitry to divide the cavity-tuned oscillator frequency to match each range. As a consequence, many tunable filters are present to produce a good and pure output sine wave.

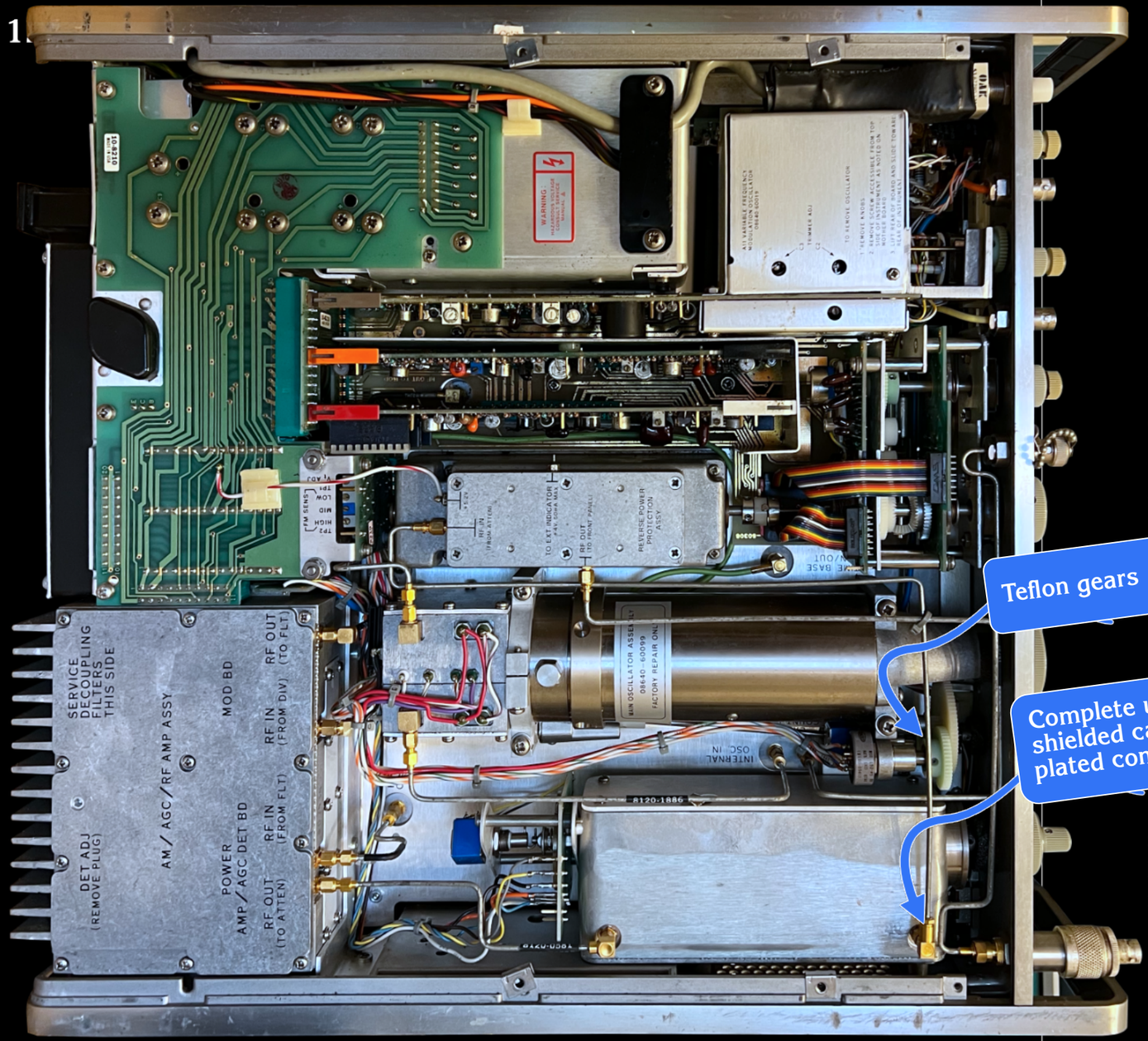
The cavity is tuned by a mechanical arrangement covering something like eight turns of the tuning knob and each range has a decent overlap so in fact the cavity oscillator tunes something like 230MHz to 550MHz.

The cavity oscillator output passes to a digital divider chain consisting of a set of nine divide by two stages in series providing x2, x4, x8, x16, x32, x64, x128, x256, x512. The lowest range









uses all nine stages and covers about 449KHz to 1074 kHz which represents 230/550 MHz divided by 512. The next higher range has divide by 256 giving 898KHz to 2.148MHz and so on.

Coupled to the oscillator tuning control is a potentiometer which signals to the filter assembly that relays should select either the Low or High filter.

Stability

What about stability? Ordinarily a design would be based on an oscillator having relatively low frequency because its easier to keep stable but the HP VHF oscillator is inherently very stable at the expense of a rather large mechanical layout. The 8640B does however incorporate a clever technique whereby the master oscillator can be locked to a 5MHz crystal or, if desired, an external reference.

Output circuits

The 8640B has a level control system which normally places at the input to its attenuator an RF voltage which results in precisely 10dBm of RF output with the output attenuator set to +10dBm. This is achieved by an AGC system whose input comes from an RF detector and whose output drives an amplifier. HP call this amplifier a modulator and it takes the form of a hybrid held within a case that looks like a large gold TO3 can. Following the modulator is a second identical-looking hybrid carrying a 16dB RF amplifier. Within this second hybrid is the RF detector whose output is flat from 450KHz to 550MHz. The detector provides a negative voltage whose magnitude exactly relates to the RF output of the hybrid which drives the output attenuator. If the RF output rises for any reason the detector drives it back down via the modulator to reduce its output. The AGC system is straightforward in principle, but has a number of extra features. Firstly a boosted RF output is possible, taking it to almost +20dBm by modifying the loop parameters when the output attenuator is switched to +20dBm. Secondly, one can adjust the output to correspond with meter readings, and thirdly AM or FM can be selected which require changes to the AGC system and to the circuitry which handles the output meter.

I stole most of the above from a very interesting web site: the Allan's Virtual Radio Museum, that has an exceptional description of the 8640B repair, and a lot of others. I strongly recommend you to visit it (https://www.radiomuseum.co.uk/index.html).

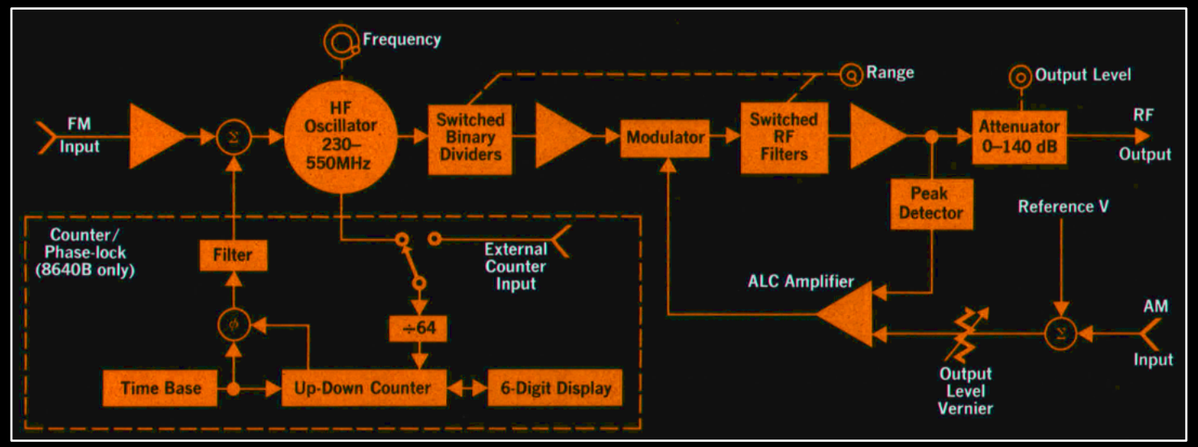
The cavity

As told, the major aim of the 8640 project was mainly the spectral purity of the produced signal, even when producing FM signals; this this conditions all the design choices.

Normally I try to describe here what I understand of an instrument; in this case I admit that the fundamentals of this project are beyond my skills, and, if you want to know more, I recommend reading the HP Journal 2/1973, that contains a lot information about the 8640 design, analyzing also the possible solutions that they evaluated before choosing the final road,.

Below you can see the simplified block diagram of the 8640B. The most interesting point is the resonant cavity used in the main HF oscillator, that is the heart of instrument. The active device is a low-noise transistor (HP-21), operating in common-base configuration. Cavity is less than 1/4 wavelength long so that, short at bottom end, causes opposite end near tuning plunger to appear inductive. Capacitance between tapered tuning plunger and center post resonates with resulting inductance at selected frequency. When you, turning the knob, move the plunger, the capacitance changes and then the resonating frequency. A slug into the cavity is used for fine tuning.

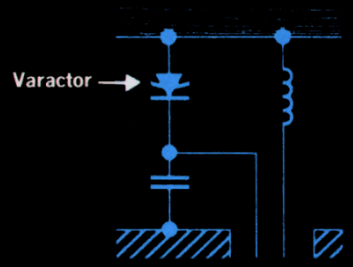
The feedback for oscillation is by collector and emitter loops coupled magnetically through the cavity. AGC, necessary for stable oscillation, is accomplished by modulating the conduction angle with self bias

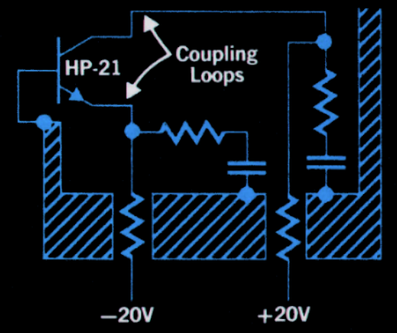


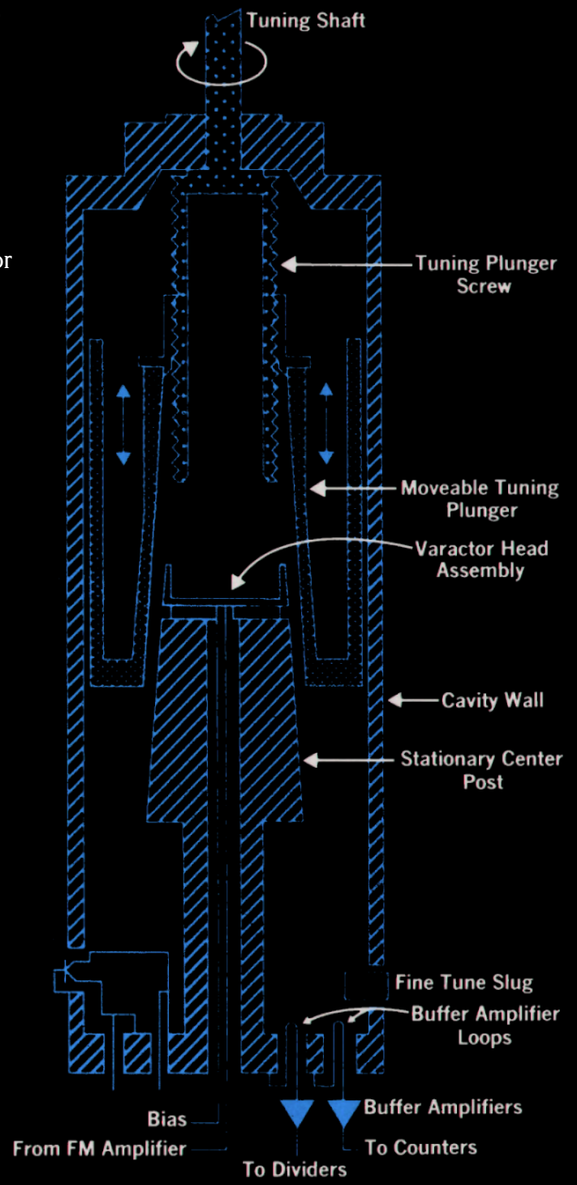
developed by rectification in the oscillator base-emitter junction.

Varactor diodes are in series with capacitance between Varactor end cap and plunger and are used for frequency modulation.

Two outputs are provided: one is used for the output signal, via the digital dividers, and one for the counter display (in the case of the 8640B only).







Eight years

Eight years elapse between the two 8640B here shown in the photo: the upper is from 1982, the lower from 1974. Differently from Tektronix, HP used to release many partial updates, and I could not find a precise list of the modifications introduced in the years, so I limit to tell about the differences that I could spot by myself.

At first sight, you can see the different knobs, and that is not only a matter of style. The first knobs have a wing that should make easier to turn them, because the some strength is required, even more after so many years. As a consequence, the RANGE knob of this unit has been broken and I had to remove the old glue and try a new reparation (but I need to be careful when using).

Differences

Also the mechanism beneath the front panel has been modified in the younger unit, as shown in the photos ❷ and ❸, and a new PCB based switch replaced (photo ❹) the traditional rotary switches. My impression is that they were aware of the problem and trying to reduce the required torque, adopting a new wingless knob, impossible to break.

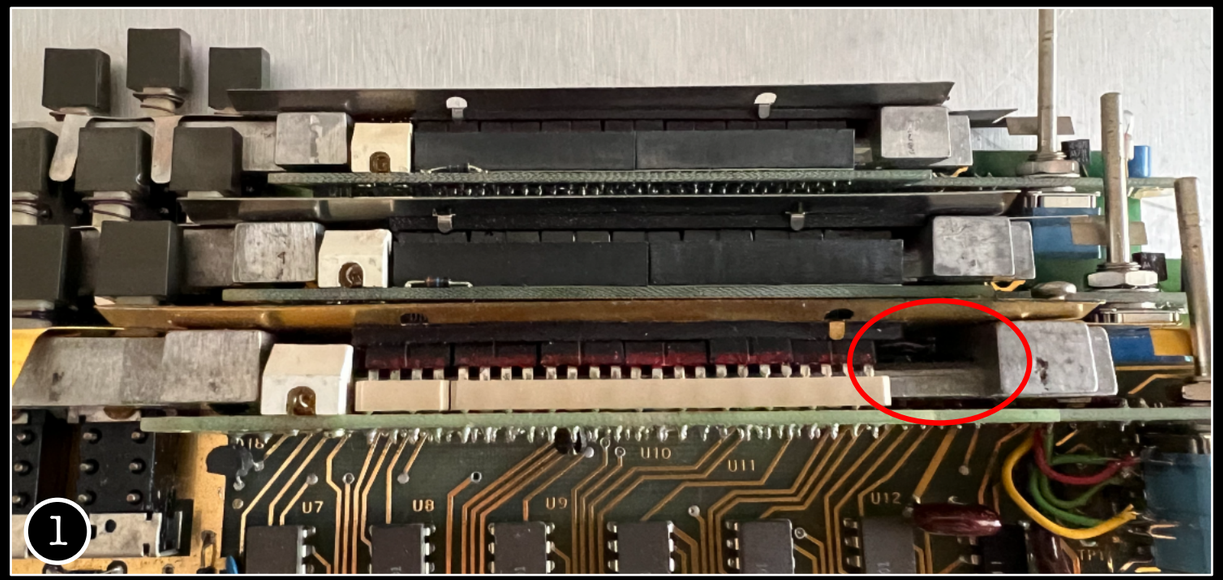
Another difference is in the meter circuits. Comparing the photos on the previous pages, you can observe that the control boards near the indicator instrument have been reduced from two to one. At the same time, the auto-ranging function of the VOLT LEVEL metering has been removed. The old model can switch automatically the scale when reducing the output level (from 0-3 to 0-10).

Also the internal seems to be slightly modified, to be more ordered and still more cured in details.

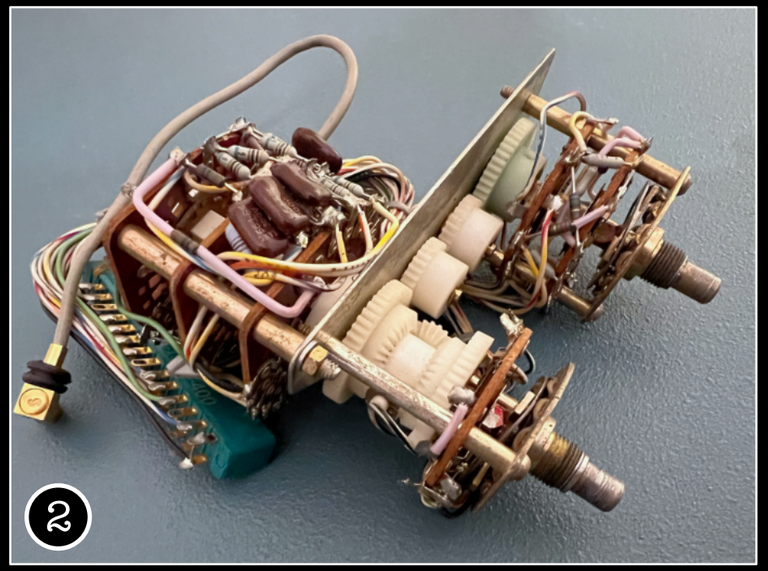
I could identify another modification; Francesco gave me also a set of spare parts, that I used to repair the two 8640B. Among them, there was a display unit with a digit less (photo ❶). That makes me think that the first models had not the + ½ DIGIT function, described later, because the last digit is used only for this purpose (showing nothing or '5').

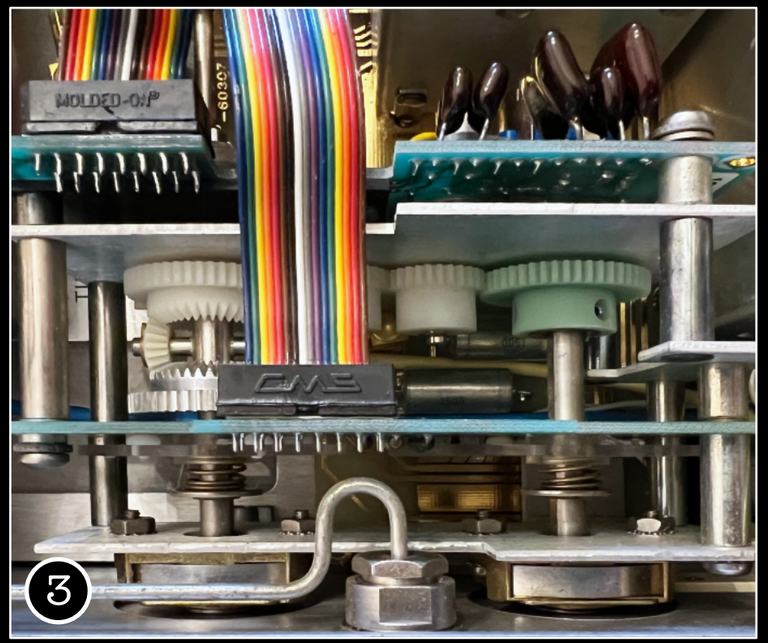
Another difference between the two are the options: the newer has the Opt. 001 and Opt. 003, i.e., the variable frequency modulation oscillator and the reverse power protection up to 50W. The older does not declare any option in its label, but is equipped however the Opt. 003.

Here three different display modules; as you can see, the first has a digit less respect to the others. Probably the + ½ DIGIT function has been introduced later. It is possible also that comes from an AN/USM 323, that seems to have not this key.



1


2



3



4

Misleading keys

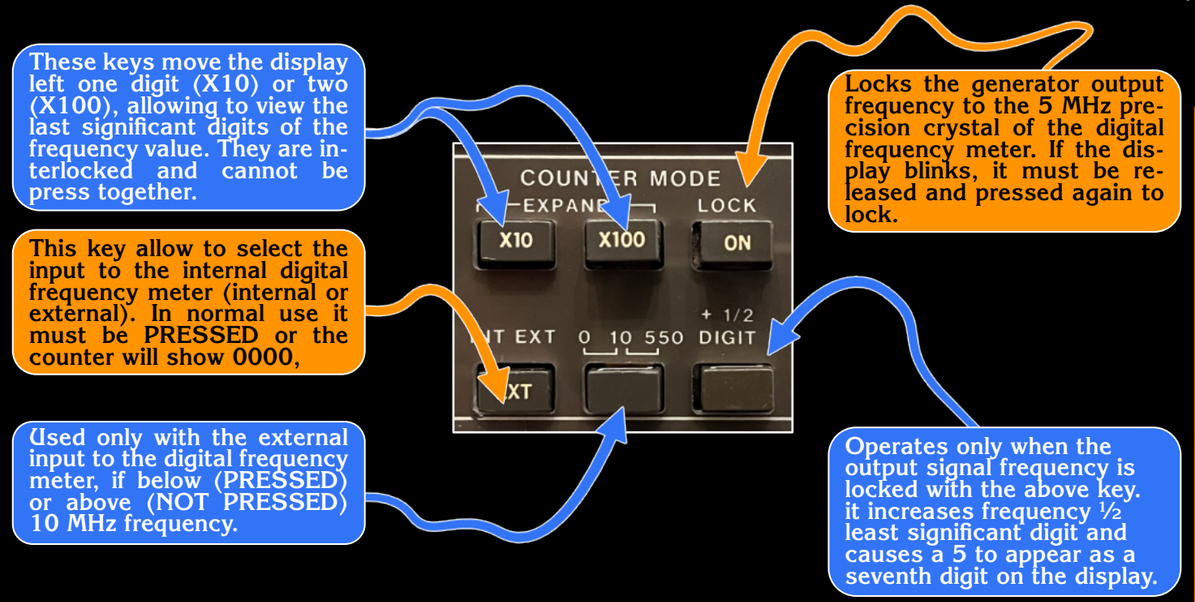
I don't like too much the bistable buttons used in the 8640B, similar, if not the same, to those used also in many Tektronix scopes. They tend to become unreliable, even after you have deoxidized them with special spray products. In one of the 8460Bs, a key was broken (INT/EXT, photo ❶) and my attempts to fix it failed; I could replace it, but I feared to produce even more damages while desoldering the old one from the PCB, so I decided to keep it as is, moving it forth and back by hand (it is used seldom or never).

In addition, if you are not aware of the 8640B secrets, you have two ways to be led to think that your just bought 8640B is faulty:

- having forgotten to **press** the INT/EXT button, the display is fixed to 0.0000;
- having forgotten to **release** the LOCK button, the display is blinking at about half second period.

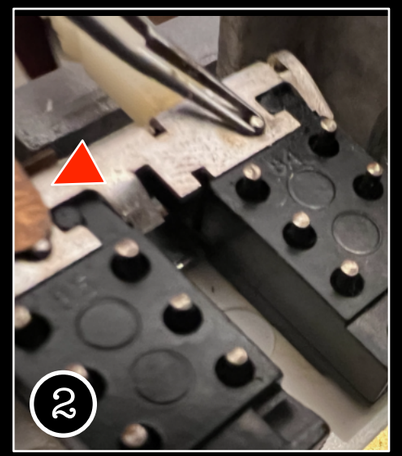
So, considered that the panel indications may be misleading, let's see the exact purpose of each of the COUNTER MODE buttons, listing in orange those keys I just warned you to beware of:

- EXPAND: X10 expands resolution one digit, moving the decimal point one place to the left; X100 expands resolution two digits, moving the decimal point two places to the left. EXPAND XIO and EXPAND X100 buttons are interlocked so that only one button can be depressed at a time;
- LOCK: phase locks Signal Generator to the internal (or to an external) crystal reference. Display indicates lock frequency; loss of lock causes display to blink and indicate actual frequency of Signal Generator; sometimes more than an attempt is required to lock. It is normal that the lock is lost when you move the TUNE knob or during warm-up. EXPAND X100 is not compatible with LOCK.
- INT/EXT Source: programs counter to count frequency of Signal Generator (INT) or external input (EXT), acting as a general purpose frequency meter;
- EXT RANGE: 0-10 or 10-550 selects counter frequency range in MHz when INT/EXT switch set to EXT.
- +½ DIGIT: Increases frequency of phase locked generator ½ least significant digit and causes a 5 to appear as a seventh digit on the display. The Signal Generator must be phase locked to initiate +½ DIGIT operation. As noted elsewhere, I suspect that the first units had not this key.

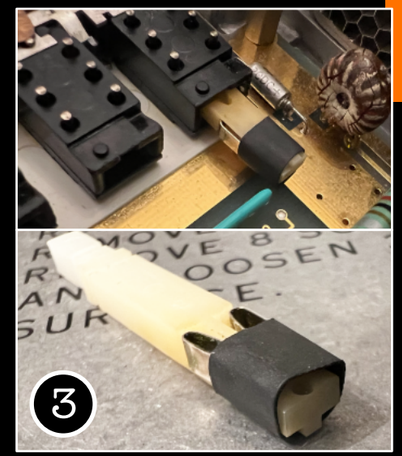




The broken key. In this case, the key does not remain pressed and acts like a monostable button.



If you know how, it is not difficult to disassemble the key. Remove the spring lock, the spring and the stopper pointed by the arrow.



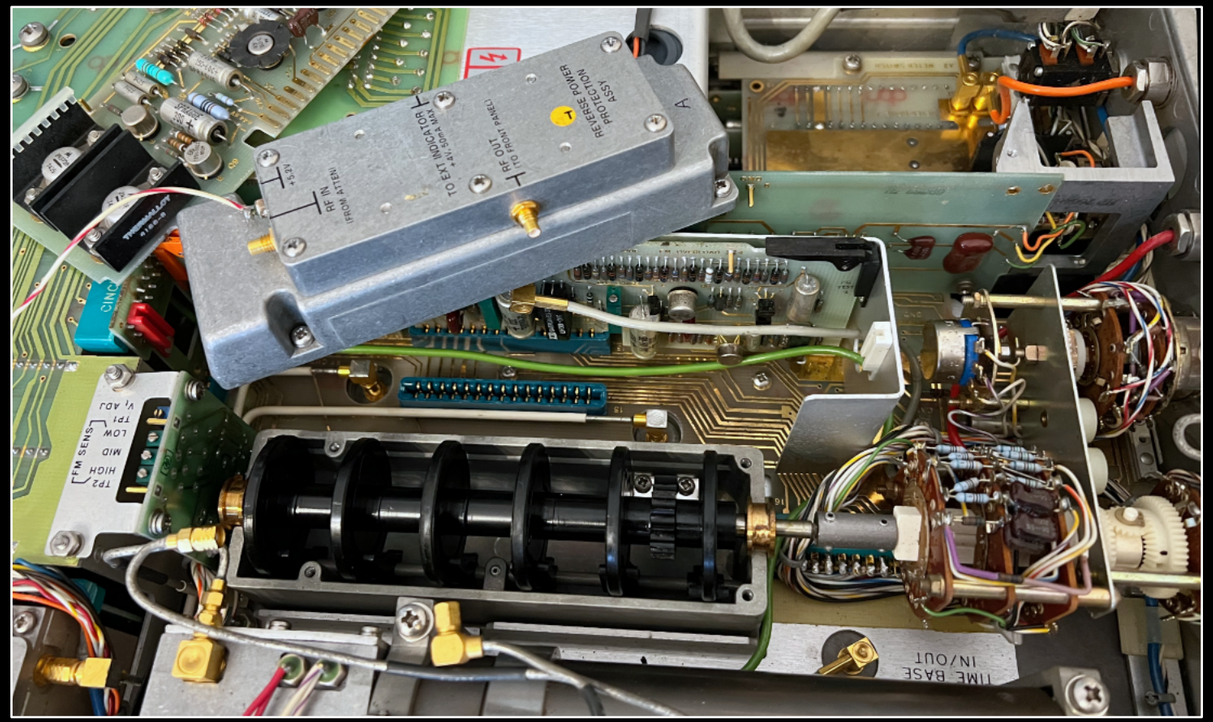
The key stick can be removed from behind. It is easy to keep the contact spring in place with a piece of small plastic tube as shown above.

Gears

According to what I have read, the mechanical breakage of the nylon gears are rather common. Here on the right you can see how someone in the past tried to fix a broken gear, but with uncertain results. Luckily, Francesco gave me also a set of spare parts, and so I could replace it.

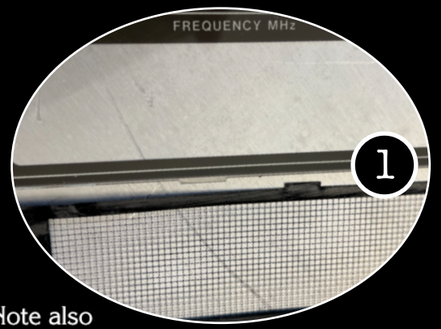
In the photo below, the tuning mechanism. The two bronze bearing might become jammed with the old grease. It is advisable to clean them and apply new grease to reduce the required torque, that in turn increases the possibility to break the nylon gears.

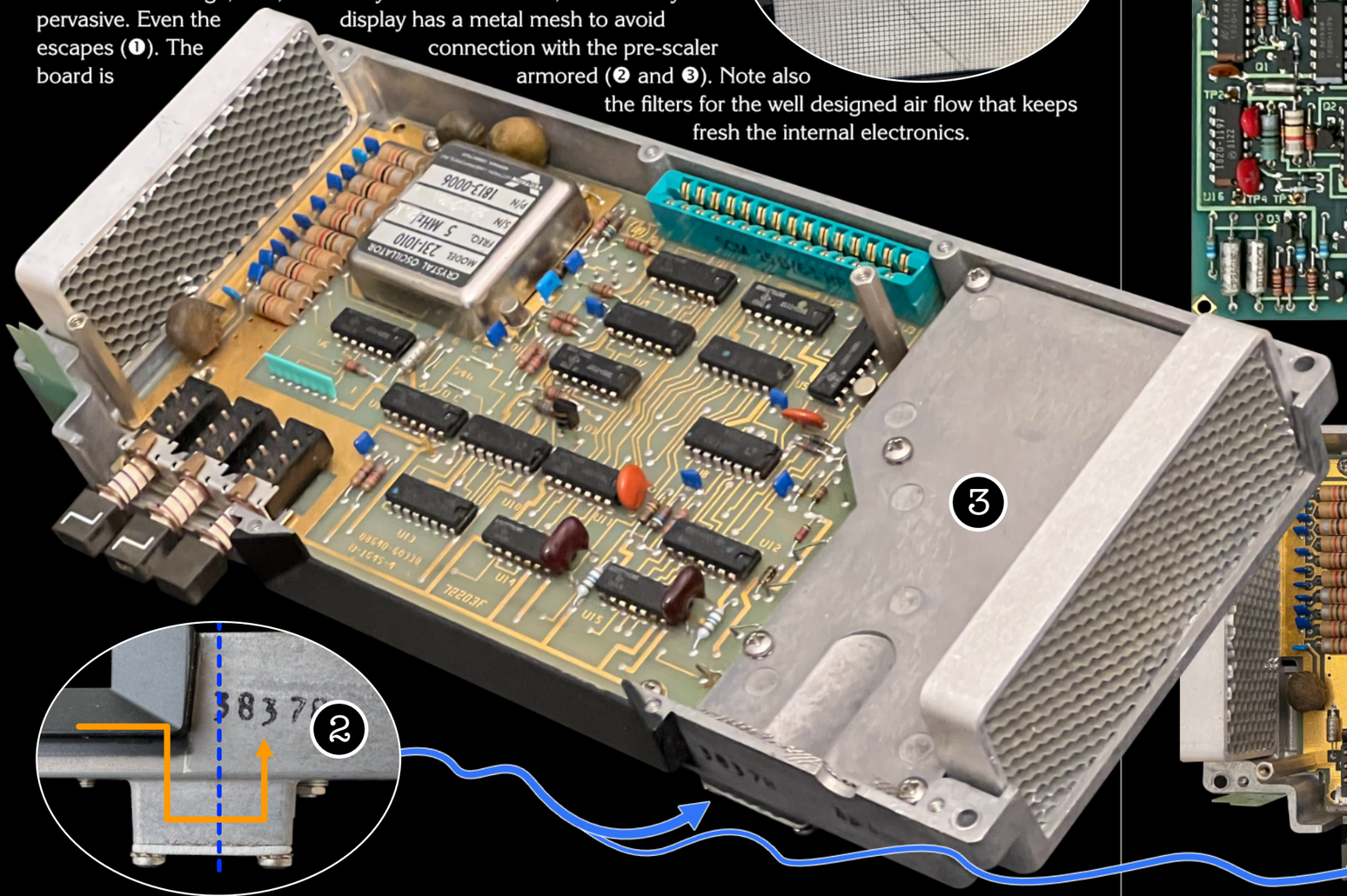
Note above the cover the reverse power protection assembly (Opt. 001) and how much of gold is everywhere!

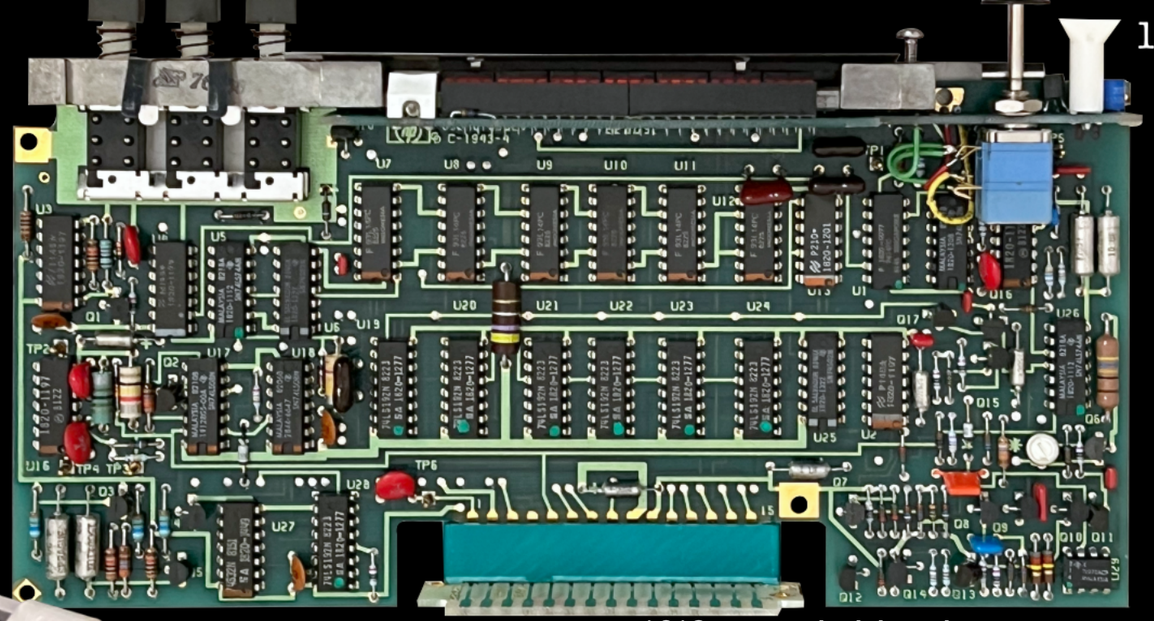


The counter

Many of us have built a digital frequency counter in the seventies and this, in general, is not very different, besides the obsessive attention to limit the RF leakage, that, like in any other TTL device, is incredibly pervasive. Even the display has a metal mesh to avoid escapes (❶). The connection with the pre-scaler board is armored (❷ and ❸). Note also the filters for the well designed air flow that keeps fresh the internal electronics.

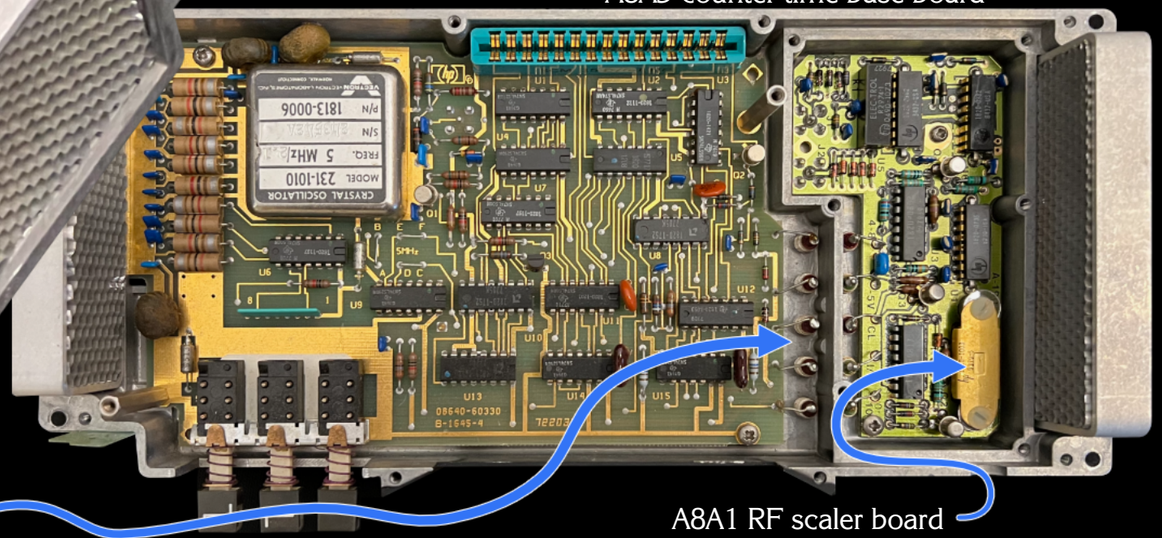




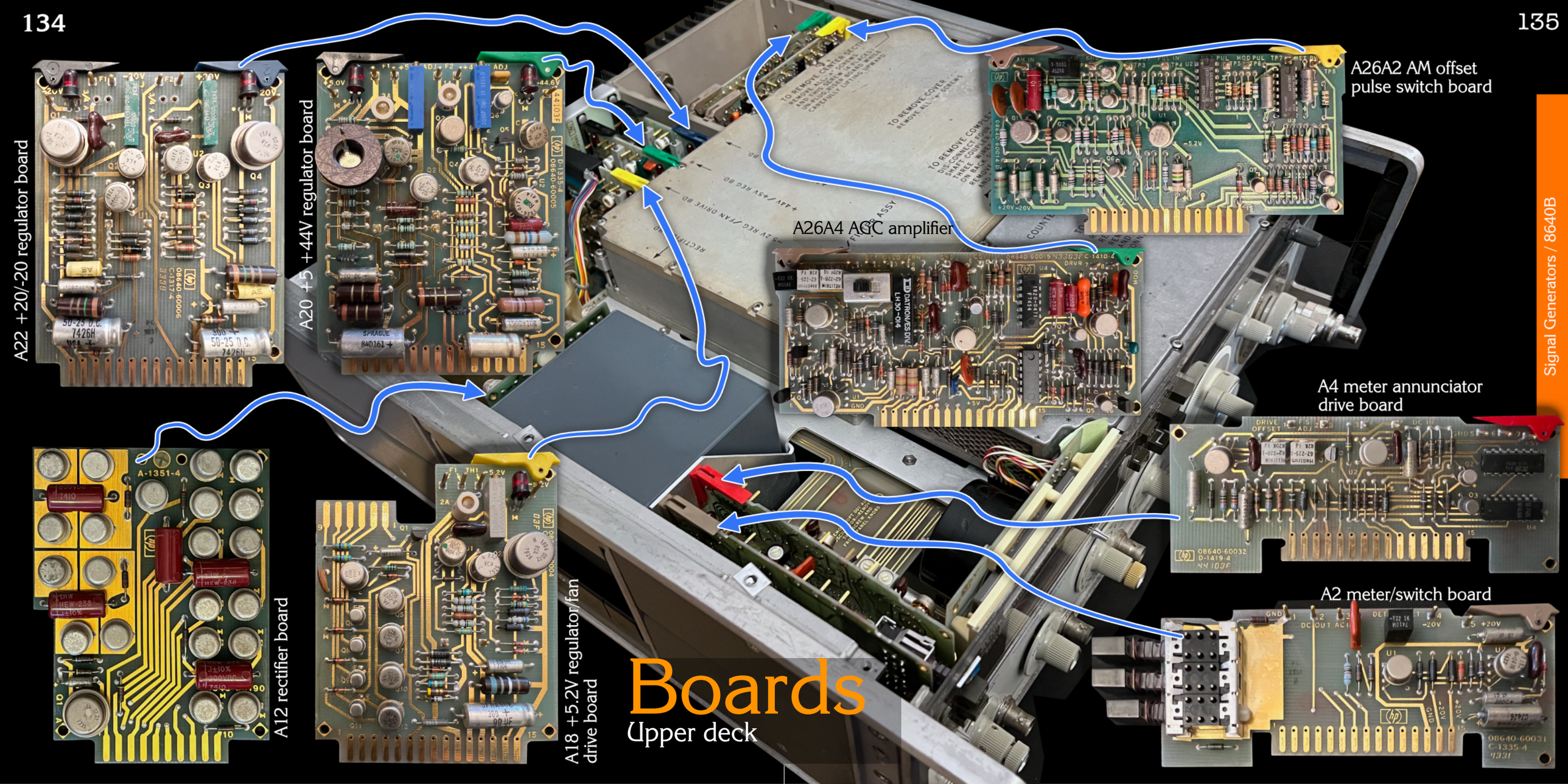


A8A2 counter lock board

A8A3 counter time base board

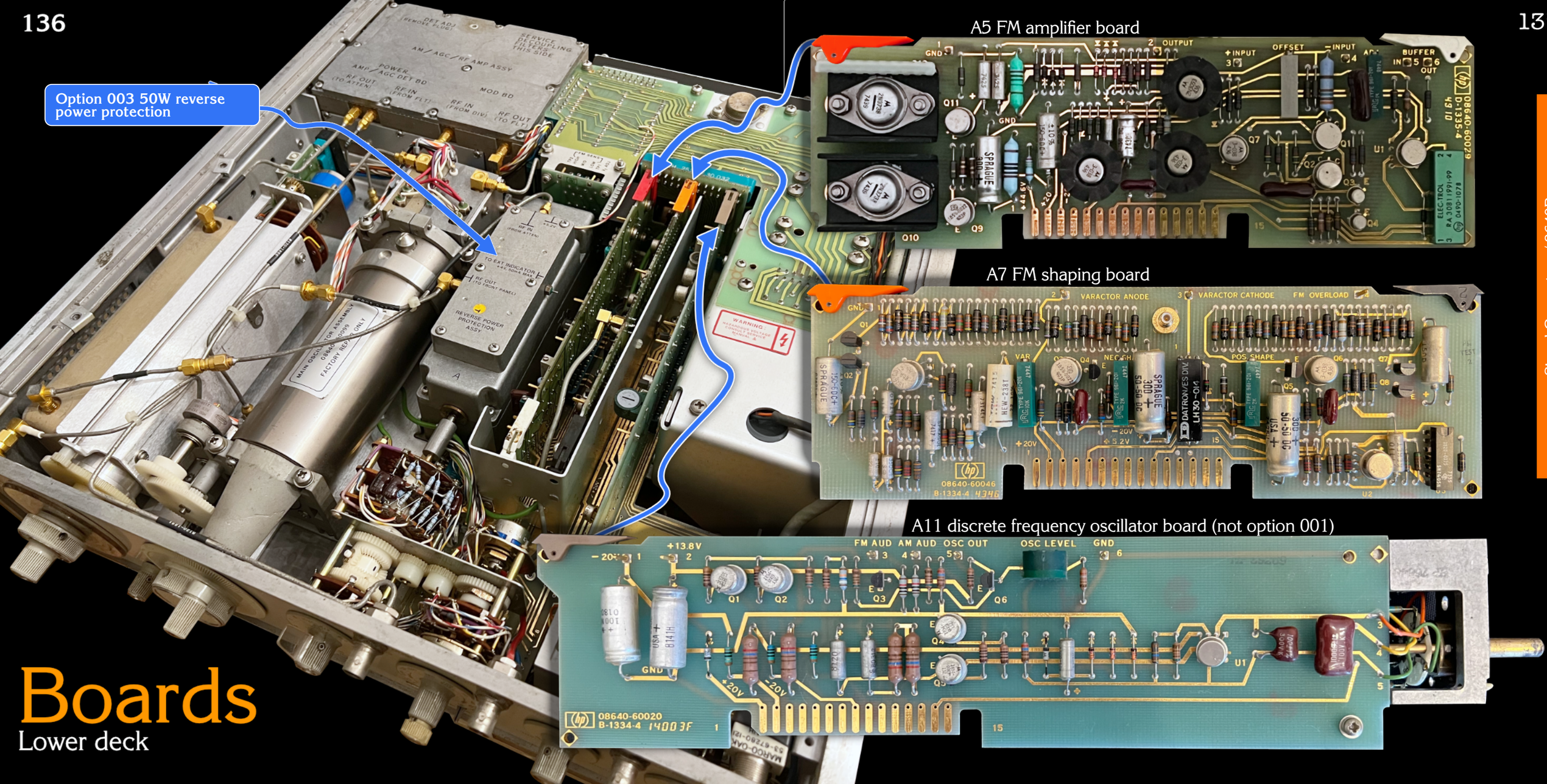


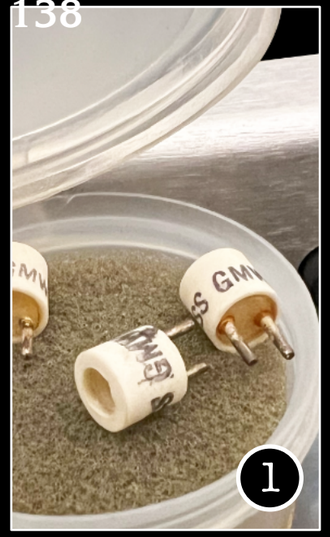
A8A1 RF scaler board



Boards

Upper deck

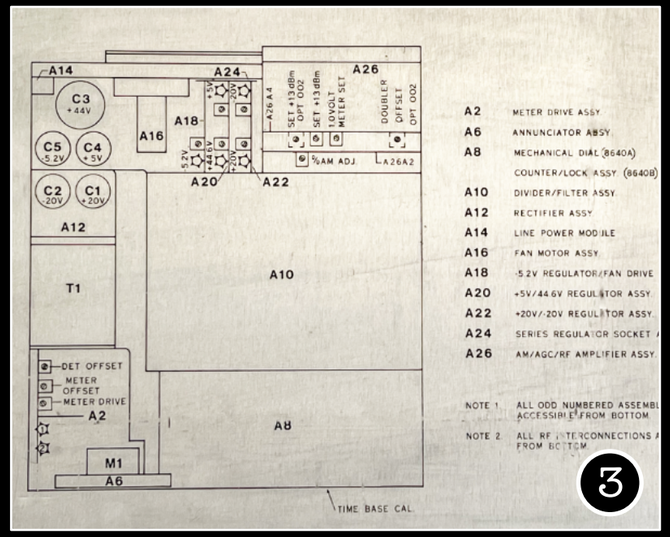

Option 003 50W reverse power protection
A5 FM amplifier board
A7 FM shaping board
A11 discrete frequency oscillator board (not option 001)
Boards
Lower deck



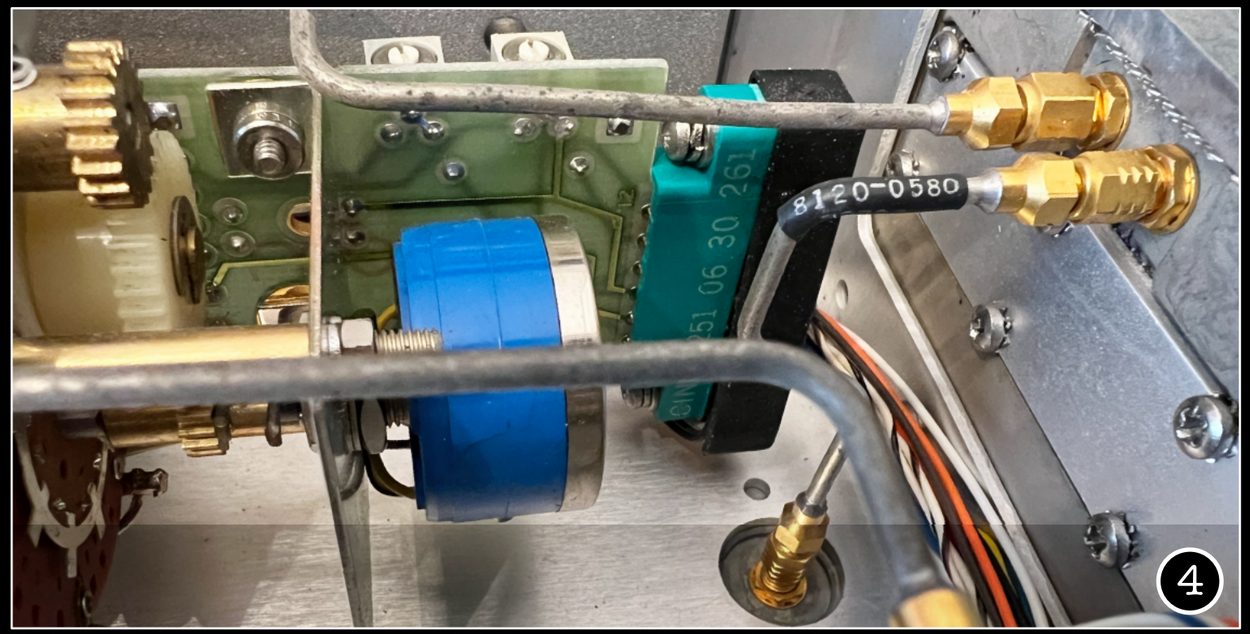
1



2



3



4

Hard to imagine a more accurate construction. ❶ Spare parts supplied in a small box. ❷ Every joint is protected by a shielding net. ❸ Upper and lower covers reports board location diagrams. ❹ Note the attention to details, like the rigid metal pipe connection with the part number. ❺ Board locations are identified by a color and many writing are reported everywhere, also on the PCBs.

Details



5

Spick & span

Let me confess that one of the phases that I prefer is washing my equipment. I find it relaxing: a not too difficult job, with few risks, that gives much satisfaction.

Washing high quality instruments like this is even more fulfilling, because their materials are normally excellent, and just removing the dirt often makes them shine again like new.

I am not sponsored by Chanteclair but I am not tired to repeat that it is my favorite degreaser for this kind of application.

Whatever degreaser you use, be however careful because in some cases it can be destructive for some kind of silkscreen ink. Test it on a small part before an extensive usage.







❶ The knobs and other details ready to be washed. It is advisable to equip yourself with a set of small USA hexagon wrenches (i.e., inches sized, not millimeters). ❷ The protective covers and the handles of the 8640B ready to be washed in my bath tub. ❸ A small nails brush can be useful to clean the knurling of the knobs.

Knobs and other disasters

The purpose

I had an incredible problem, part due to bad luck, part to my dumbness. It started because I wanted to check the output level of the Francescos 8640B, before handing it back.

The disaster

Just to see the 8640B output, I connect the 8640B to my R7844 oscilloscope. I switch on both the devices and, few seconds later, I hear a terrible electric discharge sound, like a spark, from the 7844. Scared, I switch all off and try to understand what happened.

Carefully I switch on the 7844. It works but the readout is gone. Oh, no! I start checking the 7844 and understand that the readout board is faulty. I set it apart; I will tell you about that elsewhere, after having understood and fixed the problem.

Oh no! The 8640B too!

I pass to check the HP signal generator: the display is frozen, with zeroes and more decimal points on. Oh, no (again)! I lose a couple of hours trying to fix it, replacing boards with other ones that I had checked separately. I am lost, nothing seem to work.

In the end, I note that the rear TIME BASE switch is set to EXT. Hope! I set it to INT and all works again.



1

FAULTY? Maybe that the 8640B in this photo is faulty; the display is fixed to 0000000 and three decimal points are present. Or simply the rear TIME BASE switch (1) is set in the wrong position... Another misleading command.



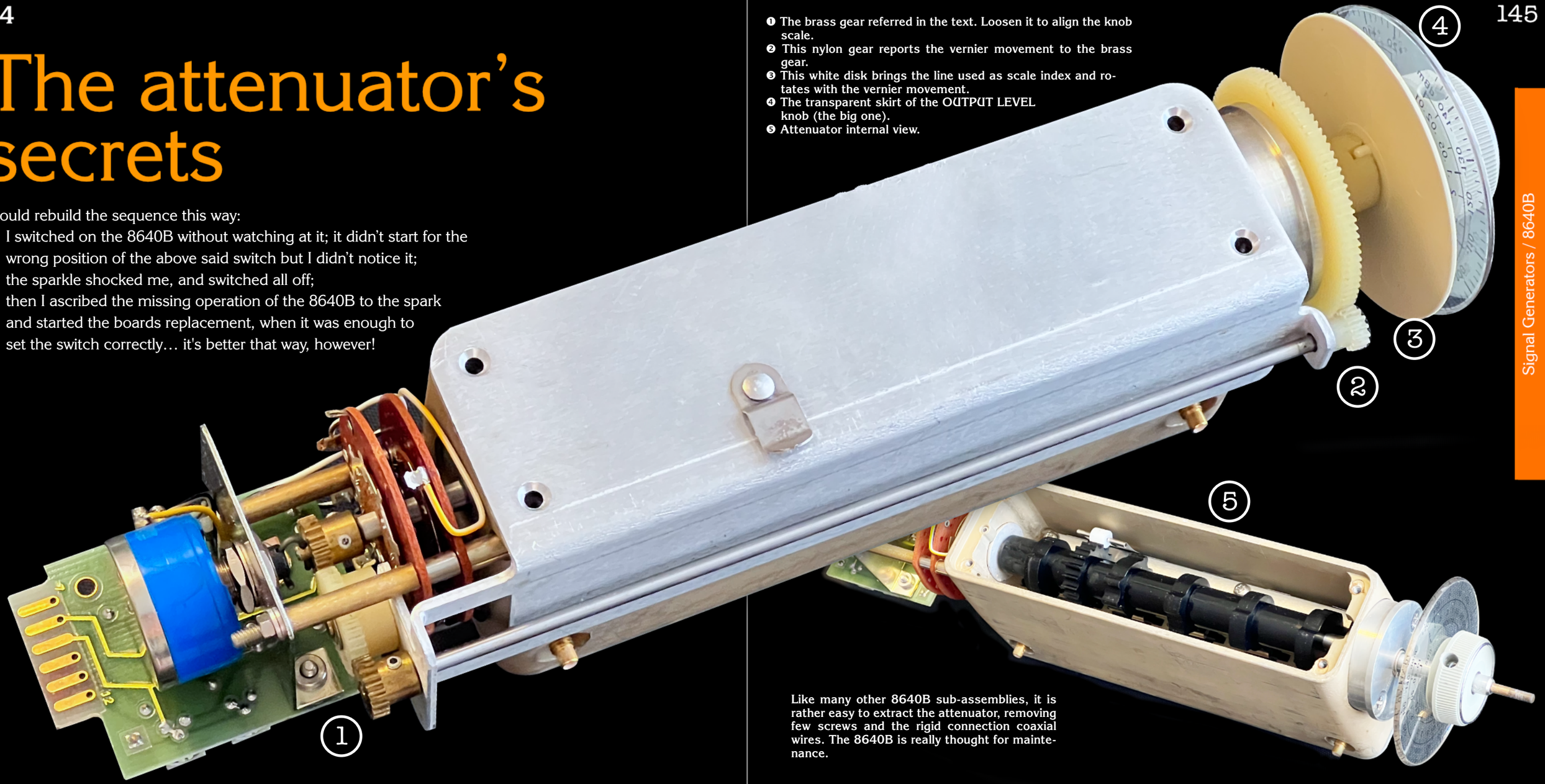
2

The attenuator's secrets

I could rebuild the sequence this way:

- I switched on the 8640B without watching at it; it didn't start for the wrong position of the above said switch but I didn't notice it;
- the sparkle shocked me, and switched all off;
- then I ascribed the missing operation of the 8640B to the spark and started the boards replacement, when it was enough to set the switch correctly… it's better that way, however!

❶ The brass gear referred in the text. Loosen it to align the knob scale.
❷ This nylon gear reports the vernier movement to the brass gear.
❸ This white disk brings the line used as scale index and rotates with the vernier movement.
❹ The transparent skirt of the OUTPUT LEVEL knob (the big one).
❺ Attenuator internal view.



Like many other 8640B sub-assemblies, it is rather easy to extract the attenuator, removing few screws and the rigid connection coaxial wires. The 8640B is really thought for maintenance.

OUTPUT LEVEL knob adjustment

Reassembled all, I return to the 8640B level adjustment and decide to start from the OUTPUT LEVEL knob, as described in the manual, par. 5-30 ("This procedure should be performed whenever the OUTPUT LEVEL knobs have been removed").

The procedure is not very clear and needs a better explanation. First, I didn't understand how the knob works. Things are as follow:

- OUTPUT LEVEL knob: the switch controls a 10 dB step attenuator that sets the output level range;
- OUTPUT VERNIER: the calibrated concentric vernier sets actual output level within a 20 dB range (the meter gives additional resolution). When you move the vernier, a thin white mark moves on the back of the OUTPUT LEVEL transparent skirt, so that you can set the desired value.

I can criticize:

- this cumbersome mechanism is useless, because eventually you can see the output value on the meter scale;
- also HP realized that, and in subsequent versions they fully removed this mechanism.

I spent some time to understand the procedure described by the manual. I have found easier to:

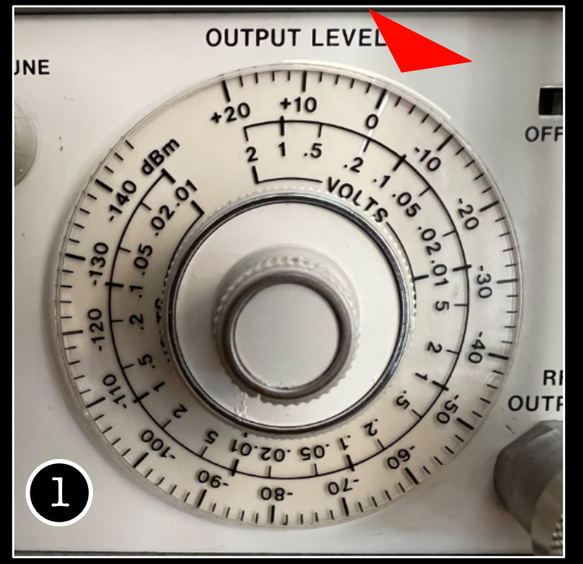
- loosen the small brass gear as prescribed by the manual;
- set the knob at 0 dBm;
- adjust the vernier so that the output is at 2.25 Vrms on a 50 ohm load (i.e. 0 dBm). If you have problems reaching this value, you can act on A26A4R1 as described below;
- tighten the brass gear.

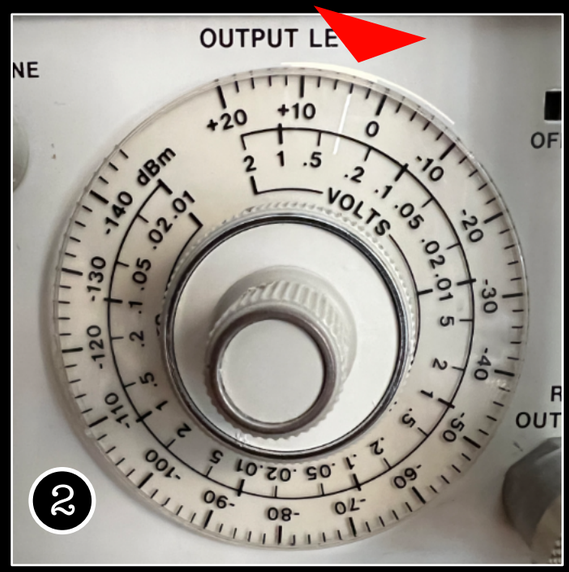
For that, I used the old HP400H millivoltmeter at 2.5 MHz, after having checked that that old meter is still telling the truth, using a reference instrument.

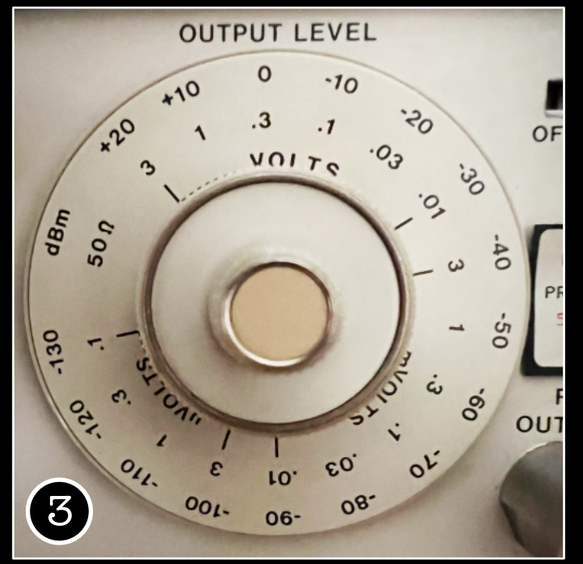
In consequence you will have the about 20 dBm range across the zero point (from 0+13 to 0-7.5, not +7.5 as the manual says).

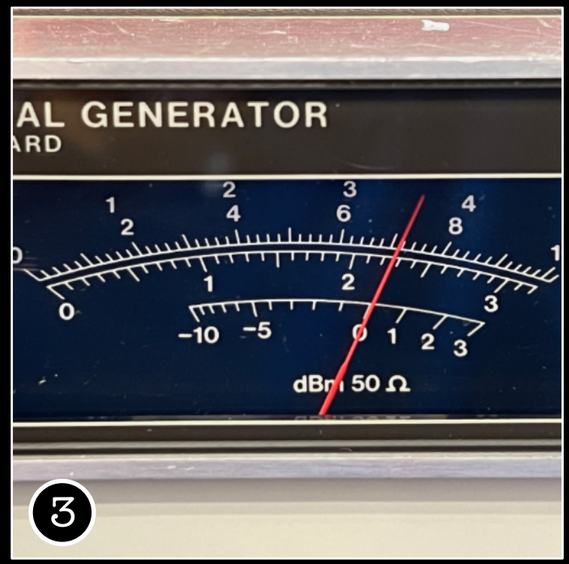
NOTE: the manual states that for optimum operation, use the vernier in the top 10 dB of its range.

❶ Hard do find a worse color for the index: white on white is not a strong contrast…In this photo, the vernier's index is set to 0dBm.
❷ The output has been incremented to 4 dBm.
❸ In the last version this complex gear has been simply eliminated. You can see the output level on the meter.
❹ 2.25 V is the output value for 0 dBm when the load is 50 ohm pure resistive.









Output level adjustment

After I finished the knob adjustment, I start the adjustment of the output level and of the meter. The manual procedure requires a complex instrumentation that I don't have, so I limit to adjust (see the photos in the previous pages for the board position):

- A26A4R1 to set the output level at 0 dBm, again using the HP400H (it should be OK at this point, if you used then knob adjustment procedure that I proposed);
- A26A4R12 to set the meter in consequence.

Troubles never end today

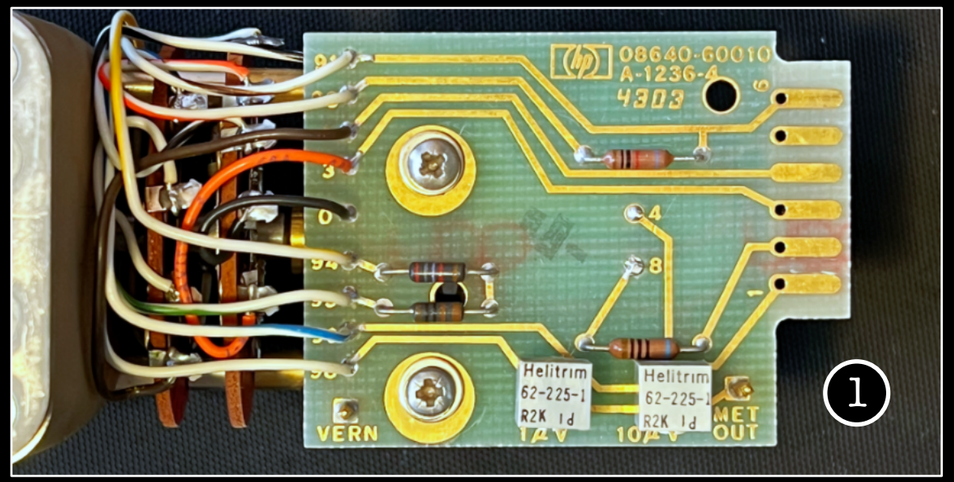
I hoped I have finished. But soon I discover that the OUTPUT LEVEL knob has an improper rotation: the end stops don't work any longer, and the knob can endlessly rotate with a bad feeling.

Fixing the attenuator mechanism

Then, I dismount the entire attenuator group, and find the reason of the problem: the stop pin that determines the block at the ends has come off. I remounted it adding a drop of Attack (see photo ❷) and so can reinstall the attenuator in the frame, and repeat the knob adjustment procedure.

I'm really done now!

The vernier's board



❶



❷

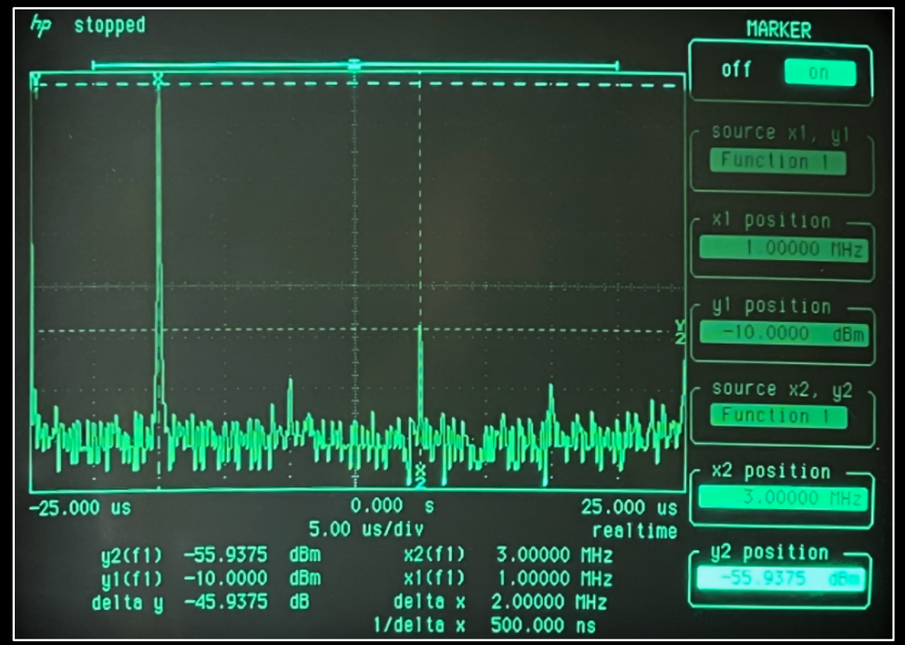
A sample measurement

Having not currently a spectrum analyzer, I used the HP 52540A FFT analysis for a simple measurement at 1 MHz frequency setting. After few minutes for the startup, I set the FREQUENCY TUNE command at 1,00000 MHz, the OUTPUT LEVEL a -10 dBm and the adjustable level knob so that reading exactly 0 dBm on the meter scale. I connected the output of the 8640B to the oscilloscope input, activating the 50 ohm internal load, so that matching the output impedance of the signal generator.

After the warm-up period, I pressed the LOCK button to lock the frequency, and the display remained stable (sometimes, it is required more than a single attempt to lock the frequency, but I believe it is normal).

Incredibly, the oscilloscope measured exactly -10 dBm @ 1MHz as expected.

The second harmonic was at about 45 dBm less. The specifications say that in the range 0.5-512 MHz it should be at least 30 dB lower, so I can understand that the old 8640B still widely meets its specifications.







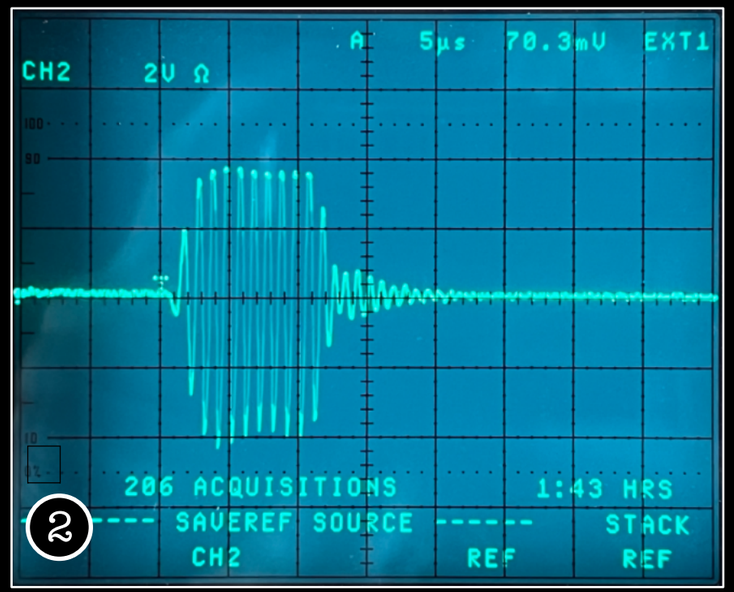
Pulse modulation

Also included on the AM function switch is a position for external PULSE modulation. In this mode, pulse inputs with repetition rates to 500 kHz and widths down to 2 µs can be applied to modulate the RF carrier. Rise and fall times vary with output frequency down to <1 µs from 8 to 512 MHz.

Pulse inputs turn the RF on. Hence with no pulse input the RF will read approximately zero on the built-in level meter. For pulse inputs within the specified range, the RF output calibration is preserved and the level meter reads the pulse-on power of the RF output. For repetition rates below that specified (❶), the pulsed RF output is still available but the pulse-on level is no longer calibrated or metered.

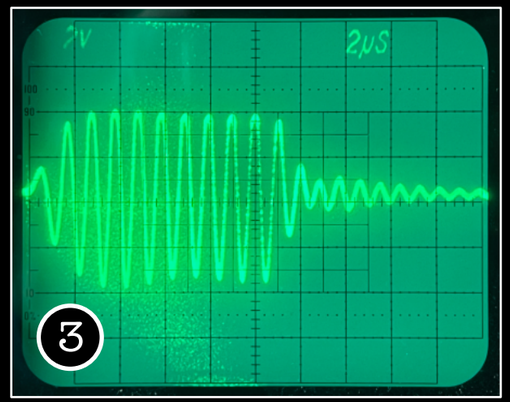
Frequency Bands (MHz)	0.5 - 1	1 - 2	2 - 4	4 - 8	8 - 32	32 - 512
Rise and Fall Times	<9 µs	<4 µs	<2 µs	<1.5 µs	<0.5 µs	<0.5 µs
Pulse Repetition Rate	50 Hz to 50 kHz		50 Hz to 100 kHz		50 Hz to 250 kHz	50 Hz to 500 kHz
Pulse Width Minimum for level accuracy within 1 dB of CW (>0.1% duty cycle)	10 µs		5 µs		2 µs	1 µs
Pulse ON/OFF ratio at maximum vernier	>40 dB					
Peak Input Required	>1 V (5 V max.) Sinewave or Pulse return to zero into 50 Ω.					

❶

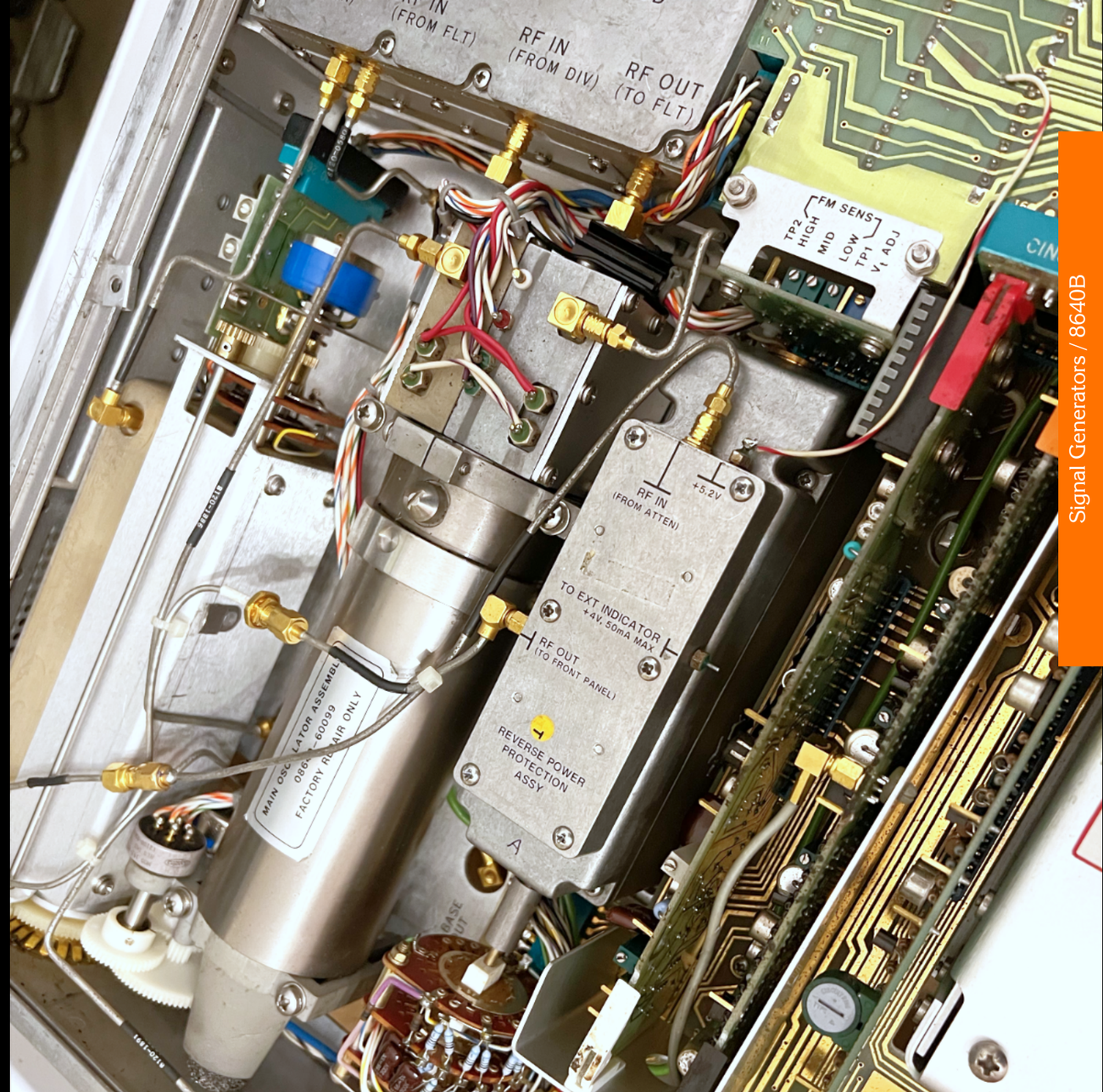


❷

To test it, I set the 8640B at 1 MHz, full output level and the pulse generator for 100 Hz, 10 µs pulses, 1V amplitude. I could not see anything at the RF output. The signal was however there, and, to see it better, you can use the trigger output of the generator as an external trigger for the oscilloscope. It is easier with a DSO (those used for the photo ❷ is the 2430A), but I couldn't help but getting a photo (❸) with the more beloved CRT storage 7633 as well…



❸



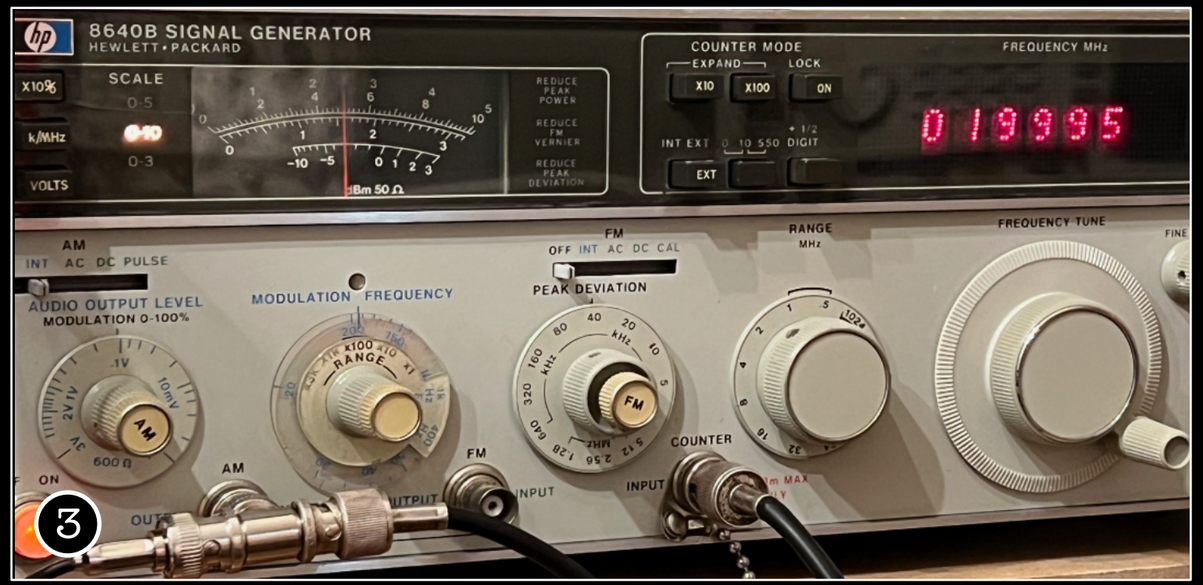




More using modes

As a digital frequency meter. You can use the 8640B as a **normal digital frequency meter**, via the COUNTER BNC input, provided that you press the EXT key, and that you avoid to exceed the allowed limits (15 dBm, AC only). Set the key **0-10 10-550** MHz according to your needs (photo ❶ and ❷).

Low frequency generation. You can also use the 8640B as a **low frequency generato**r, especially if you have the Opt. 003 that allows to generate low frequency signals from 20 Hz to 600 kHz (otherwise you are limited to 400 or 800 Hz only). To do that, you must set the AM switch in the INT position and adjust the AUDIO OUTPUT level to the value you want. The signal is available at the AM connector. The Opt. 002 generator is very stable but setting the desired frequency requires much of patience, if you want to be precise to few Hz. It is also possible to use the 8640B to measure the output frequency as shown in photo ❸. It is not like for the RF signals, but the 8640B can however save you a separate generator under its 500 kHz inferior limit.



Conclusions

This experience with the 8640B has been wonderful, and it is not yet finished, because I am going now to try the calibration for one of the two.

We are talking about one of the best and most famous signal generators in the history, that still today can offer a service more than acceptable, after more than 50 years. At the time, it was probably reserved only to big companies or institution, but now can be however afforded by any hobbyist. In my opinion, it is much better than any low-cost Chinese gear, at least because, when you don't use it, you can just remove the covers and remain for hours watching its wonderful construction, like it was a precious old painting.

I conclude these notes with a review of the available manuals I could find. As we saw, the 8640B underwent to many modification in the years. So, it is commendable to use the manual nearest in time to the unit you are working on.

Document	Code	Year
Operator's, organizational, direct support and general support maintenance manual	TM 11-6625-963-14-1	Oct 1972
Operating and service	9018-05715	Jan 1974
Operator's, organizational, direct support and general support maintenance manual	TM 11-6625-2780-14&P	Dec 1980
Operator's, organizational, direct support and general support maintenance manual	TM 9-4935-601-14-7&P	Sep 1986
Service manual	08640-90215	May 1991



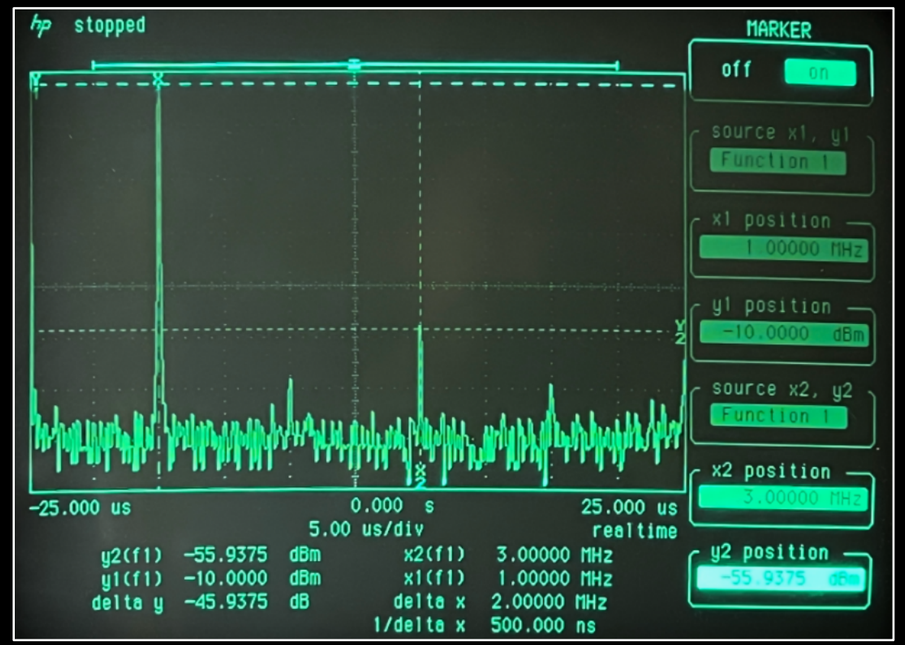
A sample measurement

Having not currently a spectrum analyzer, I used the HP 52540A FFT analysis for a simple measurement at 1 MHz frequency setting. After few minutes for the startup, I set the FREQUENCY TUNE command at 1,00000 MHz, the OUTPUT LEVEL a -10 dBm and the adjustable level knob so that reading exactly 0 dBm on the meter scale. I connected the output of the 8640B to the oscilloscope input, activating the 50 ohm internal load, so that matching the output impedance of the signal generator.

After the warm-up period, I pressed the LOCK button to lock the frequency, and the display remained stable (sometimes, it is required more than a single attempt to lock the frequency, but I believe it is normal).

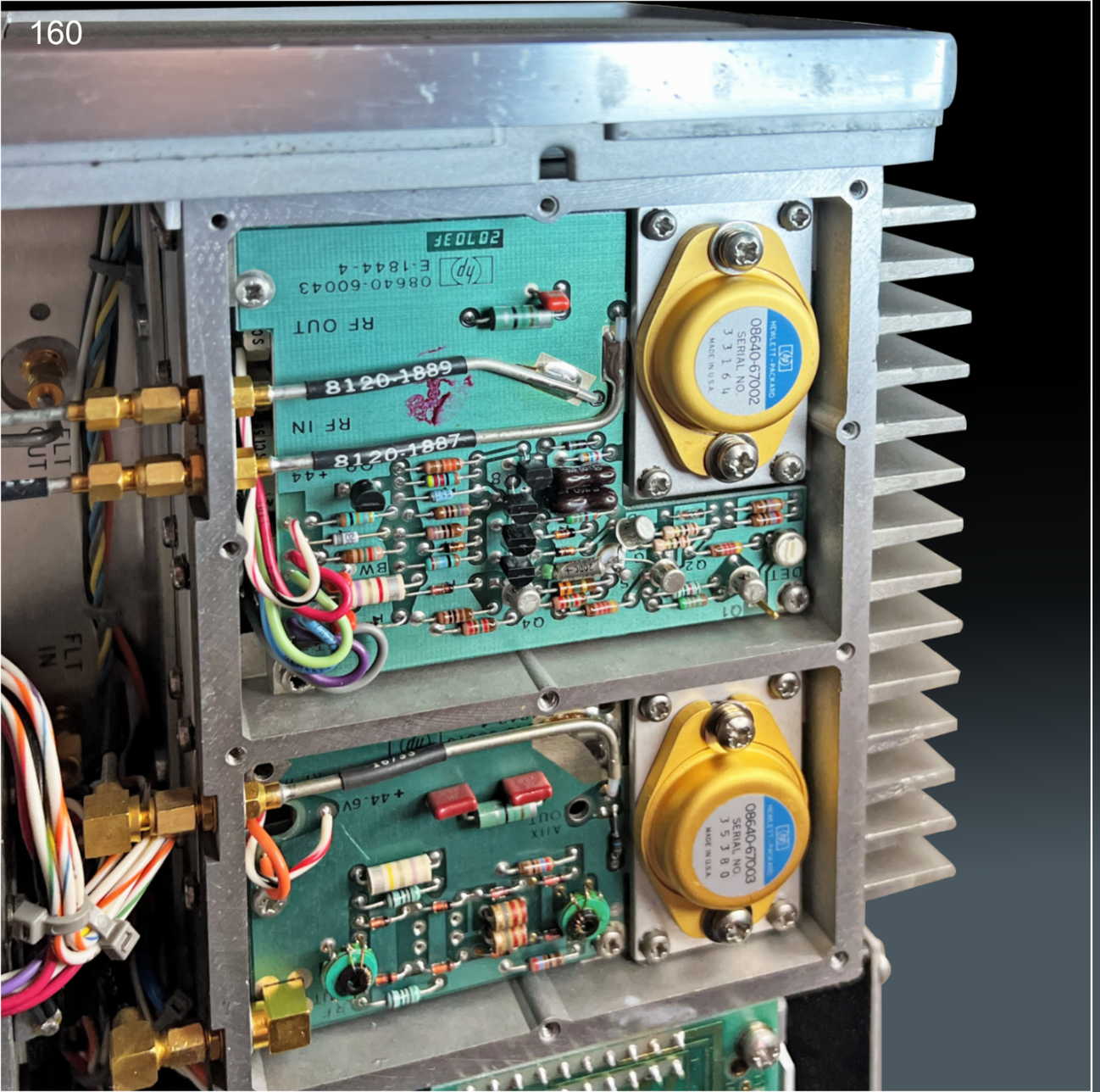
Incredibly, the oscilloscope measured exactly -10 dBm @ 1MHz as expected.

The second harmonic was at about 45 dBm less. The specifications say that in the range 0.5-512 MHz it should be at least 30 dB lower, so I can understand that the old 8640B still widely meets its specifications.









No, Something Broke!

The Fault

(Added on June 2024) I use the 8640B rather often to check my beautiful instruments. But few days ago, during a test that I described elsewhere (Telefunken E863), I was forced to return to my Marconi E2022 because the 8640B decided to produce a signal 30 dB lower than expected.

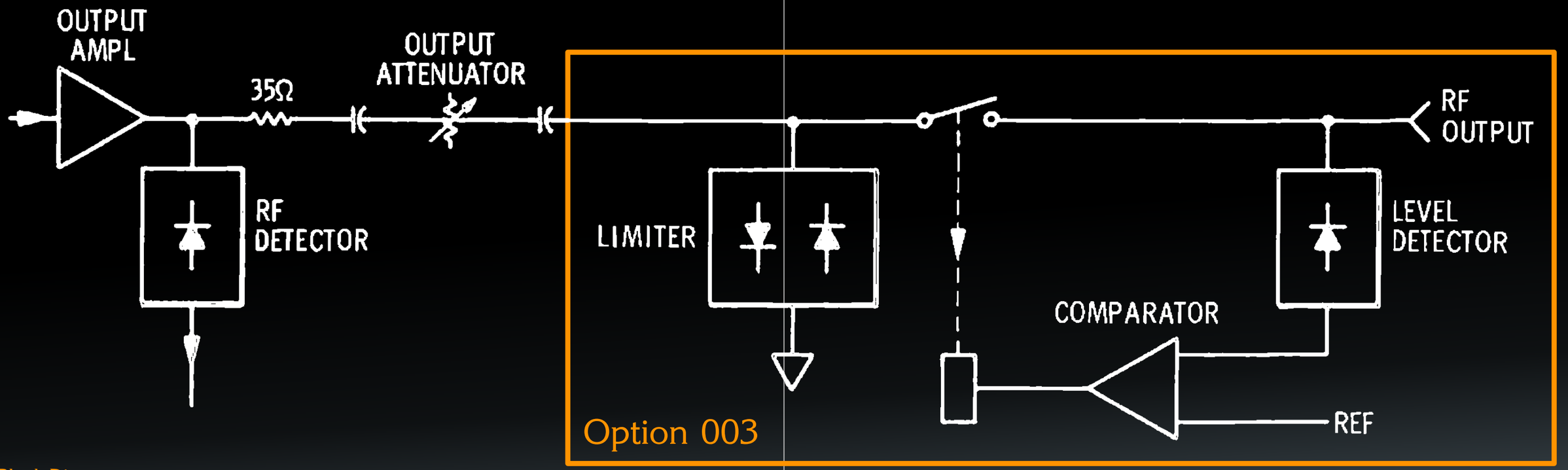
Usual Suspected Characters

After finishing the Tektronix Type 324 description, I decided it was time to possibly fix the 8640B.

I believe that you like me would first suspect the Output Amplifier (photo on the right). So I opened …the can, and checked the signals directly there. It's very easy and inputs/outputs are marked accordingly.

I was trembling, because the Output Amplifier is built in the form of a single intergraded circuit, and I feared a) that I could not find it; b) that, even if found, it was very expensive, as often it happens.

Incredibly the output signal from the Output Amplifier was good. So, the next to be suspected was the Output Attenuator, which follows the Output Amplifier (see block diagram on the next page).



Block Diagram

The RF signal from the RF Filters is amplified by RF Output Amplifier A261. The amplifier, a sealed microcircuit, drives the Output Attenuator. The step attenuator consists of resistive attenuator sections which are switched in and out by cam driven microswitches. The attenuator steps are 10 dB.

The RF detector CR1 detects the negative peaks of the RF signal from the Output Amplifier. The detector output is summed with the positive AGC reference voltage in the Summing Amplifier. Detector diode CR1 conducts whenever the RF amplifier output is one diode junction voltage drop below the voltage across C3. The capacitor is then negatively charged until the amplifier voltage rises, at which time CR1 shuts off. C3 then slowly discharges through resistors A26A1R22 and R23 until another negative peak recharges it.

But the Block Diagram was telling something more: my 8640B had also the the orange boxed section, i.e., the Option 003 that we are going to describer soon.

Documentation

The best Service manual I could find is the P/N 08640-90215, where a good circuit description is reported, but the scan quality of the schematic diagrams is definitely poor, so I present here a slightly edited version of it. Unfortunately, the Option 003 is not documented in all the other Service Manual editions. I found another valuable Service Training manual with many repair suggestions, the 08640-90131 printed February 1977, from which the above diagram comes.

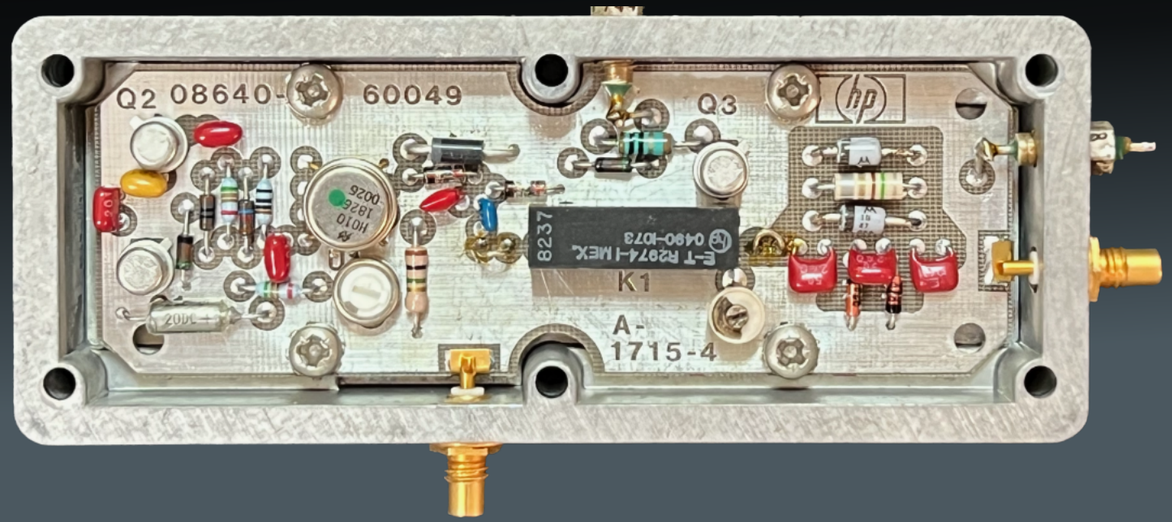
Option 003

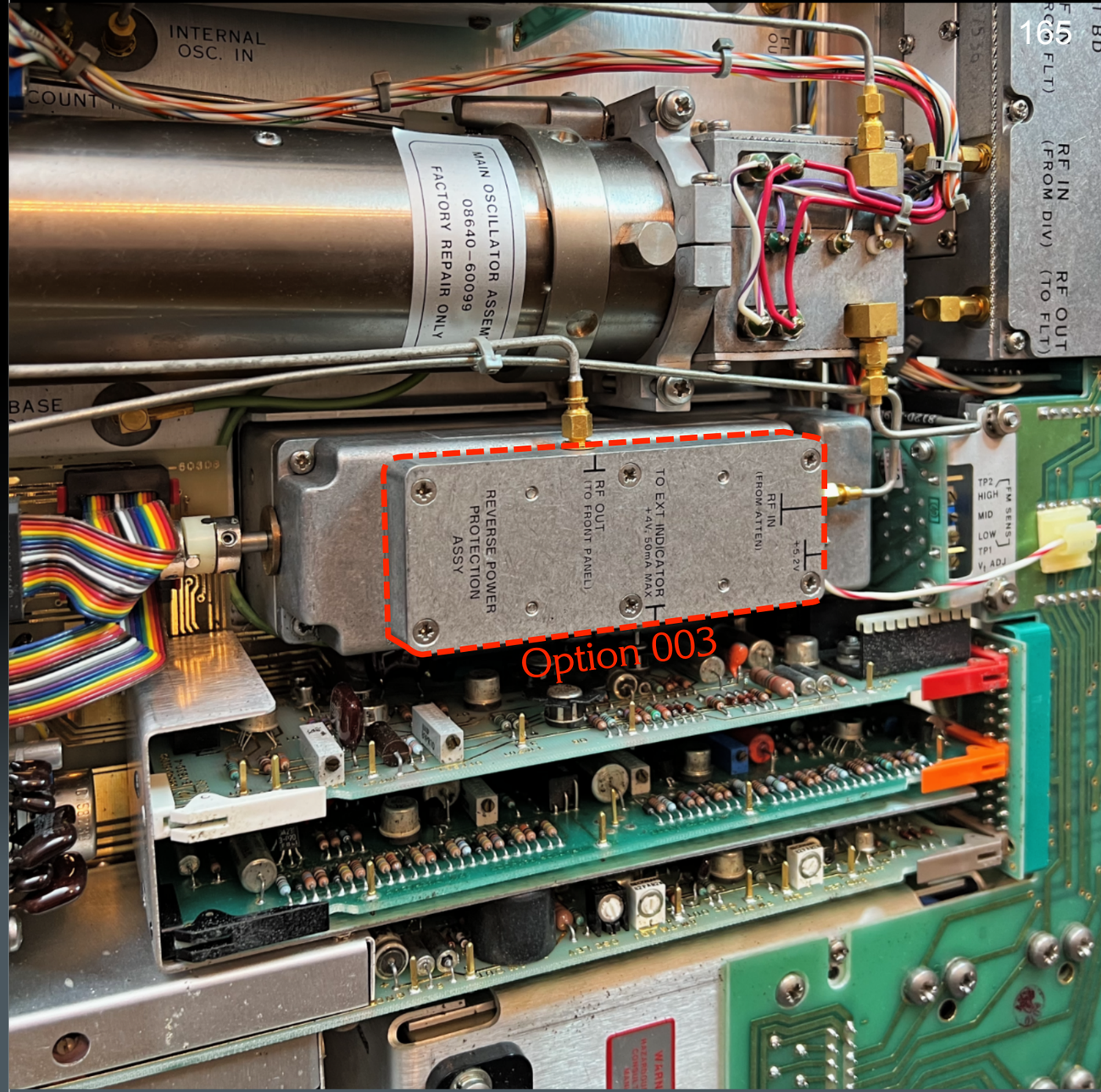
A Useful Option

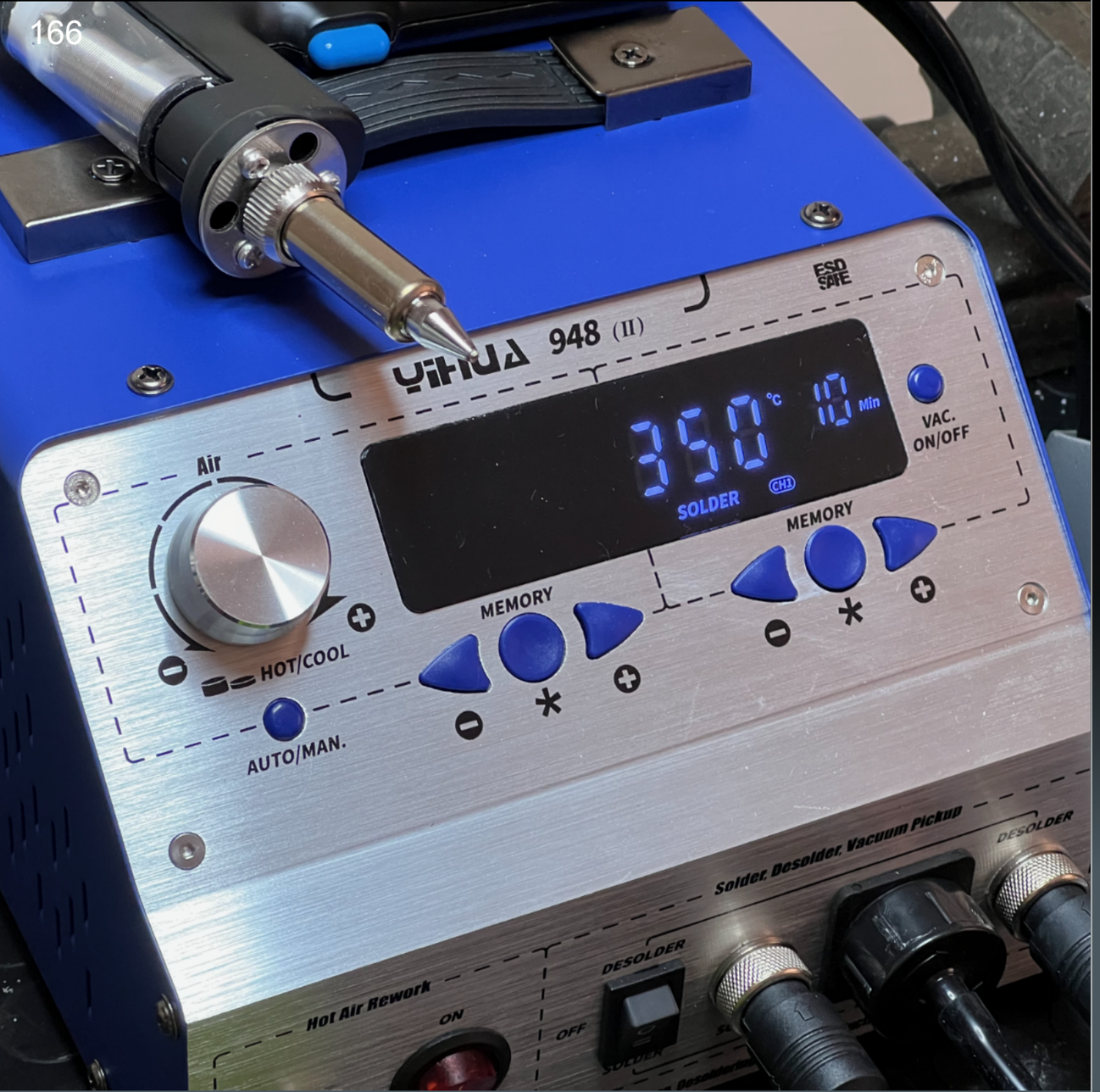
With Option 003, a Reverse Power Protection circuit (see the block diagram on the previous page) is added before the RF output. The circuit consists of a limiter, level detector, and comparator, to protect the Output Amplifier (i.e., the costly ICs). The level detector senses the level of the RF signal at the output, this level is compared to a reference in a comparator. If the output from the detector exceeds the reference, the comparator switches off the relay at its output and opens the RF path to the output. Limiter diodes protect the output circuits while the relay is deactivating.

Price

In 1976, Option 003 costed $300, i.e, $1650 today. Its circuit is very simple but some mechanics are required, and, above all, was a form of insurance on a very expensive instrument.







Catching the Guilty

Hunting the Fault

I could quickly detect that the problem was in the Option 003 box. I was lucky, because:

- it is very easy to access;
- it is not very complex;
- it can be tested on the bench outside the instrument.

The diagrams for the Option 003 are on the next page.

The K1 Relay

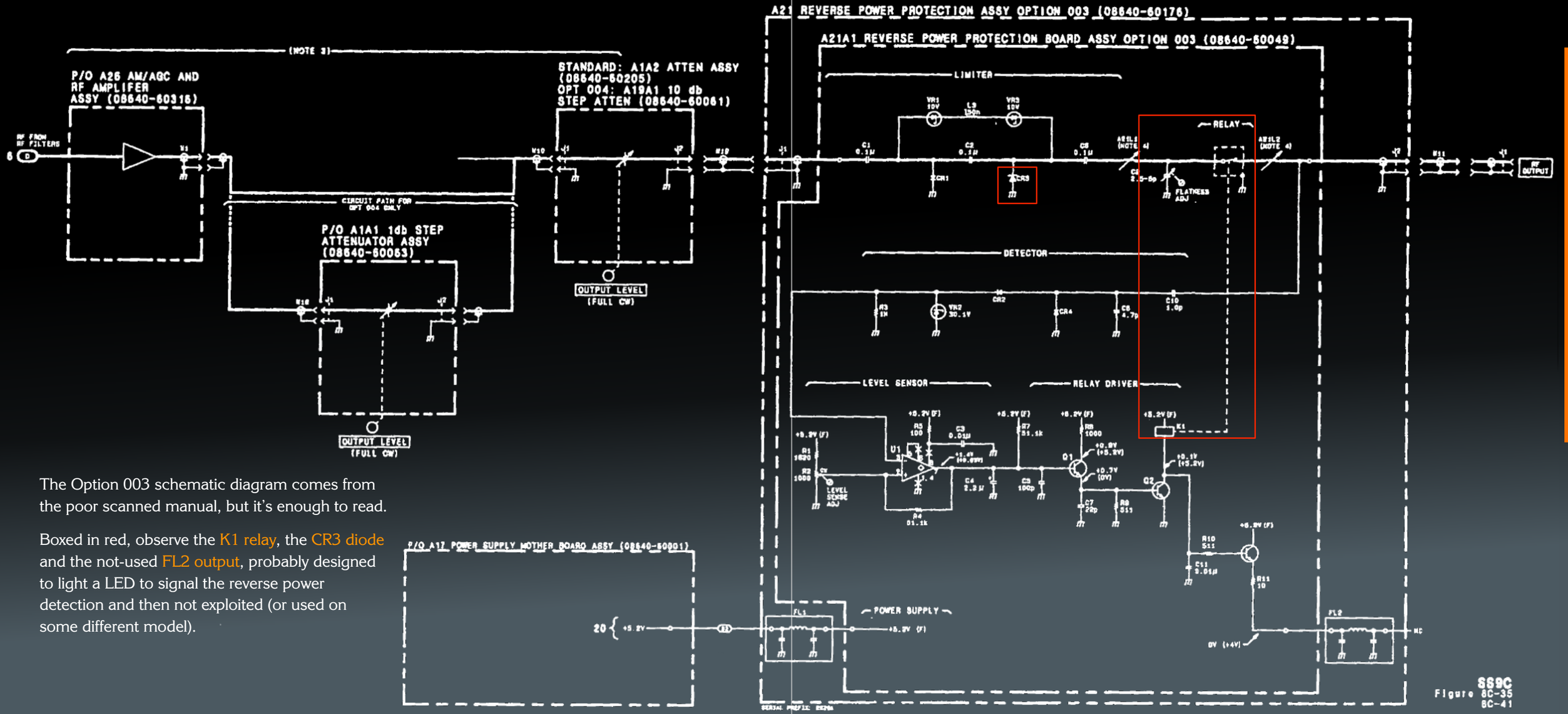
The relay K1 is normally open, and activates as soon as the power is applied. If the comparator detects a too high signal, the relay is de-energized and opens. In my case, I removed the relay (see next), and it turned out to be always closed and thus faulty. But that was not enough to explain the problem. I soon discovered that diode CR3 was shorted, and I replaced it with a 1N4148 (not ideal). That was of CR3 the real fault, while the relay was an incidental but lucky finding; practically, in these conditions, the Option 003 could not perform its useful and protective job.

Just in Time

So I had the usual problem of having to remove a component from a PCB board, thing that I hate because it forces me to stop working and go to my company to ask my friend Michele to do it for me. (he is happy to do it, but I don't like to disturb his work).

But this time I had the weapon: just the day before, in the opportunity of my retirement party, I received as a gift from my colleagues, the wonderful solder/desolder station which you can see here in the photo, together with other valuable equipment (I expected a gift and was scared about ties, dressing gowns or slipper, usually donated in such occasions… but my colleagues are smarter and well know my weaknesses …and I love them!).

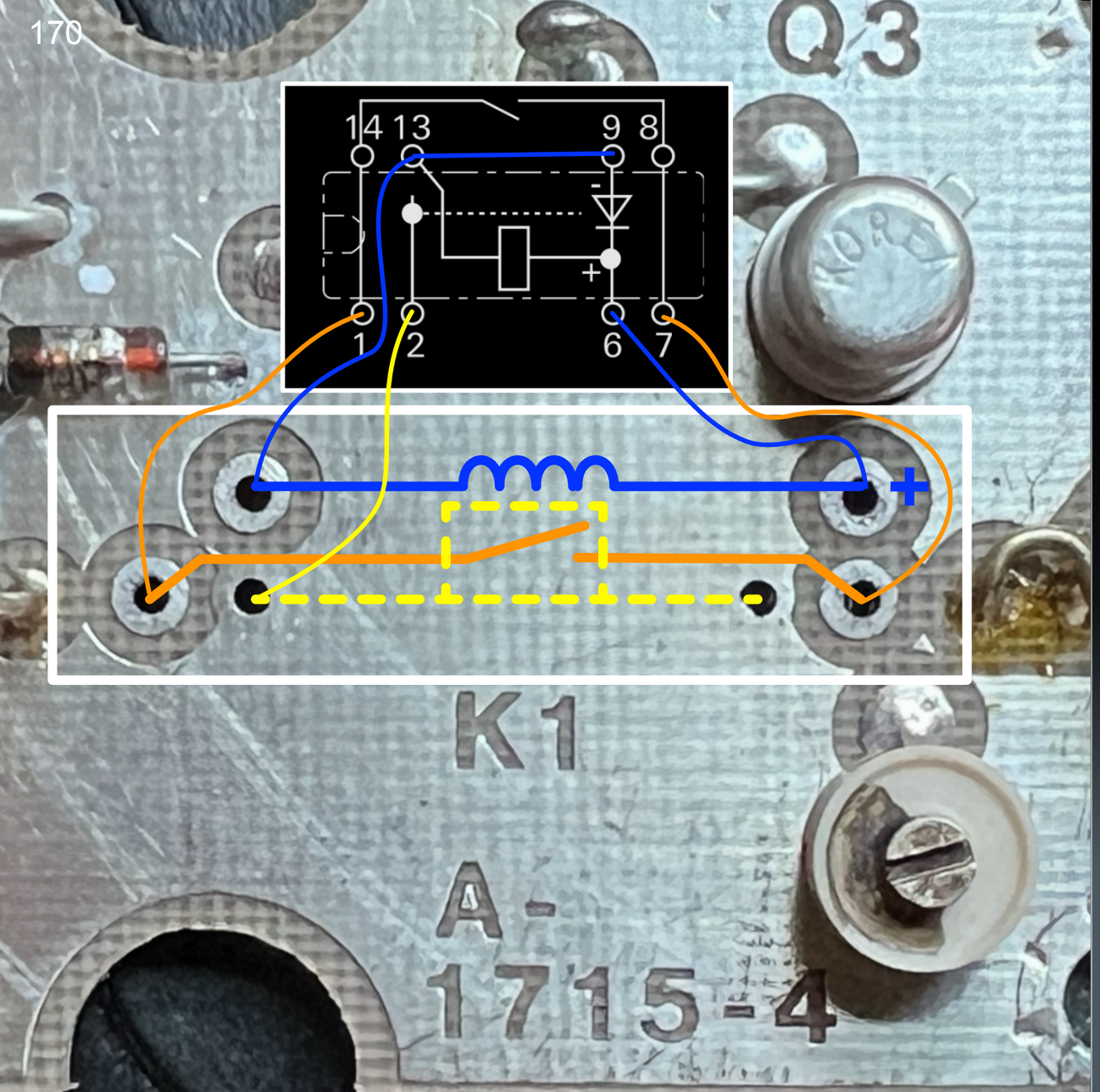
Thanks to it, the component removal was as easy as a snap. WONDERFUL!

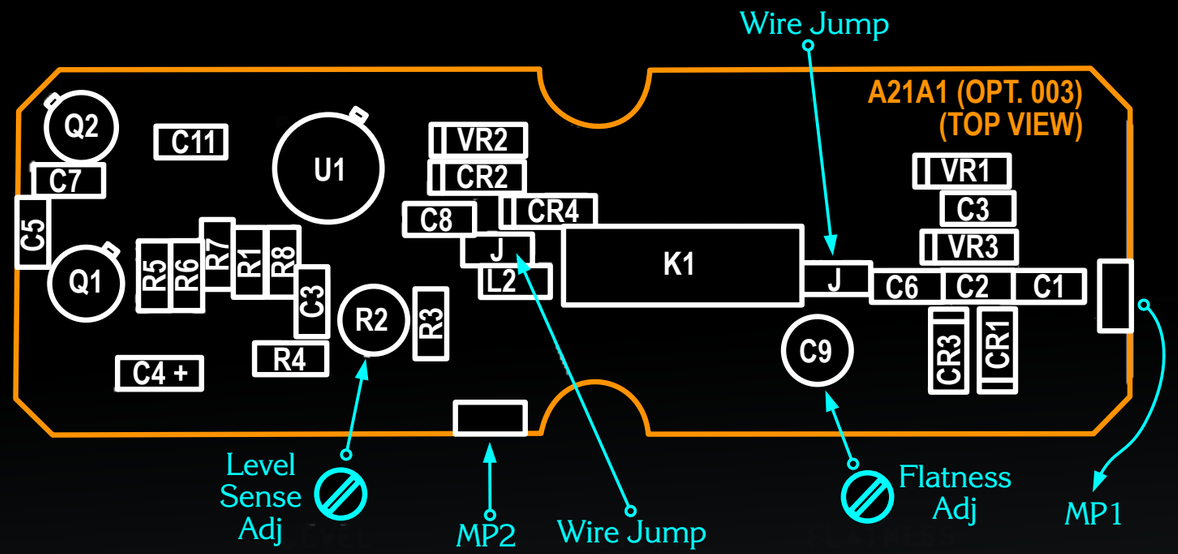


The Option 003 schematic diagram comes from the poor scanned manual, but it's enough to read.

Boxed in red, observe the K1 relay, the CR3 diode and the not-used FL2 output, probably designed to light a LED to signal the reverse power detection and then not exploited (or used on some different model).

SS9C
Figure 8C-35
8C-41





The Repair

Replacing the CR3 was easy; I had only a 1N4148 but it was not probably the better choice; I will search a faster diode.

The 5V reed relay was more difficult, because I could not find the right type, so I had to try a replacement with a different one. I had an Axicom V23100-V4005-A011, so I tried with it. On the left you can see the PCB with the original relay drawn on it and my replacement adaption with the Axicom.

See above the redrawn Option 003 component layout. Some writings could not be read, so I rebuilt the connection, but, if you need to use it, check it for possible mistakes.

The Results

The results were not optimal, because with the largest output amplitudes, the sine is somewhat distorted. But for now it is OK. When I find the relay and a faster diode, I investigate more in detail.



The Repaired Option 003

Here is the repaired Option 003 module, whose purpose is reducing the risks of applying a reverse power to the 8640B output, with the possible consequence of destroying the output amplifier.

Note the solderless spring connection of the RF connectors (circled in red), and the relay which. replaces the original one.

Signal Sources

Subsection
8015A Pulse Generator

Probably a success, in its category, but not my love

8015A pulse generator

The unit here presented is from 1977.

1975

It had to happen

Sooner or later it had to happen; until now you have always read me speak in enthusiastic terms about almost every instrument I have described in this and in the other books. This one is, in my ideal ranking, the worst until now, not aligned with the standards that HP taught me to appreciate.

What it is

The 8015A is a 50 MHz pulse generator with two outputs, each capable of 16 V or 30 V if combined. It was declared compatible with all low threshold devices, including CMOS and N channel MOS. Each output also has its own source impedance switch (50 Ω / 1 kΩ).

Not cheap

The 8015A was not cheap. The base unit costed 2.300 $ in 1975. With the options that my 8015A has (Opt. 2 burst and opt. 5 TTL out), it costed 2300+500+150 = 2.950 x 5.65, i.e., 13.000 USD today. Despite my opinions, it seems it was a success. It was introduced in 1975, and remained listed until 1988, 13 years, confirming its market validity.



Sliding controls

The 8015A is a very peculiar instrument, rather different from most of those described here, also in the logic of the user interface, generally characterized by sliding controls. If I remember correctly, in that period they were a novelty and were in fashion, also in common equipment like radio, television and hi-fi, before understanding that they were less practical and reliable, returning to the more classical rotary type. We will find them again in the 8012B, the smaller 8015A's brother.

The sliding fever

Possessed by the "sliding fever", most of the 8015A controls are of the sliding type, also the range switches that, in my opinion, were better if rotary. For each range position of the various controls, there is a potentiometer called "vernier" for the continuous adjustment. The name "vernier" is somewhat ambitious, normally being used for some more evolved mechanical gear.

Output control

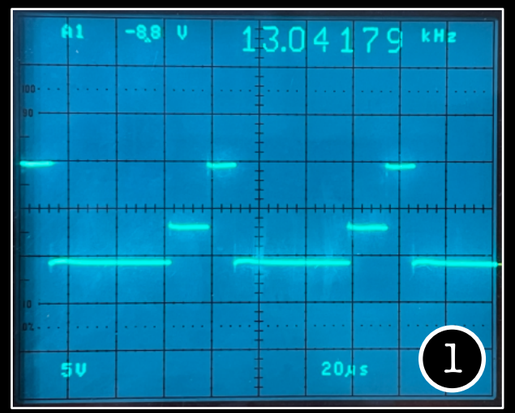
Controlling the output amplitude

A separate discussion is due for the unique pulse level controls, where sliders make sense: each channel has two independent levers, combined into a single slider. The upper for the pulse high level and the lower for the pulse low level. The two levers are not completely independent: if you try to move one beyond a certain limit, it "drags" the other one, limiting the output level amplitude to 16 V but allowing to "move" the pulse value between -30 to +30 V. It is even possible to mix A and B channels to get a three-levels output, as shown in the photos here.

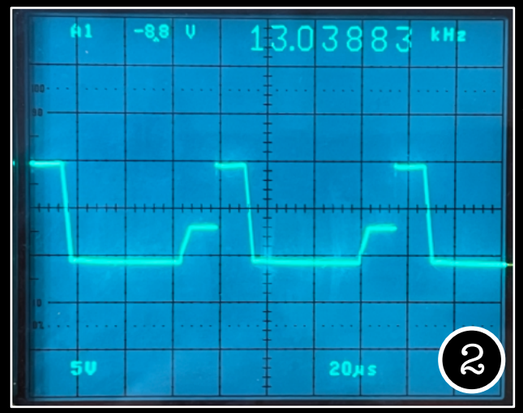
This valuable feature, together with a rather logical layout of the front panel controls, makes the basic use rather easy, but the 8015A remains not very user friendly, and also these sliders are eventually not very easy to adjust. Each time I use this generator, I need some tries to remember its logic.

Not to be used alone

In addition, the 8015A lacks precise scales or meters, besides the above-said output amplitude controls. Perhaps they assumed that who needs a pulse generator always use an oscilloscope at the same time, and could then simplify the general design. Also a digital frequency meter could be recommended, if not built in in the oscilloscope.

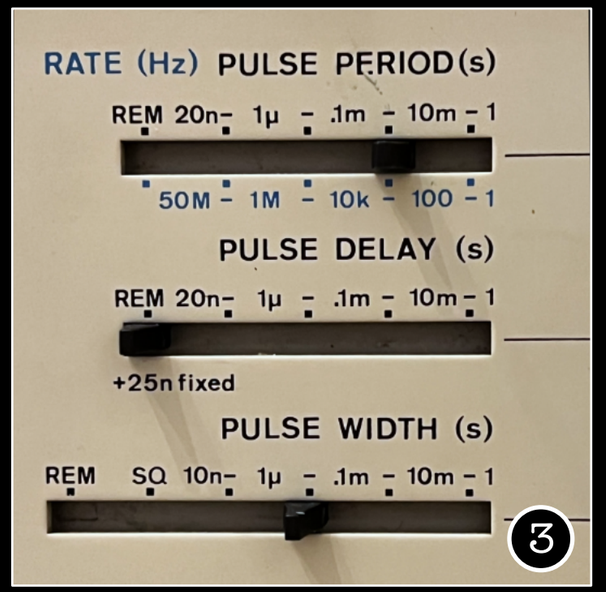


1

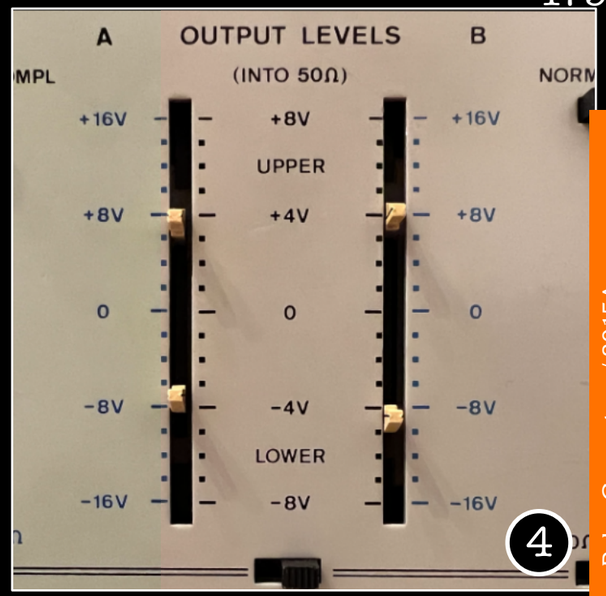


2

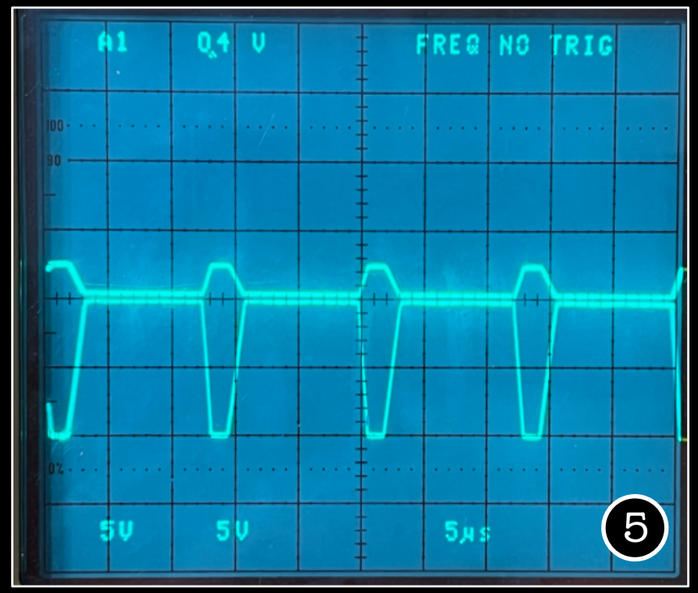
❶ Combining A and B channel, you can get a 3-level pulse. ❷ You can also adjust separately the leading and the trailing edges. ❸ Timing ranges. ❹ The output sliders are the best part of the 8015A. ❺ A TTL output connector is available with option 5, together with A and B channels. ❻❼ Option 5 gives the burst capability but an external signal is required for trigger.



3



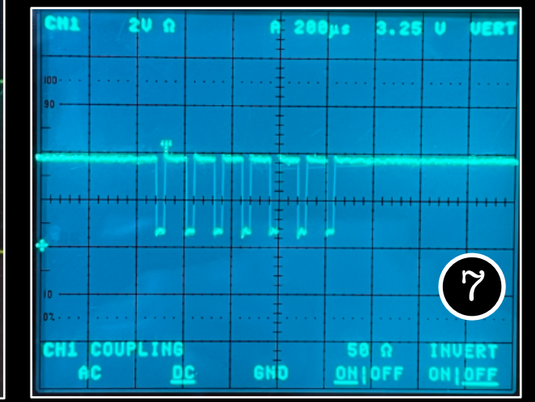
4



5



6



7

Construction



In this book, I am using perhaps too frequently the word “wonderful”. The 8015A left me colder; its construction seems not completely adequate to HP standards of the time.

Internal organisation

The placement of the boards and their interconnections are not the best, even if the chassis is well designed and very robust.

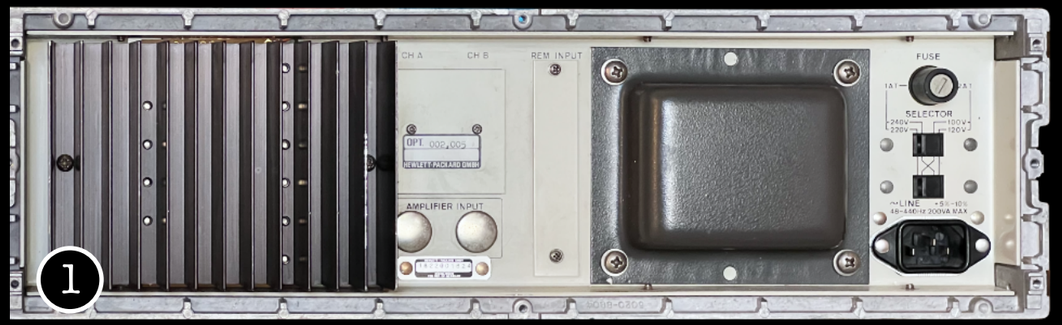
The boards connect with an edge connector to the front panel; the two amplifier boards, one for each channel, are mounted also on another horizontal board, called integrator, but just with a 3-pole connector. Other wires are added to link them together. The TTL option 5 board (pointed in the picture) looks decidedly afterthought.

Plenty of heat

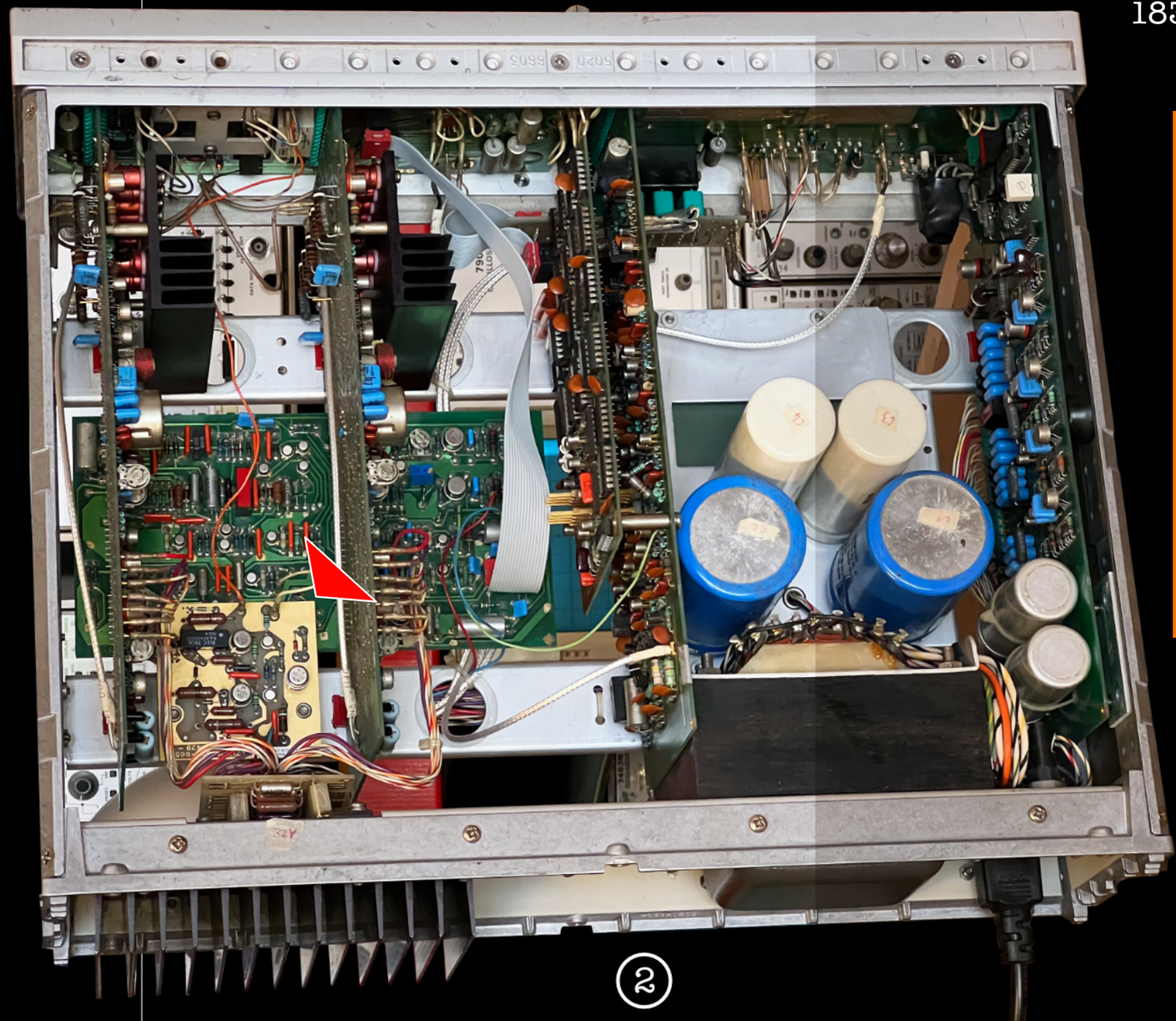
One of the first things you notice are the large heatsinks, internal and external. You can understand that heat was a problem also by the box covers, completely openwork, and working on it during the summer is not very pleasant. Perhaps a fan was due.

50-ohm are few

A reflection I had never made is that the typical 50-ohm load is rather heavy. The 8015A is capable of producing pulses 30V high on a 50-ohm load. That means that at 95% of duty cycle, a power of 30 x 30 / 50 * .95 = 17.1W is required. The 8015A can sink more than 600 mA on its output; together with the old style linear power supply, it explains the big heatsinks and the openwork covers.



1


2

Perforated

Heat everywhere

As noticed above, the 8015A is a small stove and produces a lot of heat. In consequence, the very nice outside enclosure is characterized by a lot of small holes, the last desperate solution before adequate fans.



Dead look

The only sign of life on the front panel is a barely visible LINE pilot lamp. According to the manual, you have to wait at least 8 seconds from a switch on to the other, and if you don't do that the instruments doesn't get up (but the transformer hums).

Stability problems

The full analog design and the heating does not contribute to stability. The repetition frequency changes a lot with minimal knob's movement and is very difficult to adjust; it drifts about one Herz per second. Maybe I have not been able to restore this instrument as I should, but however it is not a champion.

Amplifier circuits

The 8015A includes two A2 amplifier boards; each of them contains mainly the channel amplifier/ attenuator and the interface with the sliding front panel amplitude controls. In my opinion, they are the best part of the instrument.

Amplifiers

The amplifier includes three cascaded differential amplifier stages and a cascaded common base output stage, in a circuit in someway similar to a differential version of the the **cascode amplifier** that we learnt to know talking about the 7A18 7000-Series vertical amplifier plug-in. It offers many advantages, such as high gain, high bandwidth, high slew rate, high stability, and high input impedance, with a very low parts count.

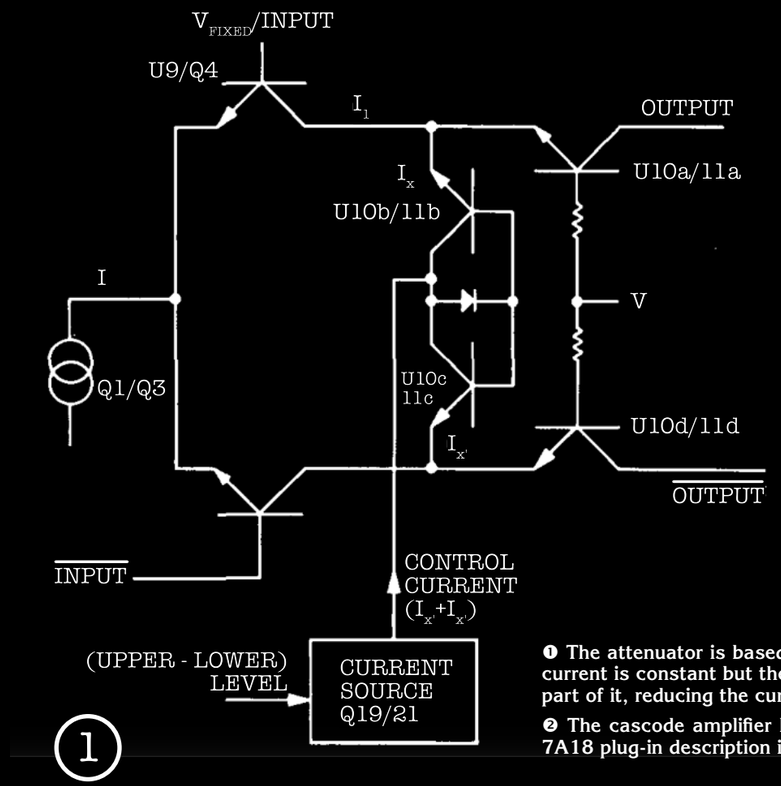
One of the differential inputs is held at a fixed voltage, while normal or complement pulses are selected from the appropriate side of the differential amplifiers by mean of a relay (K1). At the output of the common base stages are two voltage clamps which restrict the output swing to ±16V maximum.

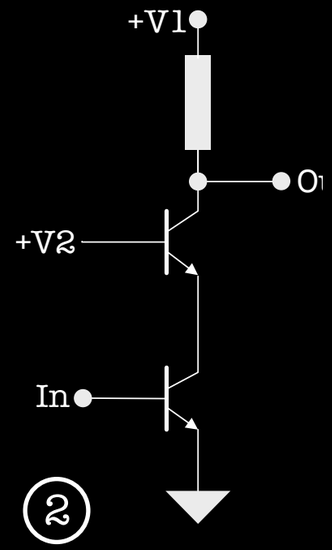
Controlling the gain

An important piece of this instrument is represented by the front slider that allows to establish the output pulse voltage swing and it absolute position in the vertical axis. HP chose a very simple and intuitive way from the user's point of view. The controls, as we noticed, are not too professional, and the scales rather rough, but they are however precise and linear enough. How could this goal achieved? Using active attenuator stages between each of the differential amplifiers, that we could call "current stealer". These attenuators are controlled from the variable current sources (Q19, Q21) which are in turn controlled by the difference between the position of the two sliders of each OUTPUT LEVEL control.

The attenuators operate on the current sharing principle of a differential amplifier, i.e., the current flowing in each collector is proportional to the potential difference between the two bases. The input signal (figure 4-2) controls the share of current I which flows through each input transistor. Similarly, the signal

delivered by Q19/21 controls the division of current in U10b/11b and 10c/11c. Suppose an attenuation factor of 2:1 and (for simplicity) I = 1 mA. If the INPUT is such that I is shared equally then I1= 0.5mA and I-I1, = 0.5mA. Also, Ix = 1/2 (I-I1) = 0.25mA and Ix' = ½ (I1) = 0.25mA. Now, suppose that the INPUT changes the sharing of current I so that I = 0.2mA and I-I1, = 0.8mA, then, Ix = 0.4mA and Ix' = 0.1mA. In both cases the sum Ix + Ix' = 0.5mA or Ix + Ix' = k (constant). This is true for all INPUT current sharing and attenuation ratios.





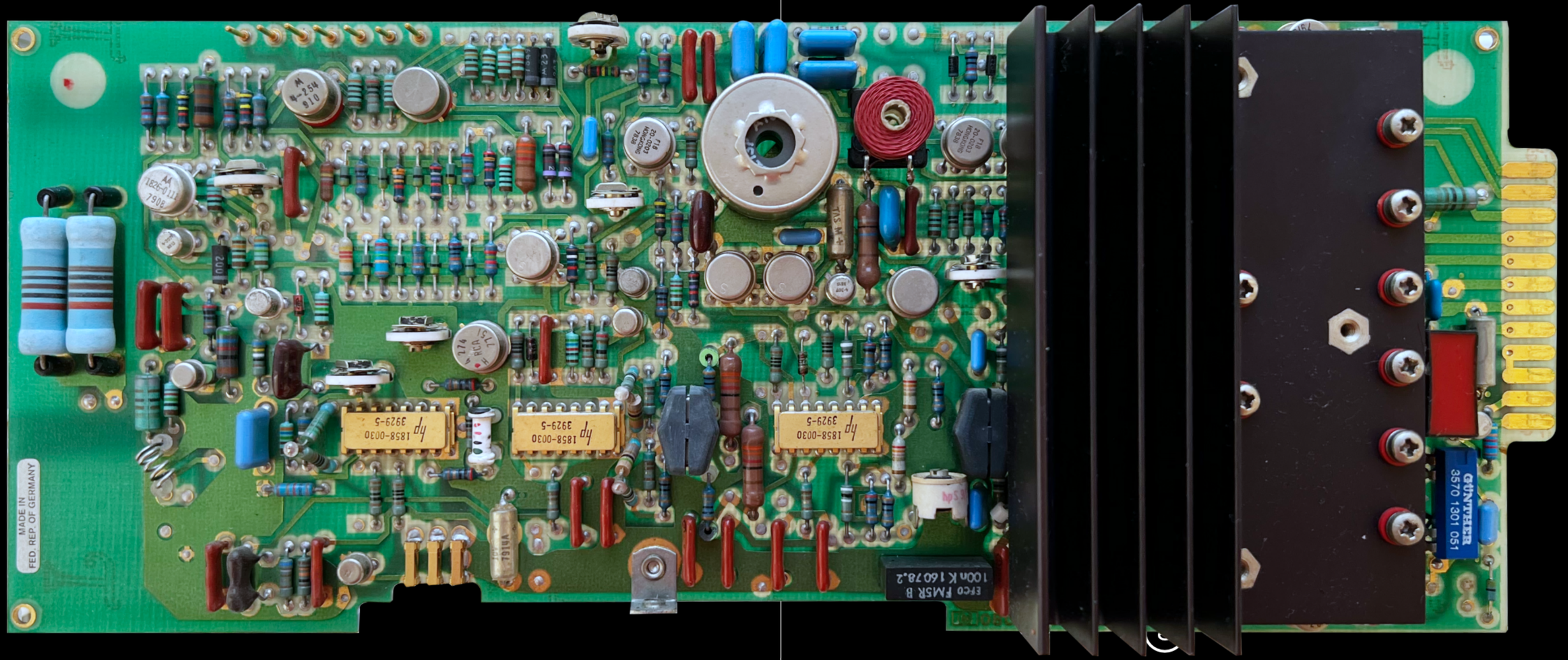
❶ The attenuator is based on the current theft by a current source. The I current is constant but the Upper and Lower level slider controls derives a part of it, reducing the current in the output.

❷ The cascode amplifier has a long story; for more information, see the 7A18 plug-in description in Tektronix 7000-Series description.

Amplifiers (A2)

Each 8015A includes two amplifier boards, named A2A and A2B, one for each output channels.

Like most of the other boards,, the amplifiers are made up with discrete components. The ICs are only array of transistors and not any form of more complex circuits.



Timing circuits

I spent a lot of time trying to make more precise the timing circuit board; the results were not very exciting. Maybe that I did not understand something, but it seems not a top circuit. I am talking of the repetition rate generator. It is an oscillator with four speed ranges:

- 20 ns to 1 μs (50 MHz to 1 MHz, 50 times);
- 1 μs to 0.1 ms (1 MHz to 10 kHz, 100 times);
- 0.1 ms to 10 ms (10 kHz to 100 Hz, 100 times);
- 10 ms to 1 s (100 Hz to 1 Hz, 100 times).

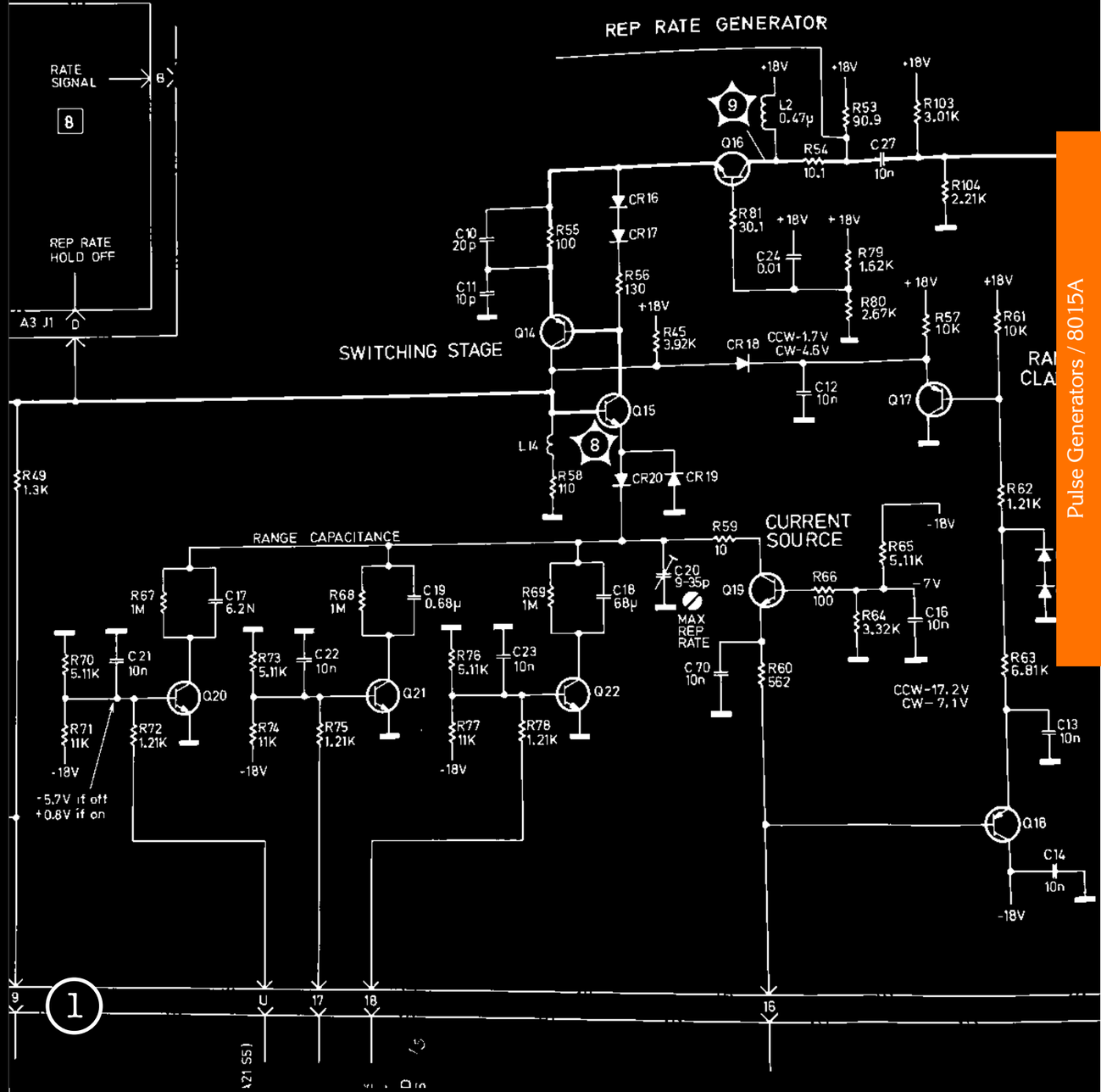
As you can see, the ranges are very wide; if the scale were linear, each rotation degree should change the speed very much. For example, in the second range, each potentiometer degree (of its 270° total) would be about 4 kHz. The stability is not exceptional, and an external instrument to see your setting is always mandatory.

The **Repetition Rate Generator** follows a scheme that I didn't meet again before. It consists of a ramp generator (Range Capacitors and Current Source) and a Current Switch (Q14, Q15). Understanding it was not simple for me, either because the manual gives little information, either because, in my opinion, **this information is wrong**. I spent a lot of time trying to understand the circuit and now I can remember it by hearth, from how long I studied it. I report here what I believe I understood and checked, not the manual text.

The Range Capacitor is a capacitance that can be:

- C20 only for the fastest range;
- C20 plus C17 or C18 or C19 for the other ranges, selected by the range switch that puts to -18 V the base of Q20, Q21 or Q22.

The Switching Stage (Q14 and Q15) connects the +18V to the Range Capacitor, charging it. Then the Current Source Q19 drains the charge of the Range Capacitor linearly, producing a ramp that drops to zero.



Thus, the repetition rate depends by:

- the initial value of the ramp, i.e. the value to which the Range Capacitor is charged;
- the value of the Range Capacitor;
- the current drawn by Q19.

To reach the higher speeds, the 8015A does not rely only on the drawn current but reduces also the initial value of the ramp, This is done by setting the voltage on C12 (collector of Q17). When the Switching Stage closes, it brings up the voltage until CR18 conduces, limiting the initial point of the ramp. This limiting value is indirectly set by set by the repetition rate vernier (1.7 V CCW, 4.6 V CW) via Q18 and Q17.

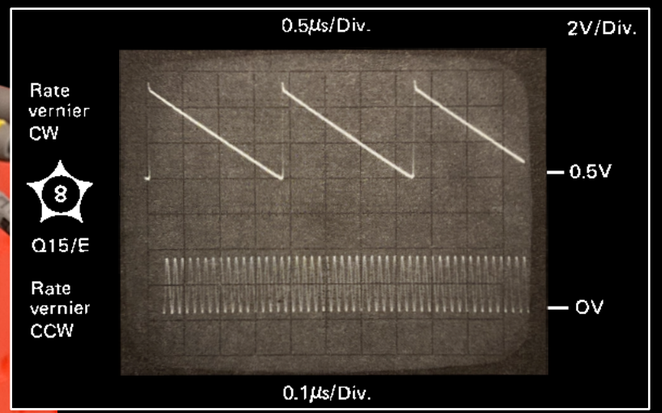
All what I said, is confirmed by the oscillogram 8 below, that I report here from the manual, and from all the measurements I made on the real instrument. It is rather different from the manual description.

As I noticed before, the performances of this solution are not exciting; the ranges are too wide and the control rather imprecise, while the stability is definitely unsatisfactory.

What to do with it?

As I told you, I am not impressed with the 8015A. What can I do with it? I think I can use it as a generic pulse generator to check and repair oscilloscopes, keeping it as is. Another idea could be using and inexpensive external digital pulse generator to drive the 8015A from the EXT INPUT, obtaining stability and exploiting the channel amplifiers. In this way I could also generate the bursts (big photo), that require anyway an external pulse.

If I do that, I will update these pages.



Pulse Generators

Subsection

8012B Pulse Generator

8015A' smaller brother.



Perseverare Diabolicum

I wrote that the 8015A is probably the less beloved in my small collection, so it is not easy to understand why I though it had been a mistake to buy the 8015A, and then decided to purchase the 8012B I present here. The reason is very simple: someone was selling it on eBay almost for free, so I didn't resist, even if it was declared spares only.

The worst ever

The 8012B didn't deserve my sympathy; actually, to tell the truth, it was my worst case ever, and I remained stuck on a single point for at least a week of continuous try. I felt like Wile E. Coyote trying to catch the Roadrunner… whatever I tried, it failed.

When arrived, the 8012B was almost dead. The power supply voltages (+17 and -17 V) were present and good, but no pulse was generated, whatever I did. I will describe in detail all the repair story.

The Family

The 8012B is another member in the rich 800x HP pulse generator's product line from the seventies, which extended from the simplest, most economical model with a limited number of variable parameters to the most complex model with all variable parameters, very fast transition times and a wide variety of output configurations, for a total, in 1975, of as many as eleven models (214A, 8002A, 8004A, 8005B, 8007B, 8010A, 8011A, 8012B, 8013B, 8015A, 8082A). Prices went from $500 of the 8011A to $3,355 of the 250-MHz 8082A. Another family, Model 1900, was based on a plug-in architecture. We already saw the 8015A, at $2,250 in its base version; in 1975, this 8012B costed $995, i.e., "only" $5,360 today.

Family Architecture

8012B's architecture is rather similar to 8015A, definitely old even for the time, because they origin from the latest sixties. I downloaded and checked other schematics (e.g, the 8005B), and they are very similar, even before the introduction of slide controls, probably added more as a face-lift than for real necessity, as proved by the fact that sliding controls were abandoned later. All of these generators didn't use any TTL ICs, but only discrete transistors (apart from two uA741 in the power supply).

Upon reflection, in 1976 I had already built my first digital counter and also a TTL pulse generator, so the great HP could have designed a better circuit than this, as they did toward the end of the seventies, for example with the 8165A Programmable Signal Source or the 3325A Function Generator, that we see in other part of this book. A better solution was due, at least for the repetition rate generator, that, IMHO, is the most evident weak part of the equipment. Probably they felt more comfortable with transistor, or wanted an electrically less noisy instrument, but, more likely, they wanted only to reuse old projects; never change a selling product. The result was rather critical and not exceptional, so the 8012B didn't improve my 8015A's scarce consideration.

Let's see also the positive part of the apple: when in order, in some way …it works. Neither very stable nor precise, but it allows to produce several kind of output pulses and still today can be used. For example, I used the 8015A to repair this 8012B.

Another positive aspect for this equipment is that no unobtainable parts are used inside, so we can be sure that in some way we can always fix them (even if at a price, as we are going to see).



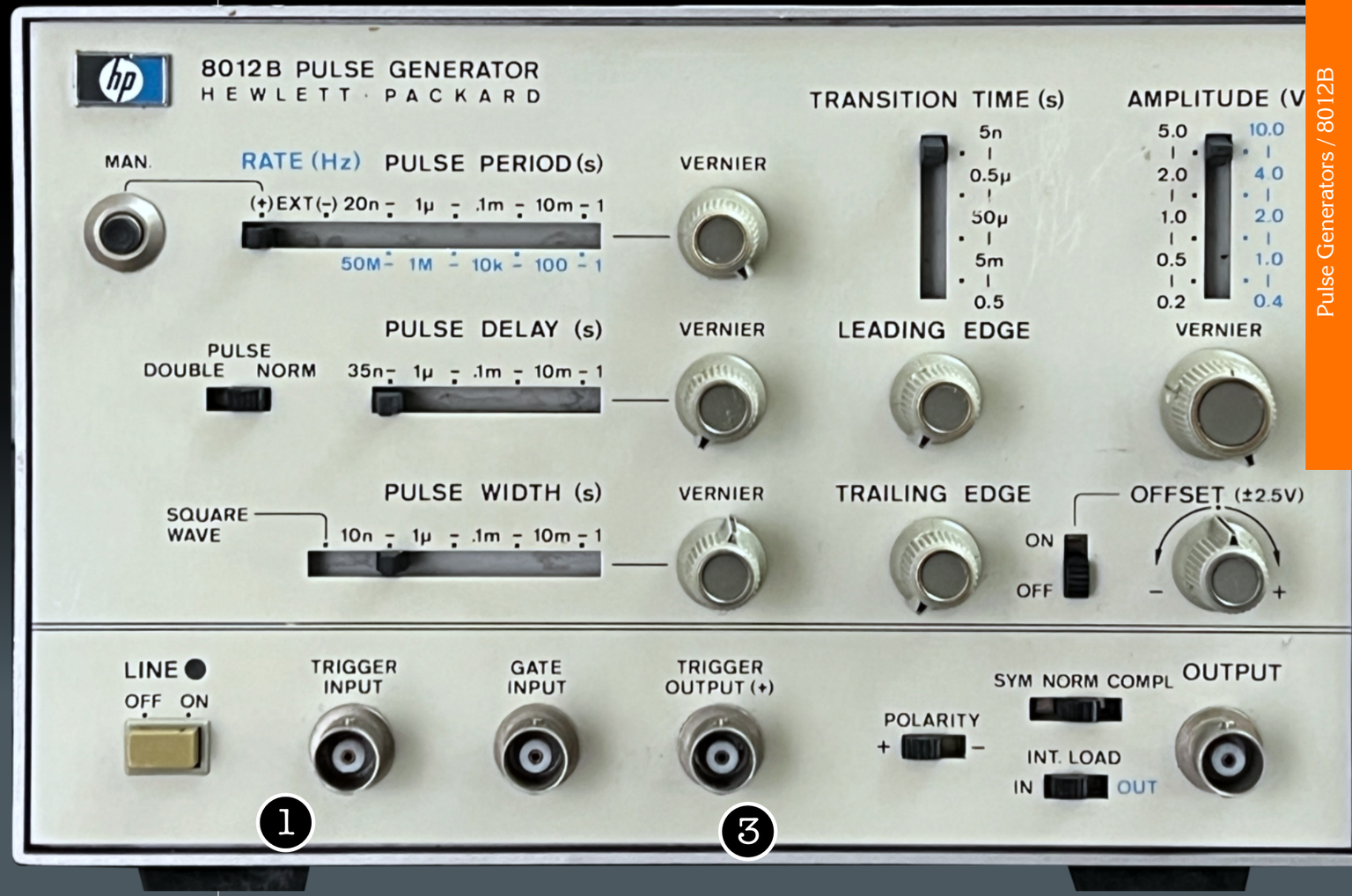
The 8000-Series Pulse Generators from a dedicated catalog, probably from the mid-seventies.

Specifications

8012B and 8013B were described as at the top of their class for versatility, ease of operation and wide range of application. According to HP, they provided the ideal solution to almost all digital logic testing problems with fixed 3.5 ns transition times on the 8013B and variable transition times down to 5 ns on the 8012B. In truth, I didn't notice that the front panel had a logic, with horizontal controls for horizontal parameters and vertical controls for vertical parameters; that should enable output pulses to be set up quickly and accurately with minimum risk of incompatible settings, with normal, complement and inverted output and a switchable internal 50 ohm load.

The 8012B has good specs, at least on the paper:

- Transition time: 5 ns - 0.5 us (load in) or 6 ns - 0.5 us (load out); 4 ranges, verniers provide separate control al both edges within ranges up to max. ratios of 100:1;
- Source impedance: 50 ohm (load in) or > 50 ohm (load out);
- Maximum output: 5 V across 50 ohms, 10V across open circuit; short circuit protection;
- Linearity: for transition times >30 ms, maximum straight line deviation is 5% of pulse amplitude.
- Pre-shoot: <+5% of pulse amplitude;
- Pulse width: <10 ns to 1s in four ranges. Vernier provides continuous adjustment within ranges.
- Width jitter: <0.1% + 50 ps on any width setting.
- Maximum duty cycle: > 75% from 1 Hz lo 10 MHz, decreasing to ≥40% at 50 MHz. Up to 100% in COMPL mode;
- Polarity: positive or negative selectable, NORM/COMPL/SYM selectable;
- Pulse delay: <35 ns to 1s (with respect to trigger output) in four ranges; vernier provides continuous adjustment within ranges.
- Delay jitter: <0.1% + 50 ps on any delay setting.
- Repetition rate and trigger: 1 Hz to 50 MHz in four ranges, continuous adjustment.
- Period jitter: <0.1% + 50 ps on any rate setting.
- Square wave: 0.5 Hz to 25 MHz in four ranges.
- Trigger output: >+1V across 50 ohm;
- Dimensions and weight: 200 mm wide, 142 mm high, 330 mm deep, 4 kg
- Other features include external triggering, gating, external width and RZ.



Architecture

8012B's architecture is rather similar to 8015A, definitely old even for the time, because they origin from the latest sixties. I downloaded and checked other schematics (e.g, the 8005B), and they are very similar, even before the introduction of slide controls, probably added more as a face-lift than for real necessity, as proved by the fact that sliding controls were abandoned later. All of these generators didn't use any TTL ICs, but only discrete transistors (apart from two uA741 in the power supply).

Hardware

Physically, the unit is well conceived (better than 8015A), and is based upon two boards with edge connectors, plus the front panel, which acts also as a motherboard. The left board (A5) is easy to remove, whilst A6 requires more relevant dismantling.



The 8012B is composed mainly from three boards: the front panel and two long boards with edge connectors.

The Circuit

Manuals

I could find just one 8012B manual on Internet (part No. 08012-90005, printed October 1977), but its graphical quality is the worst. So, I purchased one from Artek Manuals for 12$, and it is almost perfect. As mentioned, circuit descriptions in the manual are very concise and help very little the repairer.

Note: using this manual on Mac, I noted that if I set a bookmark (even unwillingly) or make any modification, on the next time it refuses to open and asks for a password. To solve this problem, just open it and print it as a pdf. You can then use this pdf almost without limitations.

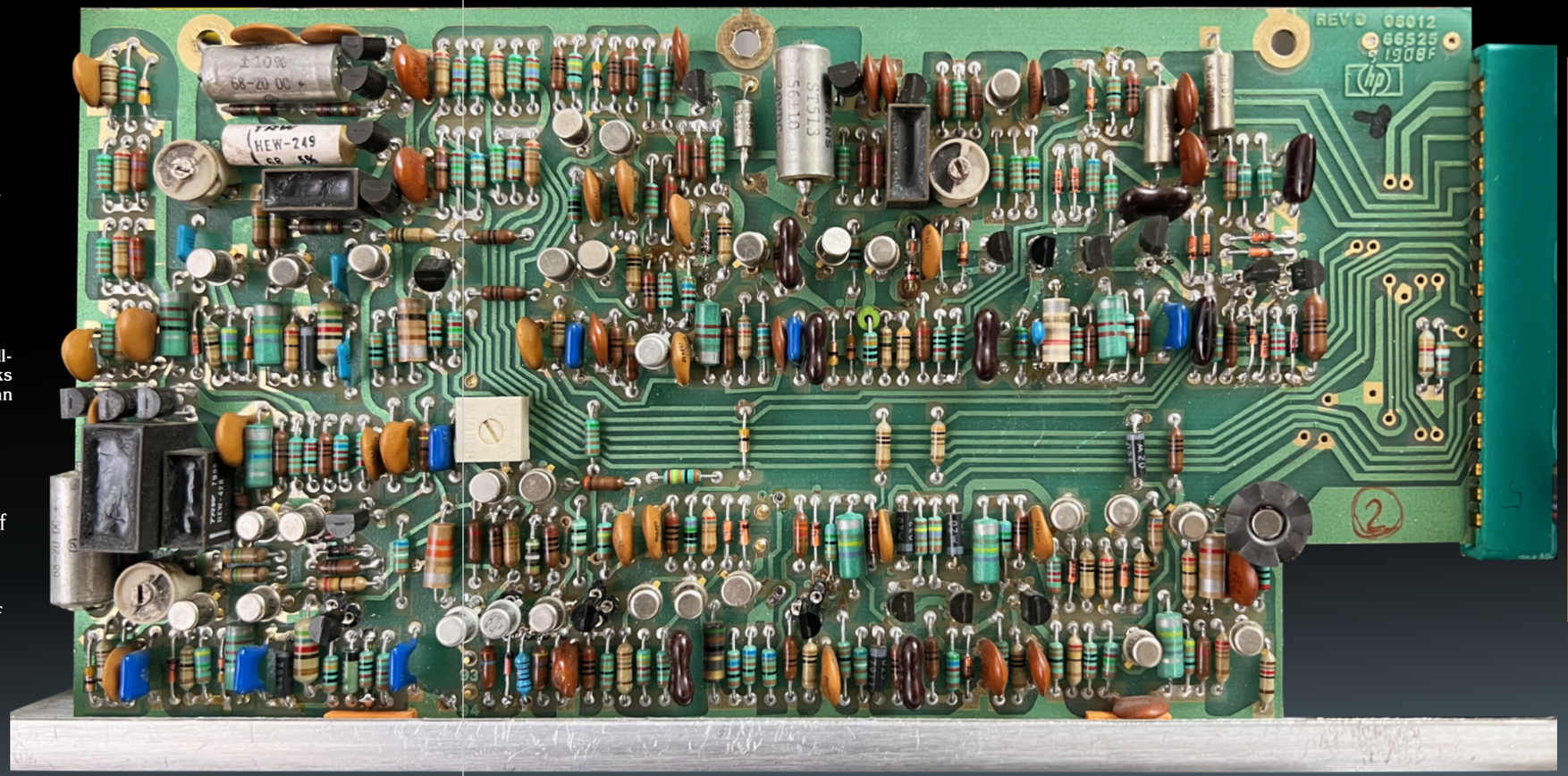
Donkeys go to study

I am not an expert in transistor circuits, and here consider myself a donkey. In consequence, I am very attracted by the possibility to learn things that, in my working life, I never had the opportunity to afford. In the case of the 8012B, you have a lot of transistors, and the circuit is not very straightforward; I would rather define it as "intricate". Who designed it was clearly very expert and clever, but decoding their logic is sometimes difficult to me, while the manual doesn't help.

8012B's circuits are rather simpler than 8015A. I focused on the parts I needed, and only these parts I am going to describe.

Ltspice

As a donkey apprentice, I had many difficulties studying the 8012B's circuits, but I found a countermeasure to the lack of information and to my ignorance: Ltspice circuit simulator. It is free and very simple to use: just look one of the YouTube tutorials and you can immediately start to work. With it, I could understand many things and could finally repair my baby.



The 8012B A5 board, the "logic board", if we can say so...

Building blocks

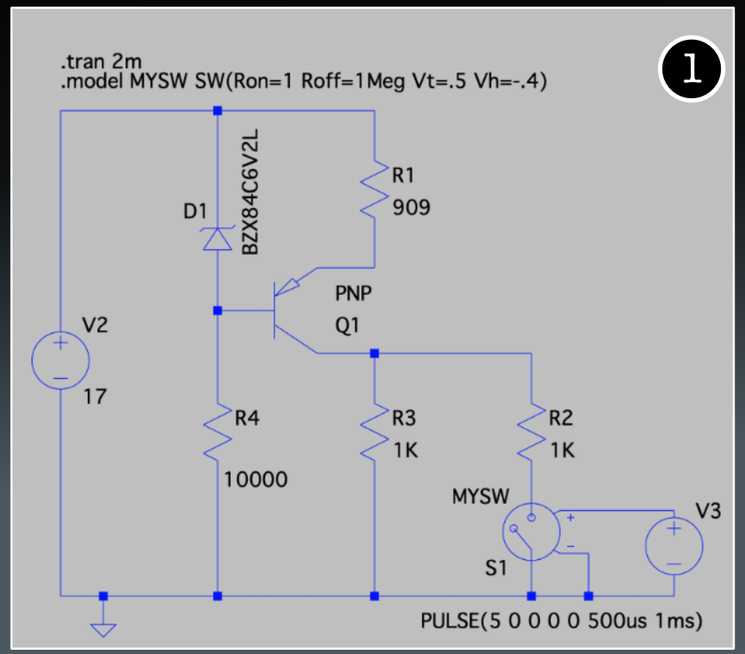
Before describing my 8012B faults and repair, let's deepen the circuit analysis. I am starting to see that the designers used more times some basic building blocks, and we are going to describe them before talking of the repair; specifically we will describe Constant Current Sources, the Schmidt Trigger and Pulse Shapers.

Constant Current Sources

The basic working principle of a constant current source is to use feedback mechanisms to maintain the current flowing through the load at a constant level, regardless of changes in load resistance or input voltage. The constant current source circuit will adjust its output voltage to keep the current constant, thereby compensating for any changes in the load resistance or input voltage. In the 8012B (and family), the current source is used also to linearly charge a capacitor to create precise delays. Figure 1 shows the typical current source circuit.

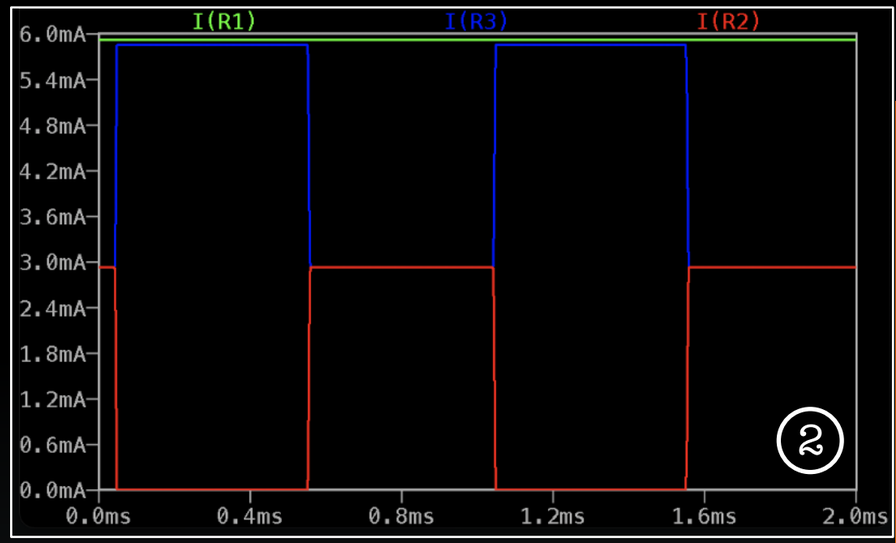
Classic current source

A simple way to obtain a constant current source includes a transistor and a Zener diode. You can see its schematic diagram in figure 1, while figure 2 shows the circuit simulation: the current in R1 is constant, while the current in R3 varies, according the position of the electronically-operated switch S1. We can say that the sum of the current in R3 and R2 is constant.



How does it work?

A Zener diode, when reverse biased has a constant voltage drop across it irrespective of the current flowing through it. Thus, as long as the Zener current (Iz) is above a certain level (called holding current), the voltage across the Zener diode (Vz) will be constant.



Resistor R4 supplies the Zener current and the base current (Ib) of PNP transistor Q1. The constant Zener voltage is applied across the base of Q1 and emitter resistor R1. Voltage across R1 (VR1) is given by Vz + Vbe, where Vbe is the base-emitter drop of Q1. The emitter current of Q1 which is also the current through R1 is given by

- IR1 = VR1 / R1 = (Vz + Vbe) / R1

Since VZ is constant and Vbe is also approximately constant (for a given temperature), it follows that VR1 is constant and hence Ie is also constant. Due to transistor action, emitter current Ie is very nearly equal to the collector current Ic. Thus, the load current is constant and the circuit operates as a constant current source, independent of the supply voltage, R1 and the transistor's gain.

R1 allows the load current to be set at any desirable value and is calculated by:

- R1 = (Vz + Vbe) / IR2

where Vbe is typically 0.65 V for a silicon device.

(IR2 is also the emitter current and is assumed to be the same as the collector or required load current, provided hFE is sufficiently large).

Resistance R4 is calculated as:

- R4 = (Vs-Vz) / (Iz + K x Ib)

where K = 1.2 to 2.

❶ The transistor constant current source schematic.The electronic switch MYSW open and closes an additional load on the transistor collector.

❷ The current plots, for R1, R2 and R3. As you can see, I(R1) remains constant while R2+R3 = R1.

Simplified version

The use of a Zener diode is not necessary, as shown in figure 3. The current source operates because of the fact that the collector current in a transistor circuit is β times the base current. This is independent of the collector voltage, provided that there is sufficient voltage to drive the current through the load device in the collector. By setting the resistors R1 and R2 it is possible to set the base voltage. The emitter voltage will be 0.6 volts less, assuming a silicon transistor. By knowing the emitter voltage, it is possible to calculate the emitter current from a simple knowledge of Ohms law.

The simulation presents in this case similar results. In the 8012B, this kind of circuit is used (i.e., without Zener diodes).

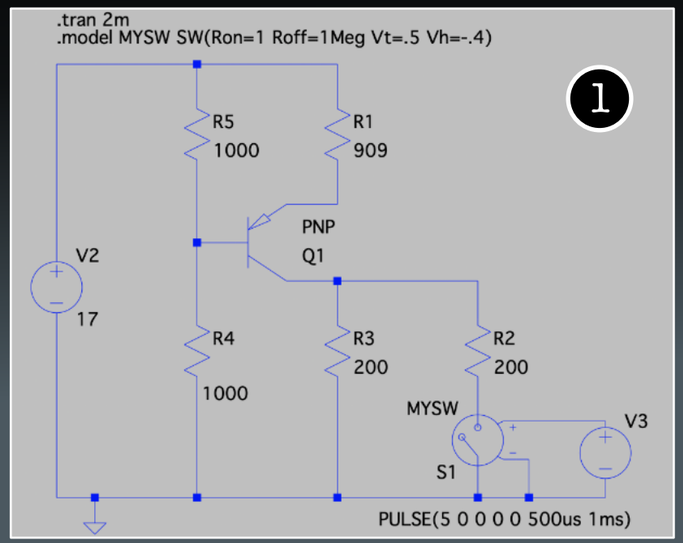
Constant current in the 8012B

In the 8012B, like in many old oscilloscopes, the constant current source is used to moreover measure time. The principle is simple:

- a capacitor is quickly charged;
- the capacitor is discharged by mean of a constant current source;
- the voltage across the capacitor is therefore a ramp;
- a circuit detects when the ramp arrives at a certain value and triggers.

The time to arrive at the trigger level depends only on the constant current, the capacitor and the trigger voltage. We described the repetition rate generator talking about the 8015A; the 8012B is very similar.

So you probably guess that there is another reason why I described all this, and there is, but before affording the 8012B repair theme we need other elements: triggers and pulse shapers.



I realize now that I never had to deal with it. Or better, I used it a million times, but it was so easy to add a simple 74HC14 to forget what probably I learnt at university. So, in this my “second life” repairing old equipment, I think it’s time to understand something more about it, and the terrible 8012B forces me in this direction. As usual, we will exploit Wikipedia in these notes, but trying to be simpler, even if less scientifically precise.



❶ Constant-current source Ltspice simulation.
❷ 8012B rear panel view.

Schmidt Triggers

After the current source, the second building block, necessary to afford the repair, is the Schmidt Trigger (or simply “trigger”). As everybody knows, it is a black box with an analog input and a digital output, which Tektronix calls often multivibrator, even if, to be precise, that is a slightly different circuit.

The ST’s input has two thresholds, the upper and the lower ones.When an increasing (in voltage) input signal crosses the upper threshold, it triggers the HIGH state of the output. If this signal decreases below this level, nothing happens. It must decrease below the lower threshold to return the output to the LOW state; the ST thus possesses memory.

This dual threshold action is called hysteresis and is very common, even in mechanics and in many every-day objects (thing for example the button of many ballpoint pens).

The 8012B, like many old instruments, does not use 74HC14s or 74HC132s, but creates these triggers with discrete transistors, as shown in figure 1. Old oscilloscopes, like Tektronix 545, do the same with tubes, with similar circuits.

Observe that:

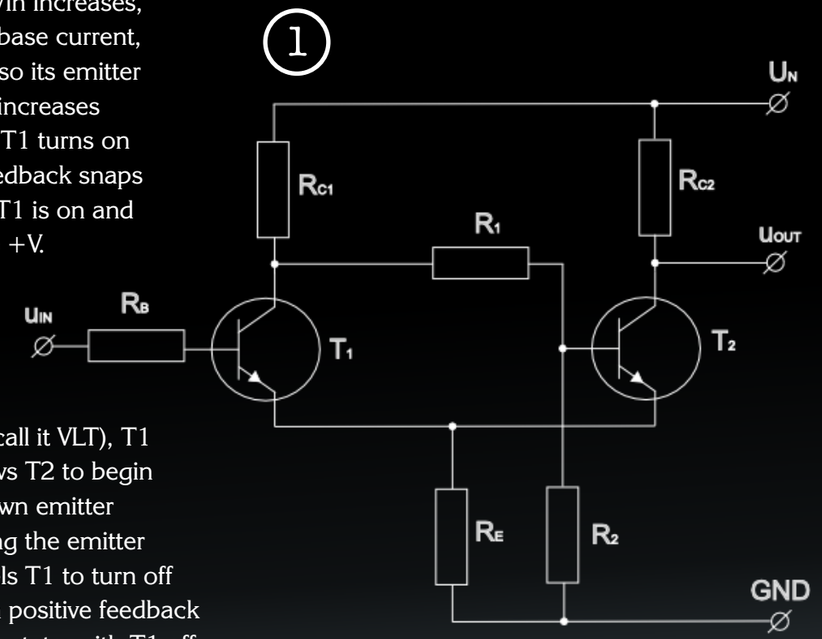
- both transistors T1 and T2 have a collector load, Rc1 and Rc2 respectively;
- the two transistors’ emitters are fed by a common resistor Re, and thus the circuit acts as a differential amplifier/comparator;
- T2 base is polarized by a voltage divider composed by Rc1, R1 and R2;

No input signal: suppose the input voltage Vin is zero. T1 has no base current, so it's off. T2 draws base current though Rc1 and R1, so it's on. Vout sits at the mid-point of the potential divider formed by Rc2 and Re.

Increasing input signal: now suppose Vin starts to increase. T1's emitter voltage is held fixed by the current flowing in T2, so when Vin reaches about 0.6v above this value (call it VHT), T1 will draw some base current and start to turn on.

LOW to HIGH transition: As Vin increases, T1 begins to steal part of T2 base current, so T2 begins to turn off, and so its emitter voltage starts to fall. But this increases T1's base-emitter voltage, so T1 turns on more quickly. The positive feedback snaps the circuit into a state where T1 is on and T2 is off. Vout is now close to +V.

HIGH to LOW transition: T1's emitter voltage now is determined by its emitter current. When Vin falls to about 0.6v above this value (call it VLT), T1 will start to turn off. This allows T2 to begin to turn on again, adding its own emitter current to T1's and so nudging the emitter voltage upwards. This compels T1 to turn off more quickly, and once again positive feedback snaps the circuit into its other state, with T1 off and T2 on.



In the picture, a transistor-based Schmidt Trigger, from Wikipedia.

The schematic is by Di Audrius Meskauskas - Opera propria, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=633382

Formulas: (neglecting junction voltages)

- VHT = Re / (Re +Rc2) x V+
- VLT = Re / (Re+Rc2) x V+

Simulating the ST

The 8012B’s circuit is exactly as the one described by Wikipedia, with the difference of having as collector’s loads also small inductors. We are going to examine it more deeply, but before arriving to the trial where we will declare the culprit, we must talk about pulse shapers.

A6 Board



The A6 board contains the power supply, the final stages and the power output amplifier.

Pulse Shapers

❶ A pulse differentiator built with TTL ICs.

❷ A transistor with an inductor on its collector allows to produce short pulses on each end on a square pulse.

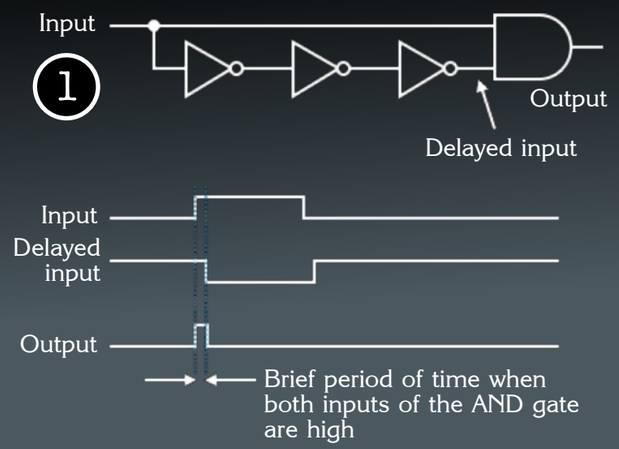
❸ The pulses generated by the 8012B (waveforms 11b and 12)

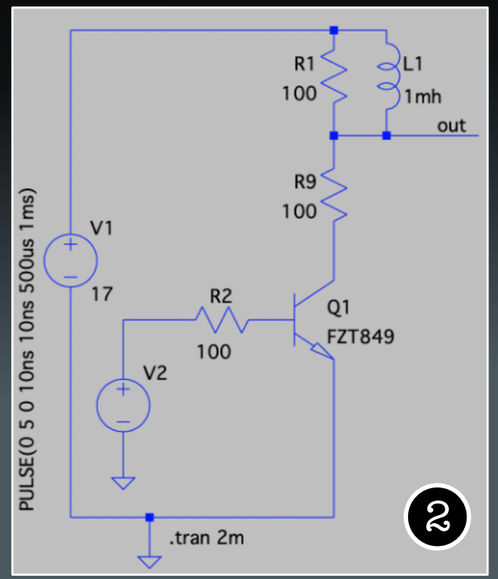
What does it mean shaping?

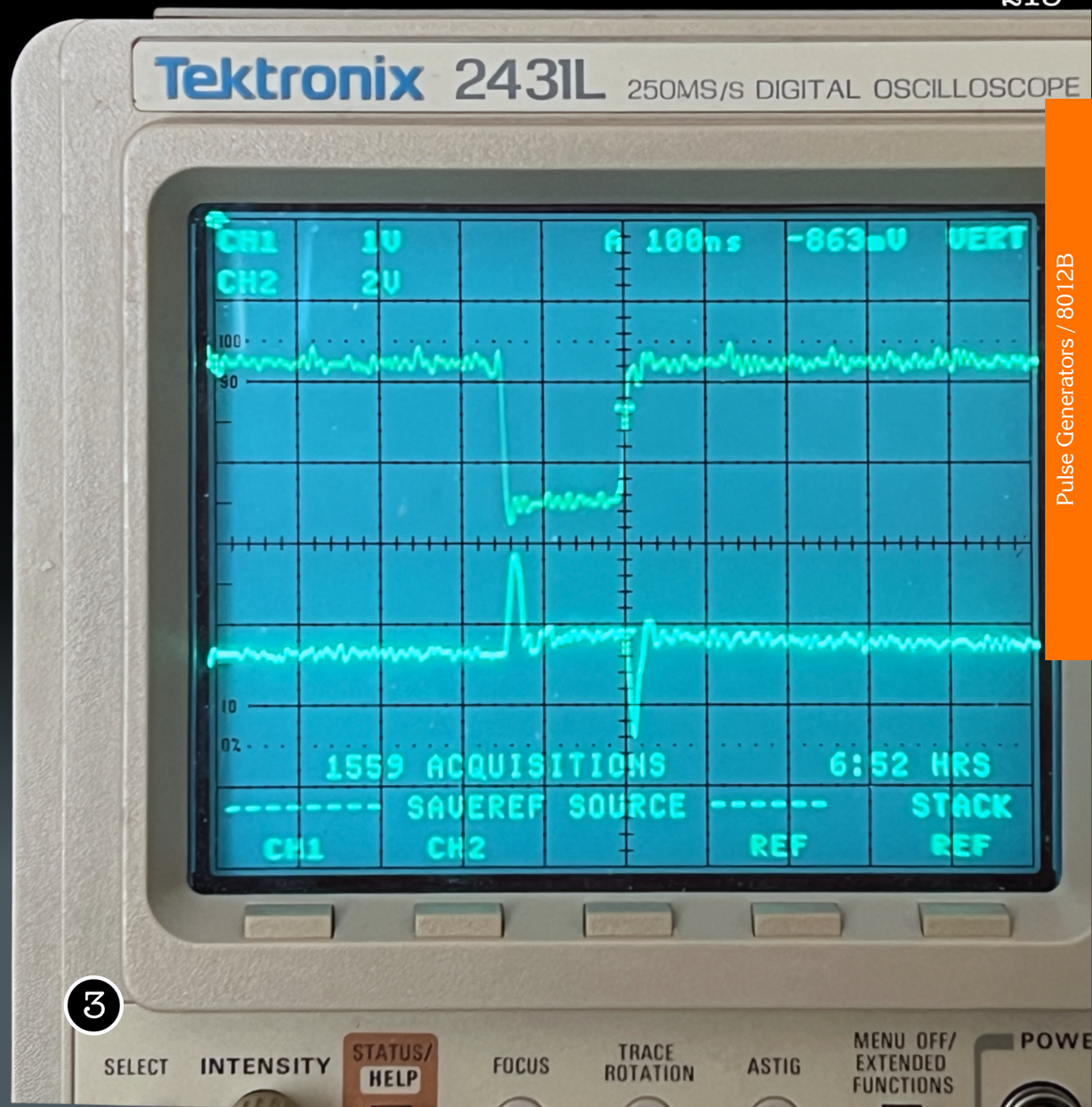
For a pulse, getting in shape is like for us humans: to assume a better shape, more suitable to our purposes. In this case, as we are going to see, it is also to shrink. With reference to the photo on the right, we want to transform a “fat” rectangular pulse in two “slender” pulses, one positive and one negative, so that these pulses can be routed to a Schmidt Trigger input, which will change its state accordingly. Having the two of them different polarity, the trigger job will clearly be simpler.

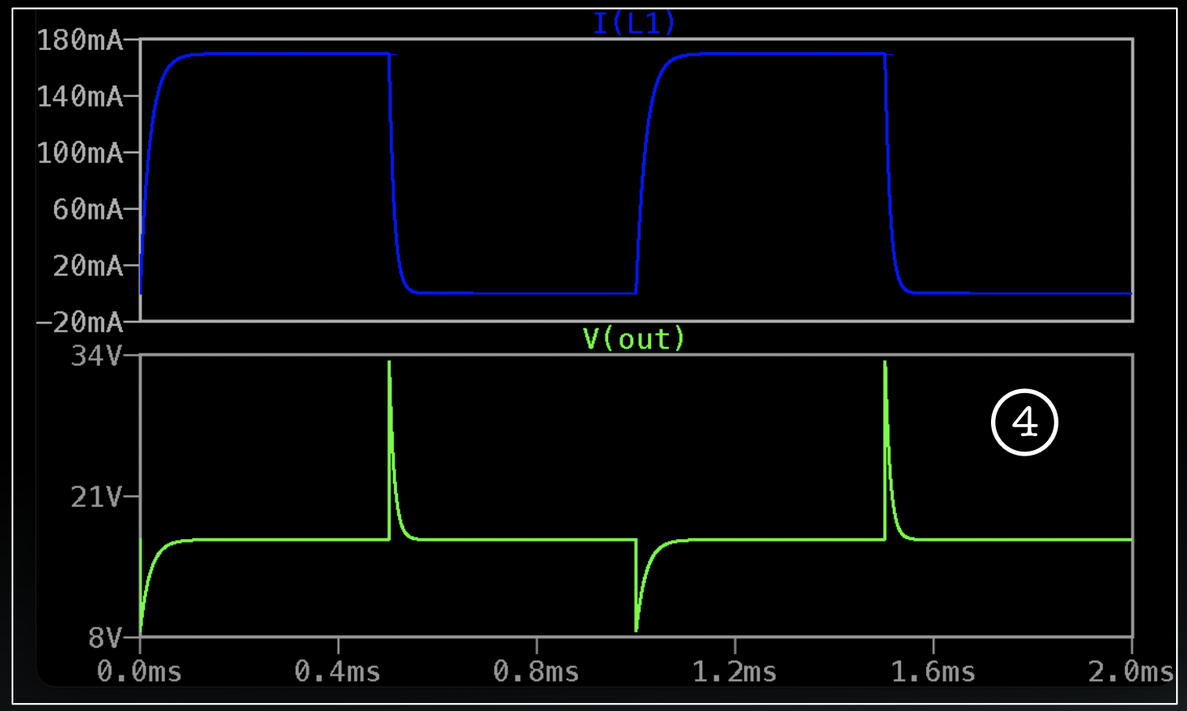
How does it work?

This operation is called also “differentiation”, because the pulse is a practical derivative of a practical rectangular front. With TTL ICs, we used to do that with the self-explanatory circuit ❶ below. With the old transistors, more often they used an inductor to do that, as shown in ❷.







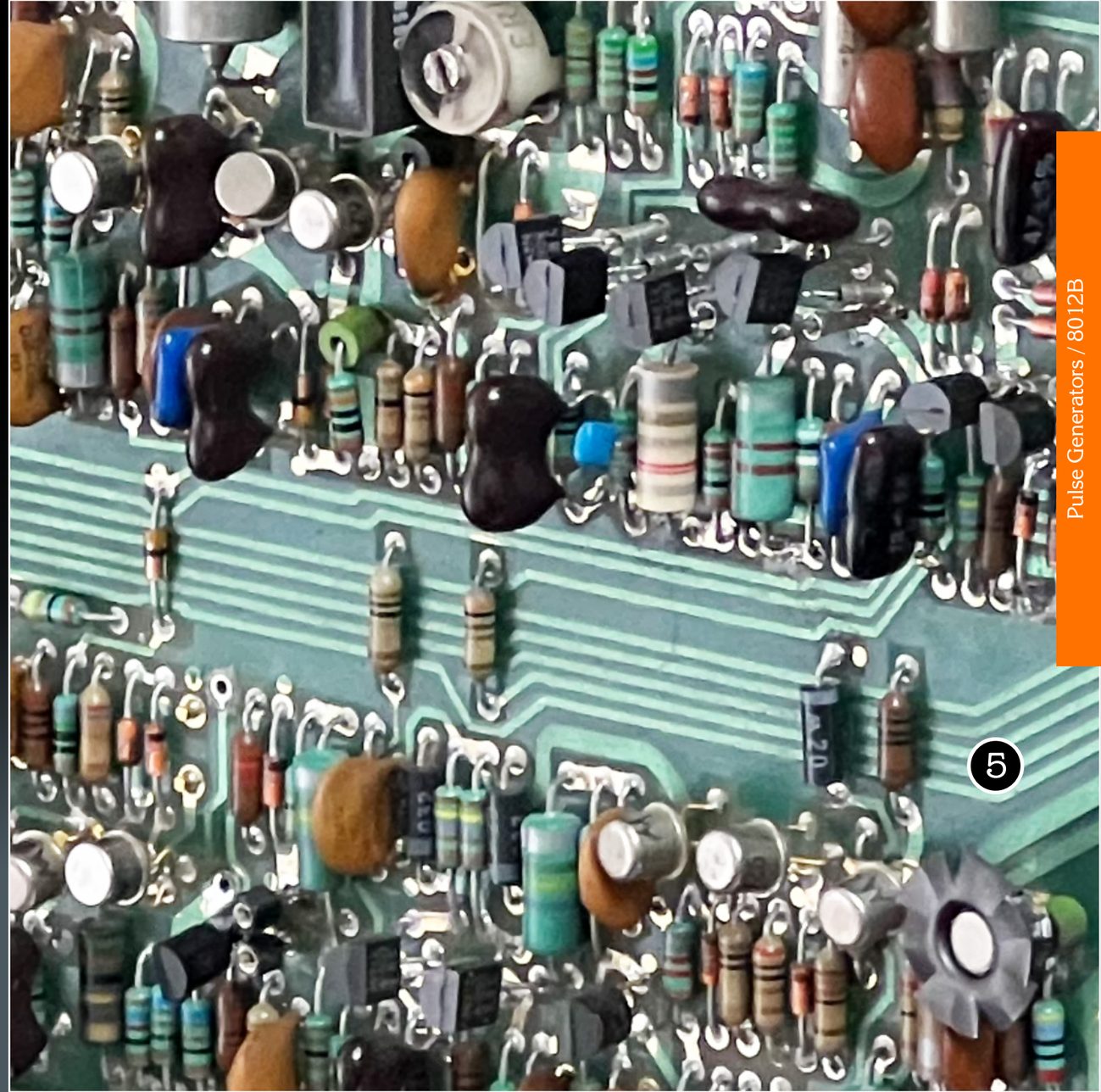


When you switch on a transistor having an inductor ("choke") on its collector, a magnetic field must be established around the choke, so the voltage increases more slowly and a negative glitch is produced. When the transistor switches off, the magnetic field return to current and a positive glitch is generated. In other words, you have a negative or positive short pulse on each front, as shown in the simulation of the proposed circuit (❹), where you can see the current across the inductor and the voltage at "out".

This way of adding inductors, allows us to obtain the desired result.

❹ When the transistor switches, the current briskly changes its value. When it grows, energy in the magnetic field is put; in consequence the voltage across it has a dip before reaching its stable value. When the circuit is open, the energy stored in the magnetic field is released and the voltage rises.

❺ A lot of transistors are used in the 8012B: 99 in total, 55 in the A5 board and 44 in A6. Those in TO-18 (metal can) have been chosen for a better power dissipation (up to 400 mW versus 300 on the plastic TO-92). Some of them have furthermore an heatsink. In general, much heat is dissipated.



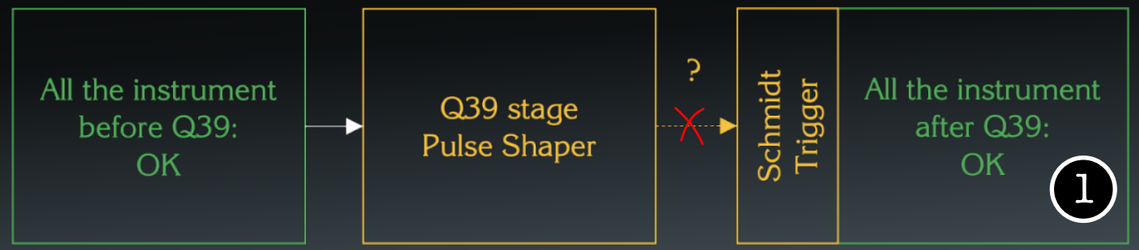
Finally, the Problem

You bothered us with constant current sources, inductors and slimming diets for pulses. After all this stuff, isn't time eventually to talk about the 8012B problem? Yes, you're right, but only thru this path you can understand the problem where I remained stuck for days.

I could determine that all the instrument before a pulse shaper based on Q39 was working, and all the part after Q39 was working (diagram below), but the signal could not go across this Q39, even if, with an (inaccurate) exam with the oscilloscope, it seemed to be correct. This part of the schematic diagram is reported on the right, in compliance with the manual. The circuit is composed by Q39 on the A5 board and its load on A6 board, or, at least, that is what I understood initially.

How should it be

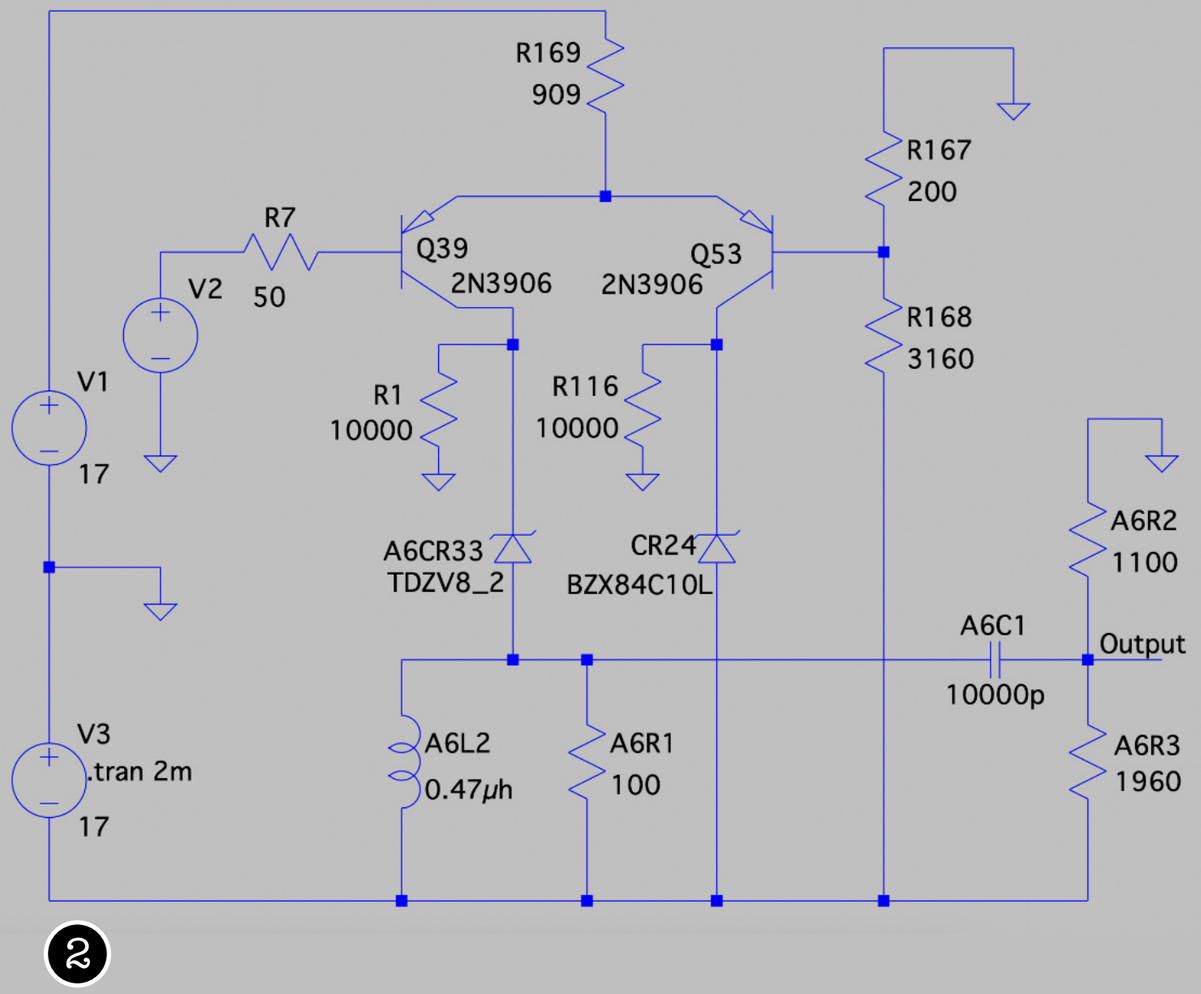
Q39 (on the A5 board) has as a load L2 and R1 on the A6 board. The spikes produced thanks to the inductor are transferred via A6C1 to the Schmidt Trigger first stage of the Integrator stage, which produces the variable slopes of the final pulse.



The manual clearly defines the expected signal toward Q39 base (waveform 11b, see the manual) and on Q39's collector (waveform 12). The 11b waveform was correct on the real instrument, and also the 12 at first sight. Looking at it better, it was right from the timing point of view, but its amplitude of the spikes was much lower than expected (1 V instead of 2).

I tried in every way to make it increase, with no success. In hindsight, my attempts were definitely stupid; I tried to change the various parameters, added some capacitors, and even thought a FET

❶ The fault of my 8012B: all the instrument before and after Q39 stage was acting correctly.
❷ Q39 stage.



amplifier. As usual, you must first understand and then act, not the contrary. For example, the base signal amplitude (11b) has no effect on the pulses. To make them increase, you can act only on the current step or on the slopes' speed.

At a certain moment, I thought the problem was in the subsequent stage, and that's the reason why I studied the Schmidt Trigger. Applying the formulas and a DC precise level generator, I verified that the trigger was working well, and in accordance with the calculated thresholds. So I used the 8015B to produce proper pulses, which allowed me to check that the remaining part of the instrument (after Q39) was in order.

Devil's tail

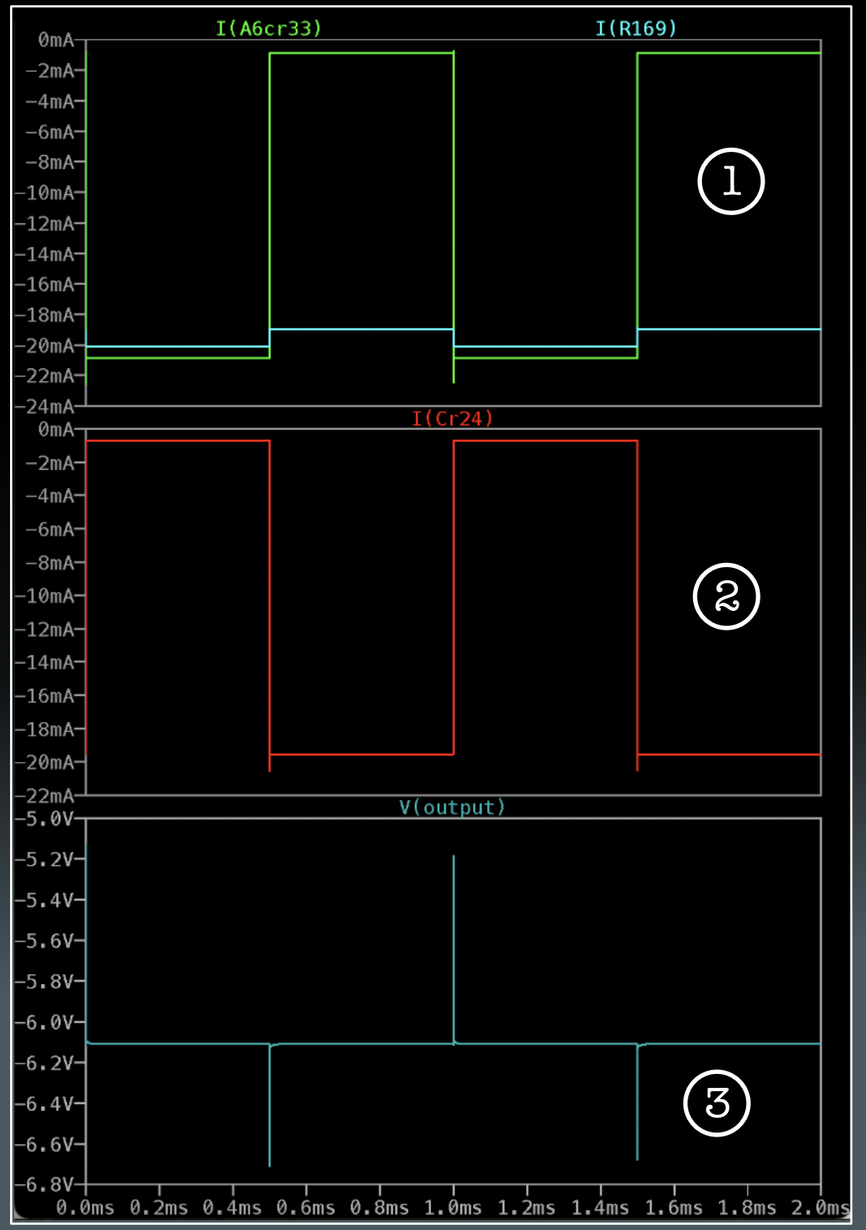
As sometimes happens, circumstances lead me to fall into error; in Italian we say that the Devil puts its tail into the problem. In this case, I saw that R116 and CR24 were not installed in my unit. After much reflection, I realized that this was explained by the manual revision history, and then wrongly accepted the concept that Q53 (whose collector is left open) was not part of the problem. So I concentrated for days on the rest of the circuit, which, needless to say, was perfect. The simulation allowed me to understand that the pulse I physically got was in accordance with the theory (simulator output).

The turning point

So practice (8012B) was confirming what theory (Ltspice) said. And then? Just as an experiment, I added the missing components to the simulator (Q53, R116 and C24). The results were very good, so I went to the real instrument and tried: the first attempt was not good, and, then, I wanted to check Q53. It was broken. As usual, I replaced it with a socket, to ease future replacements, and I replaced it. It worked, and again in accord to the simulator.

Why did it work?

The explanation (once you know…) is easy. Q53 makes a constant current sink, and has the emitter resistor R169 in common with U39. This means that Q39 and Q53 share the same current. When Q39 closes, it "steals" all the current; when it opens, Q53 drains in place of it the same current. As shown by the simulation plot, in this way the current in R169 is split in the two directions and the current step on the inductor is about 20 mA. If you repeat the simulation without Q53, you can see that the current step is reduced to 2mA. No wonder that the spikes were short!



Not all the mysteries were solved

I had also to increase L2 from 0.220uH to 0.470. The idea came from the manual itself, where I noted that many inductors had been increased in subsequent product changes. But why? Surely the instrument worked in a certain moment. All the resistors kept their value, but the inductor had to be changed, if I wanted a running 8012B. I have no answer to this question.

❶ The current in the inductor leg (in blue the total current in R169).

❷ The current in Q53 compensates for the current in the inductor when this is not active.

❸ The output pulses, formed as they should.

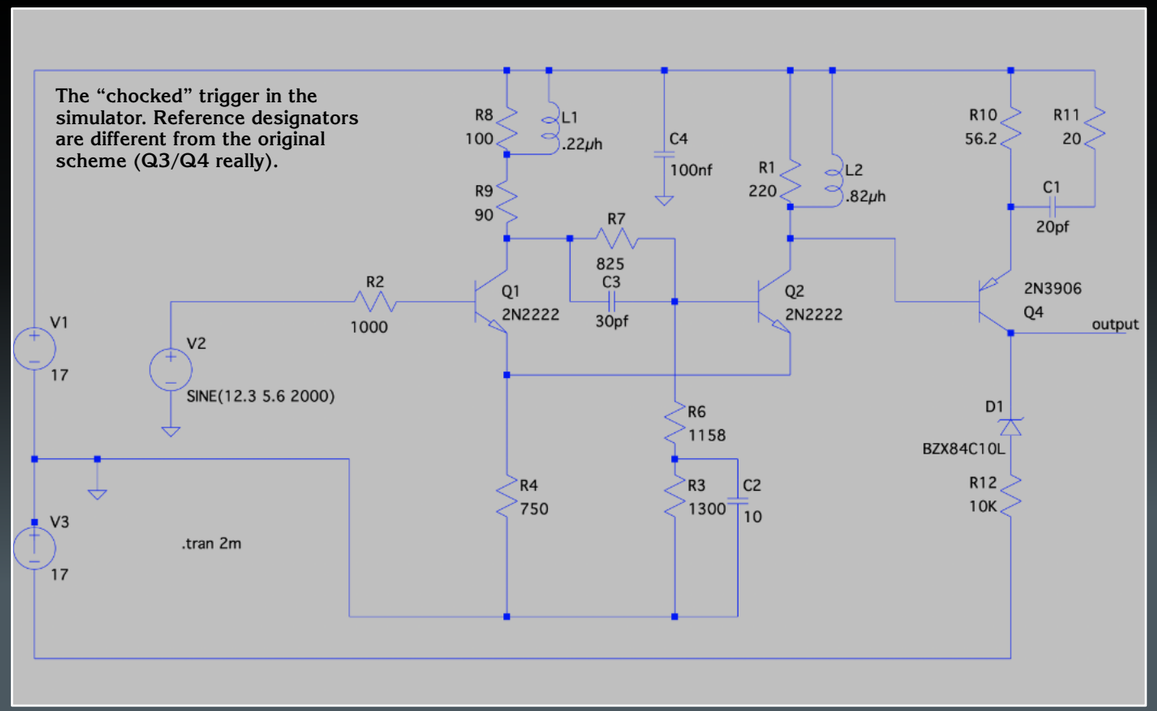
Backlash!

It was not over. Fully testing the instrument, I discovered that the external trigger input was not working. After some work, I arrived to the Schmidt Trigger composed by Q3 and Q4 (the simulator schematic diagram is correct but with different reference designators).

The Choked Schmidt Trigger

This trigger circuit is once again similar to the base scheme, but with an interesting variant, which again relies on small inductors to produce short pulses to detect signal edges.

Once again I found no other solution than increasing the inductors' values to make it work.



Conclusions

The use of inductors to differentiate pulses seems today to be the worst cause of instability in the 8012B and its family. I have no explanation for this, but …it is.

I hope however I've given you several ideas to repair your old style 8000-Series pulse generator. As I told you, my 8015A and 8212B are not my most beloved, but after all this work I started to love them a little, if only for having given me many hours of amusement, which are worth double when you succeed winning in the end.

To be honest, the winning idea for catching the bug was not from me…



Signal Sources

Subsection
8165A Programmable Signal Source

Among the first with a microprocessor and a Phase Locked Loop



1978

With a very attractive look, the 8165A was a “new” function generator introduced in 1978 as part of the complete renewal of the product line, and was probably one of the first in Hewlett-Packard based on PLL frequency generation.

Hate and love

The 8165A Programmable Signal Source generates sinewaves, triangles, ramps, square waves and pulses over a frequency range of 1 mHz to 50 MHz. The front panel was striking for its new style: instead of switches and knobs, it had digital displays and a keyboard. Pushbuttons and the LED parameter display enabled rapid and accurate setting of parameters, with no repeatability problems.

When you included other features, such as microprocessor control, remote programmability of all parameters and seven operating modes, you had an innovative and versatile signal source in just a single instrument that could be used in a wide range of applications and that abruptly made old all the other pulse and function generators in catalog.

This peculiar instrument that, as we will see, I hated and loved, was described in the 12/1978 HP Journal.

8165A Programmable Signal Source

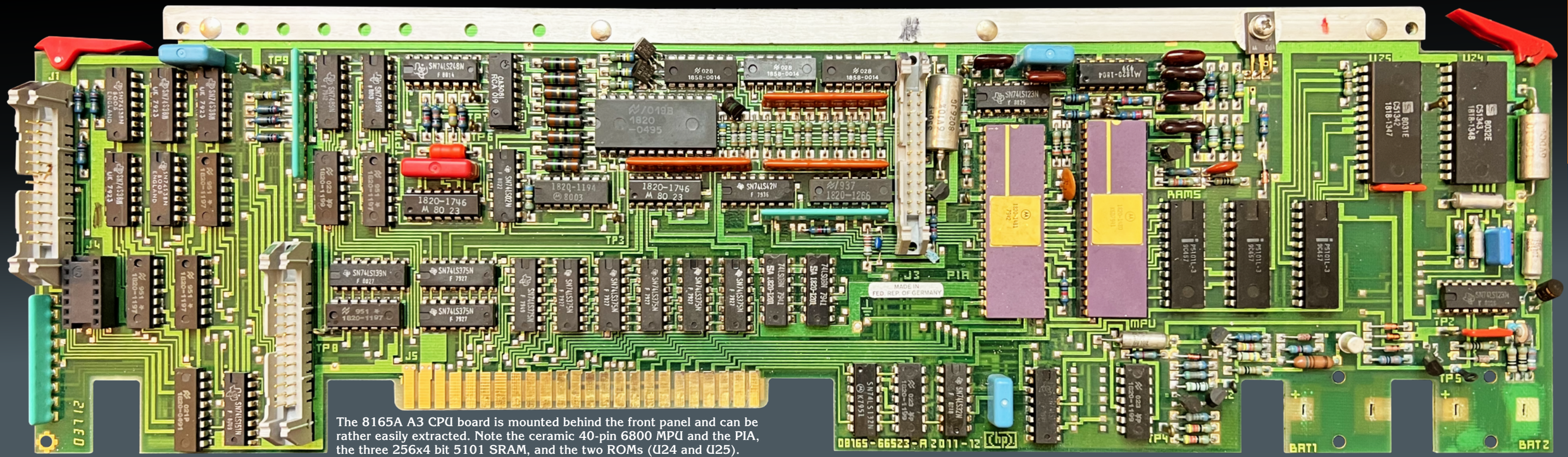
Microprocessors

Microprocessor was a relatively new word in 1978, and in Italy often we still continued to use the English term instead of the italicized *microprocessore*, to whom we were not yet used.

As I often underline, the introduction of microprocessors was **disruptive**, much more than who did not experience that period could nowadays imagine. The new user interface incredibly simplified operating and programming. Whether operating the instrument from its keyboard or from a controller via the HP-IB, the microprocessor simplified parameters and data entry. As a not secondary point, it allowed also to check for illegal operations and incompatible settings, which often trick you when using the 8015A and similar ones. The microprocessor greatly simplified front panel operation by enabling any parameter to be changed using only 3 steps: a PARAMETER key, DATA keys, and an ENTRY key (e.g., FREQ 512 kHZ or AMPL 2.3 V).

Operating set storage

Many tasks require to continuously change the instrument set-up. With the old analog instruments, that is a nightmare and the origin of many errors. Moreover, when you have to fight with knobs, maybe that you can hardly repeat exactly an identical setup. With the 8165A, you could store in the built-in memory up to 10 complete operating sets (functions and parameters). Subsequently you could recall any of the 10 sets instantaneously by pressing only two keys or using one program statement. And you didn't have to worry about losing operating sets if the 8165A was accidentally switched off or if the power failed, because internal batteries preserved the current and stored operating setups up to four weeks.



The 8165A A3 CPU board is mounted behind the front panel and can be rather easily extracted. Note the ceramic 40-pin 6800 MPU and the PIA, the three 256x4 bit 5101 SRAM, and the two ROMs (U24 and U25).

Specifications

Stability, accuracy and resolution

In addition to the microprocessor, another big novelty was the use of phase-locked loop techniques to ensure very **stable output frequencies** with an accuracy of ±1 x 10^{-5} deviation from programmed value. That means that, for example at 5 MHz (5 x 10^{6} Hz), the accuracy is 50 Hz. The previous 3310A, at 5 MHz, was in the order of 5%, i.e. 250 kHz, a true difference, while the word "stability", like for the 8015A, the 8012B etc. was …simply avoided in specifications. My 8015A, for example, drifts at least 1-2 Hz per second.

8165A's **resolution** was not exceptional: only four digits over the frequency range of 1 mHz to 50 MHz. They said that, for example, in the frequency range 1-9.999 mHz, this is equivalent to a resolution of 1 μHz, but if you think 1 MHz, the resolution is only 1 kHz, or, at 10 MHz, only 10 kHz.

Other 1979 new equipment

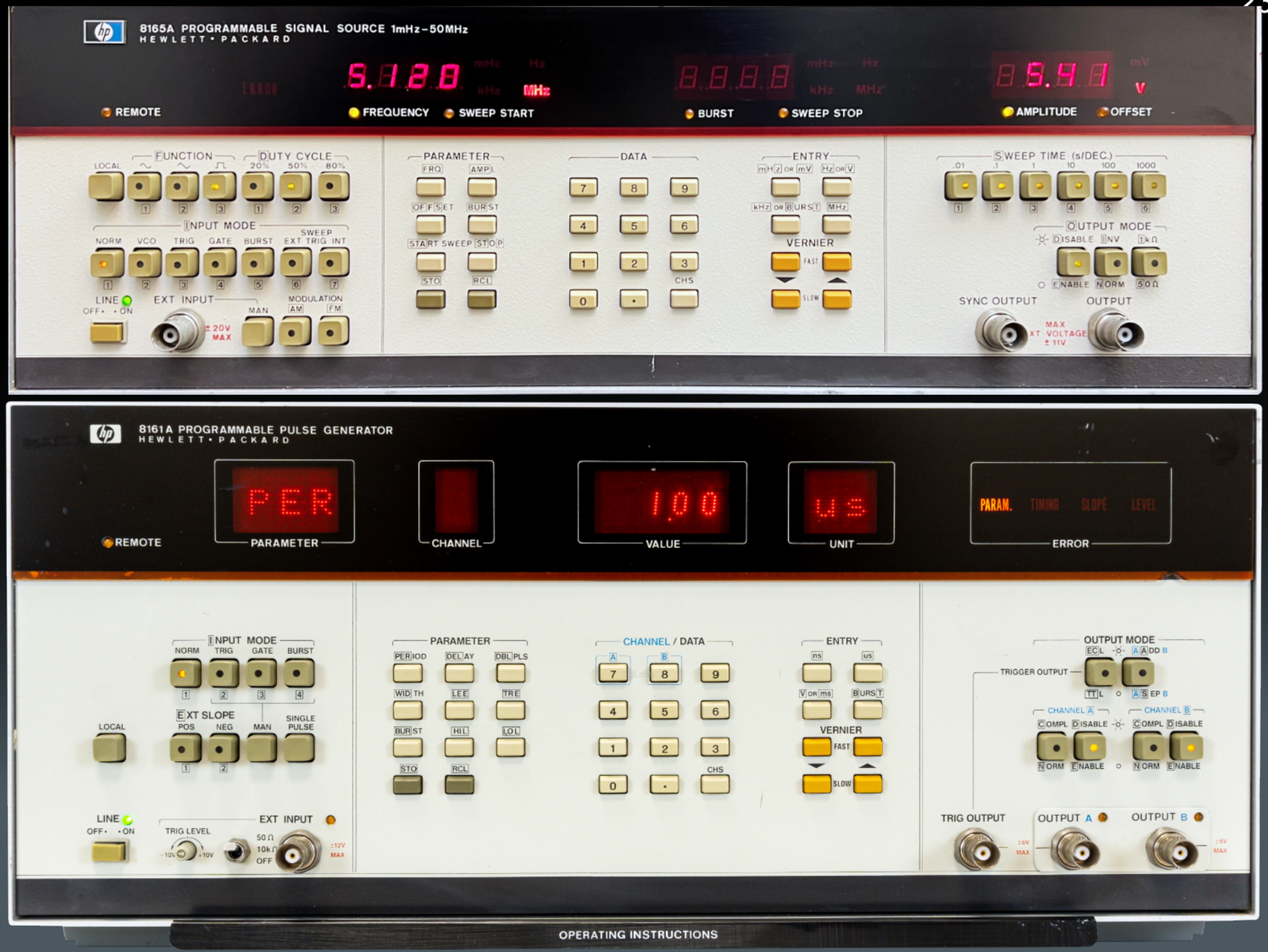
In addition to the 8165A, in1979 others very important instruments were introduced, among which:

- the amazing synthesized 3325A Function Generator, which we are going to describe in details in a next chapter;
- the "precision" 8160A Pulse Generator (the one here on the right below).

With the latter, I had a short love story prematurely ended, when I hastily read its specifications; it seemed to me that it was not a true digital instrument, but just an analog one with a digital interface. Its VCO is not phase locked and the specter of a disguised 8015A appeared to me. Furthermore, the unit I bought was completely dead; that could be better, if just one component were faulty in the power supply. But what when something tragic happened inside? So I asked the very kind seller (IRSA, see later) to pay the difference and get the 8165A instead, which is also smaller, important for me. For this reason, you are reading now the 8165A's story instead of 8160A's.

As described later in the text, the 8015A ghost, exited from the main door, reentered from the window to contribute to the damnation of my soul…

Update: after writing this, I could buy at a very low price a faulty 8160A. I could not resist the repair challenge. So expect also the 8160A in this book edition…



Multiple waveform generation

The 8165A could produce multiple waveforms: sine, triangle or square waves at frequencies up to 50 MHz (figure on the right). Nothing special for the available forms, but good the extended frequency range. In addition, a timid attempt to qualify the 8165A as a pulse generator was done, with the possibility to generate ramps and rectangular pulses with 20% or 80% duty cycle symmetry at frequencies up to 19.99 MHz (but in a not-very-precise analog way). Not a true pulse generator, but it helps.

Operating modes

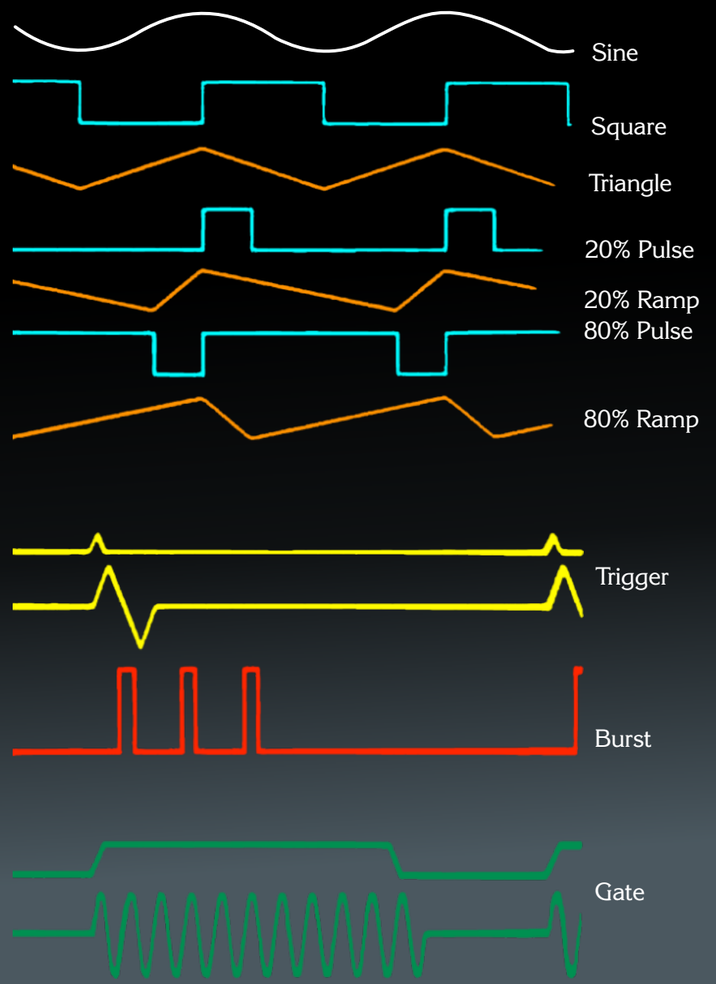
In addition to **NORMAL**, the 8165A could be operated in any of six different modes (see figure):

- **TRIG** - a positive-going edge of the pulse applied to the EXT INPUT connector initiates one complete output cycle (e.g., a single pulse);
- **GATE** - in gate mode, the leading edge of a positive pulse applied to the EXT INPUT connector initiates the output stream, and the trailing edge causes the following positive edge of the SYNC OUTPUT to terminate the stream at the next crossover;
- **VCO** - in this mode, a signal applied to the EXT INPUT connector determines the output frequency. The applied signal may change at rates up to 100 kHz. The working range of input voltage (10 mV - 10 V) sweeps the output frequency over the maximum range;
- **BURST** - up to 9,999 output cycles can be generated on each leading edge of a positive-going trigger pulse signal applied to EXT INPUT when burst mode is selected (or MANUAL button).
- **FM** - the output can be frequency modulated by applying a voltage to the rear panel MOD INP connector. The maximum deviation is ±1% of carrier frequency for which an external voltage of ±1 V is needed.

I noted only later that the 8165A adopted the same 8015A modes, also in the names, to keep the family feeling. Those accustomed to the old model were immediately at ease with the new one.

Option 002

My unit has the Option 002, which, for extra $710 (not nuts!), added sweep and AM possibility. Strange that in 1978 catalog this option was not present. Instead, there was an “Option 001 Sweep”, at $350, which disappeared in subsequent editions.



8165A waveforms. 20 and 80% duty cycles are just a little trick and cannot be set to intermediate values. Nevertheless, ample variety of forms and frequency accuracy made it a very interesting and innovative instrument.

With Option 002, Internal/External Trigger Sweep selection caused the output frequency to make one up/down sweep from the SWEEP START to the SWEEP STOP preset limits. Frequency change rate was logarithmic; sweep times were of 0.01, 0.1, 1, 10, 100, 1000 seconds per decade and could be selected on the SWEEP TIME push-buttons.

Option 002 gave you the Amplitude Modulation as well. A signal could be applied to the rear panel MOD INP connector to provide a precisely amplitude-modulated signal.

Amplitude range for the modulating signal was 0-2.5 Vpp to provide a modulation range of 0-100 %. Modulating frequency was DC to 10 KHz (-3 dB points).

Like also with the subsequent 3325A, which we are going to describe as well, all the modulations required always an external generator; not my ideal. This option was expensive, but rather limited.

Output capability

The source impedance could be set to 50 or 1 k ohm for best termination, i.e. minimum distortion and reflection in each application.

The output amplitude could be set from 10.0 mVpp to 10.0 Vpp (50Ω into 50Ω) or 2.00 Vpp to 20.0 Vpp (1 kΩ into 50Ω), with 3-digit resolution. You could also add a DC offset: 0 to ±5.00 V (50Ω into 50Ω) or 0 to ±10.0 V (1 kΩ into 50Ω), with 2- or 3-digit resolution.

The 8165A could also be used as a current source or supply a variable DC level. Use GATE mode and NORM/INV, AMPL and OFFS settings.

HP-IB programming

The use of a microprocessor made the 8165A very easy lo program across the HP-IB, and ideal in automatic test systems. All operating parameters and functions could be programmed, and, in learn mode, the 8165A could report its status and its current or stored operating sets. Programming was further simplified by the codes on the instrument front panel. The framed mnemonics are the ASCII characters required for programming. For example: "I1 F1 FRQ 1.23 MHz" sets the 8165A to normal mode (boxed “I” on the front panel), sine waveform (boxed “F”), and a frequency of 1.23 MHz.

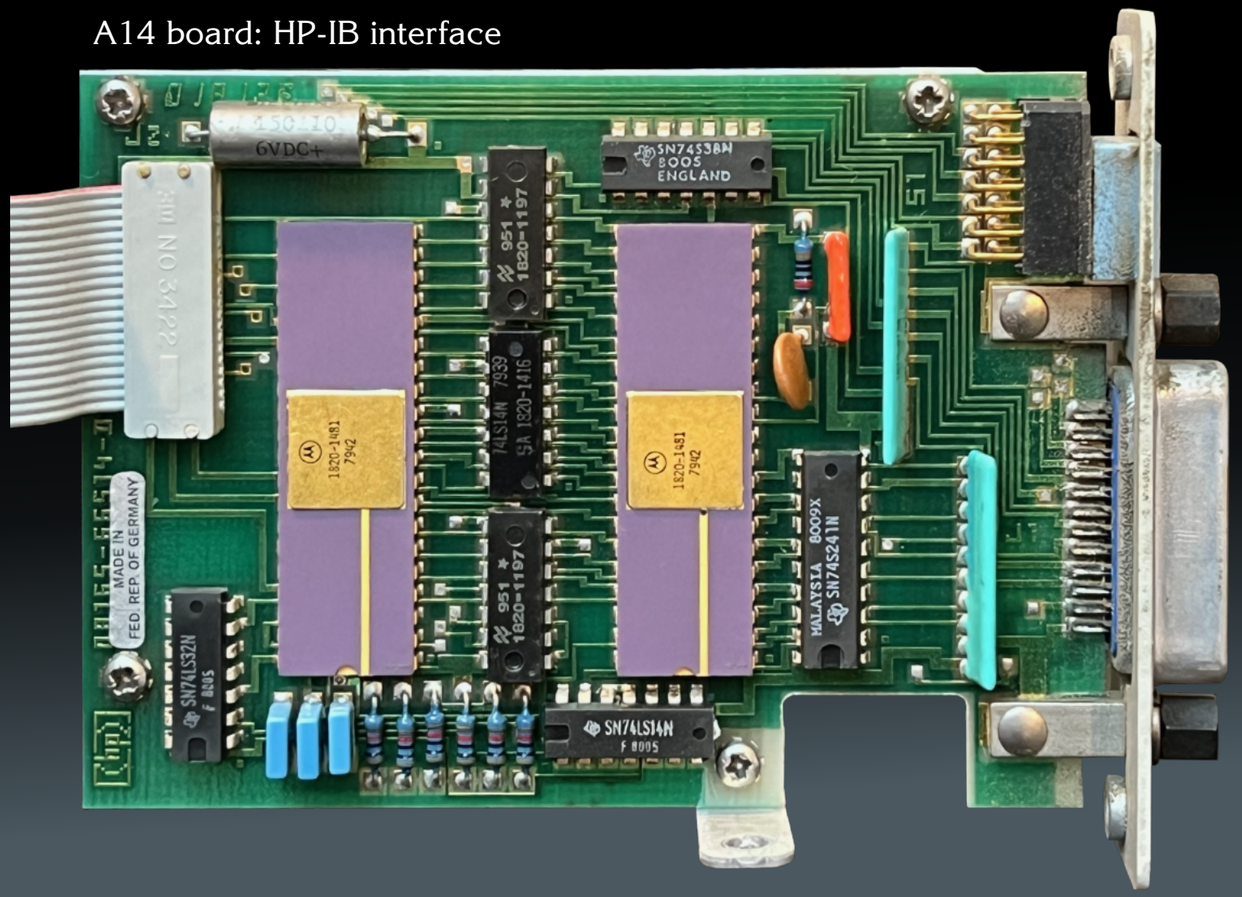
Two PIAs (MC6821, marked as 1820-1481) and some additional logic perform interfacing between the HP-IB and the 8165A, but a flat cable for the uP’s bus is not among best practices. HP-IB service is controlled by the microprocessor and the system firmware.

As talker on the HP-IB, the 8165A is able to transmit a complete set of data on request, including its current operating modes and parameter settings. Thus the system controller can learn manual settings.

Prices

The 8165A was a another luxury equipment, quoted in 1979 at $6,145, about $26,000 today, which become almost $29,000 with Option 002, a multiple of any of the old devices. Novelty and performance had a price, but the difference was like a tractor versus a pair of cattle when you had to plow a field…

A14 board: HP-IB interface



Even if today it seems part of any instruments, the possibility to be fully programmed was a disrupting innovation, for the simple reason that previous instruments’ sliders and knobs could not be moved by remote!

The Dark Ages

Not all was new

Even if substantially different, in the 8165A you can clearly recognize the same hand of those designers who had created the 8015A and the 8012B that we talked about.

Not all was good

For these reasons, affording the 8165A I started with **preconceptions**, because my experience with these generators was not so nice and, wrong or right, they mean to me:

- low reliability;
- extremely complex circuits, with a lot of transistors interacting each other.
- manuals with few explanations and waveforms, and no voltages at all. Furthermore, with some mistakes or wrong indications (…very different from Tektronix);
- often everything seems to be OK, but however it doesn't work…;
- even when it works, you are not sure that it is working as it should; etc.

In this case, my preconceptions were partly right, and I spent weeks attempting to fix this 8165A. Eventually, these HP instruments allow me not to always speak in enthusiastic terms about these ancient electronic monuments I present to you and which I am normally in love with.

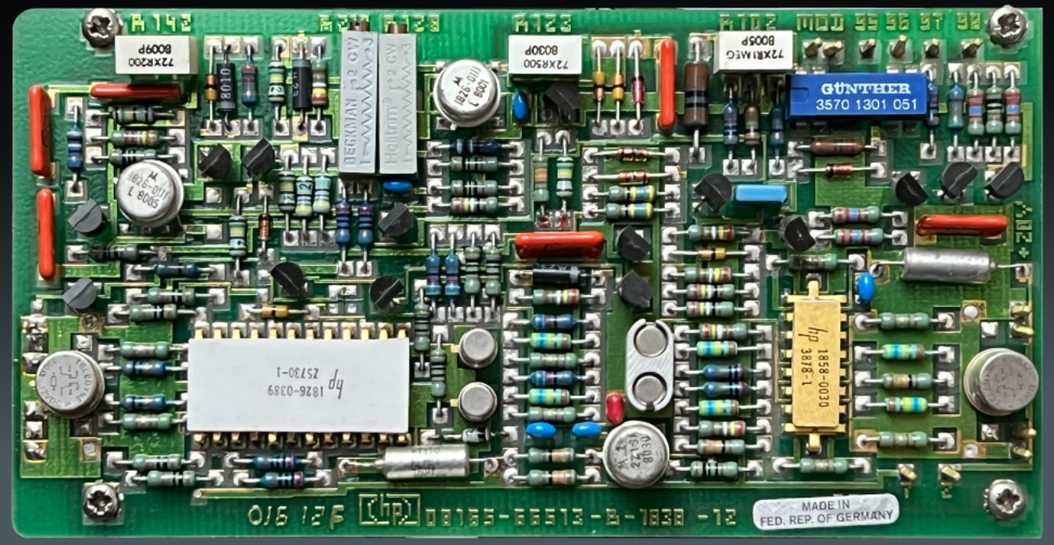
With my today's eyes, it seems to me that this breed of horses is not the best in glorious Hewlett-Packard's history, something like **Dark Ages** waiting for the 3325A etc. **Renaissance**. Yes, digital solutions begin to appear, but the effort to integrate them into an essentially analogue design is still clearly noticeable.

Reverse engineering

For these reasons, in this case of the 8165A, you will see that I went beyond the normal descriptions I report in this book, doing something more similar to a partial reverse engineering of this little monster.

The point is that repairing the 8165A was not a walk, mainly because its documentation is definitely insufficient. If I wanted to fix it, I had to fully understand how it was intended to work, and thus, substantially, to reverse engineer it.

Wishing to see the positive side of this situation, these instruments, and I include in the class also the 8015A and the 8012B, taught me a lot about transistor-based circuits, and ensured me very many hours of amusement…



A13 Board: Amplitude Modulation (Option 002)

Design Philosophy

More than ten decades

Some challenging engineering problems had to be solved to make the 8165A a reality. One major problem was that, with a frequency range of more than **ten decades**, amplifier circuits had to be designed without ALC loops, to keep the settling time short. This required exceptional gain and DC stability in all circuits. Also, high-speed amplifiers were mandatory to achieve output signals with transition times faster than 5 ns.

Switching to a switchless design

Another problem that the designers had to solve stems from the fundamental difference between conventional and fully programmable instruments. In bench instruments, dial settings are stored by the dials, the switches, and pushbuttons themselves, and can be checked and changed even when switched off. To provide a similar feature in a fully programmable instrument, the settings must be stored and rechecked automatically without enabling the output. So that power interrupt does not mean that the instrument must be reprogrammed, a **non-volatile memory** for the operating parameters had to be included.

Verniers again

I found an interesting statement in the HP Journal article: *"an added advantage of the 8165A is that no measuring instruments are necessary to verify the microprocessor-controlled parameters"*. This confirms what I suspected and wrote talking about the 8015A: the previous generation's HP generators could not be used without a pairing oscilloscope, having the old verniers of the good old times been replaced by simple knobs, to reduce costs. So, in some way, digital control allowed again to set the instruments without having to check their output separately.

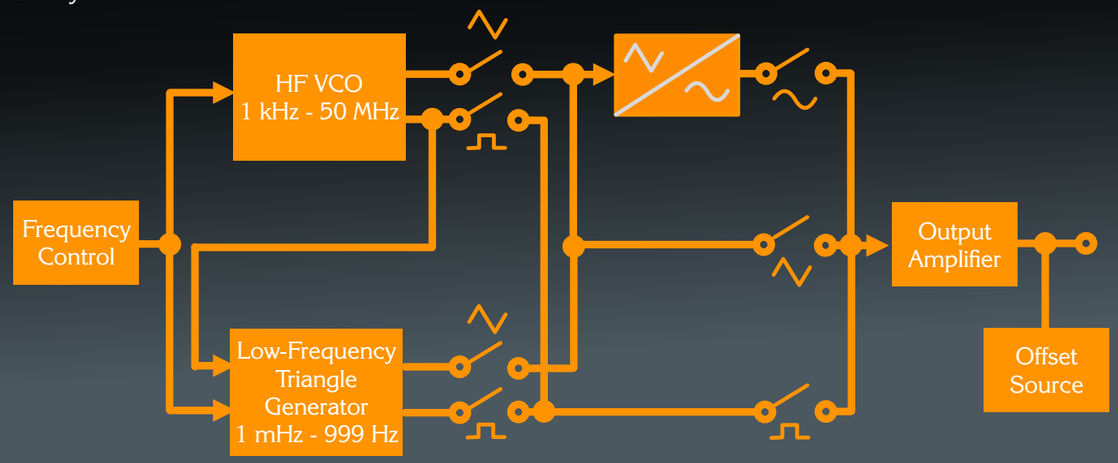
In addition, the possibility to quickly switch from one setup to another is in many cases priceless. With the old approach, you had every time to move again all those hand controls.

Block diagram

To meet these and other requirements the design concept is as shown in the block diagram, Fig. 3.

A 1-kHz-to-50-MHz oscillator (HF VCO in Fig. 3) generates a triangle output that may be used directly or fed to a sine shaper. The square wave is derived from the HF VCO's current switch drive voltage. Changing from triangle to ramp form, and consequently changing the square wave duty cycle, is achieved by varying the charge and discharge rates of the HF VCO's ramp capacitor. Duty cycles and ramp symmetries of 20%. 50%, and 80% are available. For high stability in continuous operation, the HF VCO can be phase-locked to an internal or external 10-MHz frequency reference.

Signals below 1 kHz are generated by a low-frequency generator (LFG). Simplified, it consists of an up-down counter (to divide the frequency) followed by a digital-to-analog converter (to synthesize a triangle). The counter is clocked by the HF VCO at a frequency 10,000 times higher than the output frequency of the D/A converter. This allows the HF VCO to run continuously in the phase-lock mode even when a triggered low-frequency signal is required. Consequently, the basic crystal accuracy and stability of the output are preserved in all operating modes, and also phase noise should be lower in this way.



8165A general scheme (redrawn from HP Journal). There are almost two instrument in one: the former for high frequency (1 kHz to 50 MHz) and one below 1 kHz. The second is fully digital and thus much more accurate and precise, also for waveforms quality.

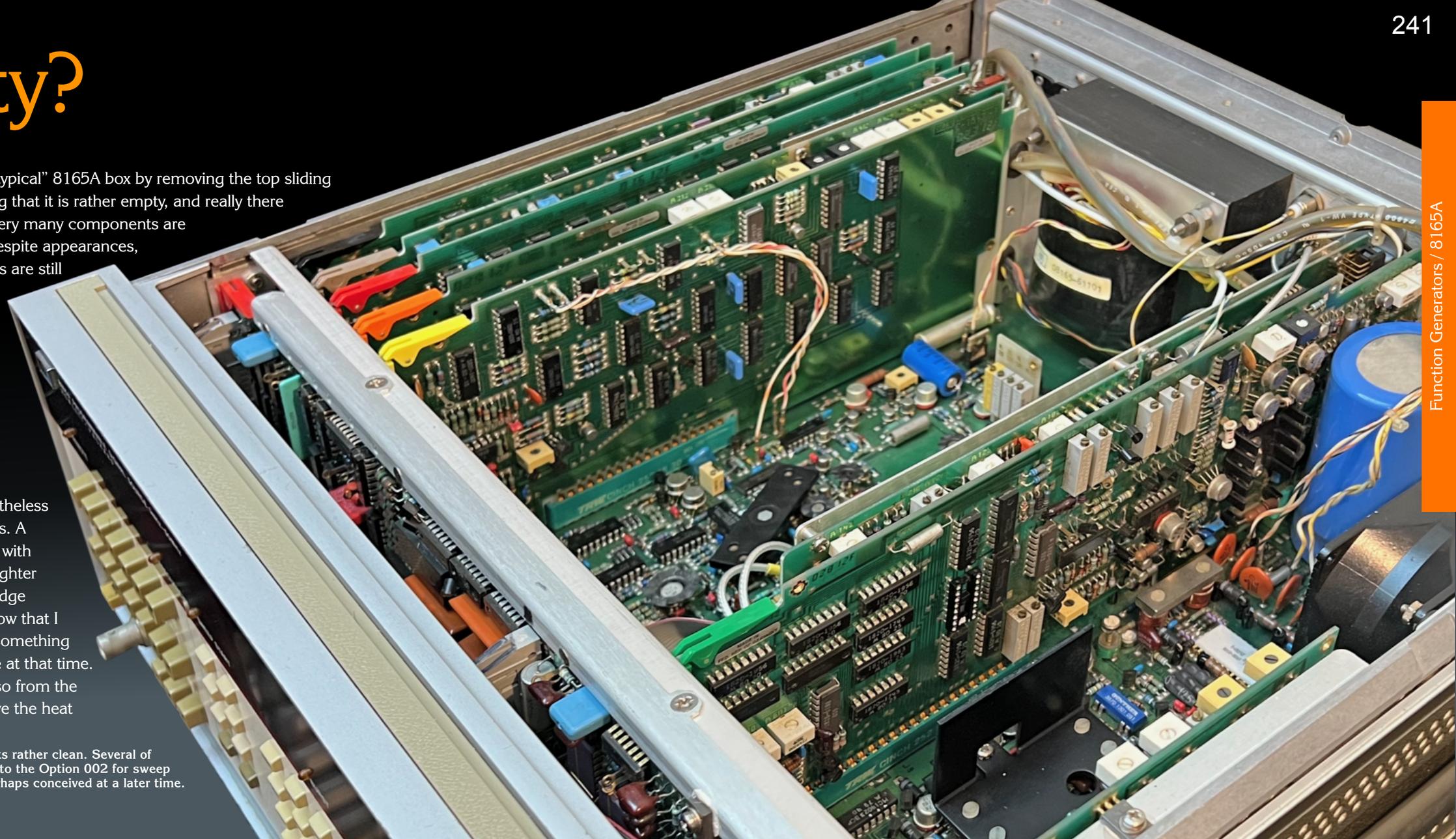
Empty?

Complex circuits

When you open the “HP-typical” 8165A box by removing the top sliding cover, you have the feeling that it is rather empty, and really there is much free space, but very many components are however packed there. Despite appearances, a lot of discrete transistors are still used in rather complex configurations, which, as noted, often nearly resemble the 8015A generation, and they will drive you crazy when you need to repair this beast.

Modular construction

The construction is nevertheless more rational than it looks. A large active motherboard with fixed position vertical daughter boards with gold plated edge connectors. I note only now that I also unawares designed something with a similar architecture at that time. Good the accessibility, also from the bottom side. Not excessive the heat dissipation.



The 8165A’s interior view looks rather clean. Several of the wires you can see are due to the Option 002 for sweep and amplitude modulation, perhaps conceived at a later time.

Frequency Generation

Curiosity

Dealing with a new (for me) instrument, I was obviously curious about its frequency generation scheme, even more after the 3325A experience, which is described later to respect the chronological order among the function generators, but which I restored first.

After having said so much badly about this instrument, I must admit that I was instead amazed by the new digital parts, still, yes, a little primitive, but certainly designed by a new generation of technicians.

The 8165A was probably **one of the first HP** instruments entirely based on a **Phase Locked Loop** (the 3300A had a PLL plug-in, but was an accessory of an analog instrument, and even the amazing 1972 8640B could be locked is some way). The 8165A PLL was conceptually standard, but with several peculiarities, or at least, the 8165A uses solutions that I didn't know before. For example, it has not just one but three cooperating PLLs, and different ways to generate low frequencies (1 mHz to 1 kHz) or high frequencies (1 kHz to 50 MHz). Another thing that struck me is that triangle waves were generated and then shaped into sines (this depends also on the kind of VCO used).

For these reasons, we will dedicate an ample space to the 8165A frequency generation description, which I found very interesting also in general, and which helped me in a better understanding of HP function generators' evolution, so much that I felt the need to modify partly what I had written before.

Frequency Generation 1 kHz to 50 MHz

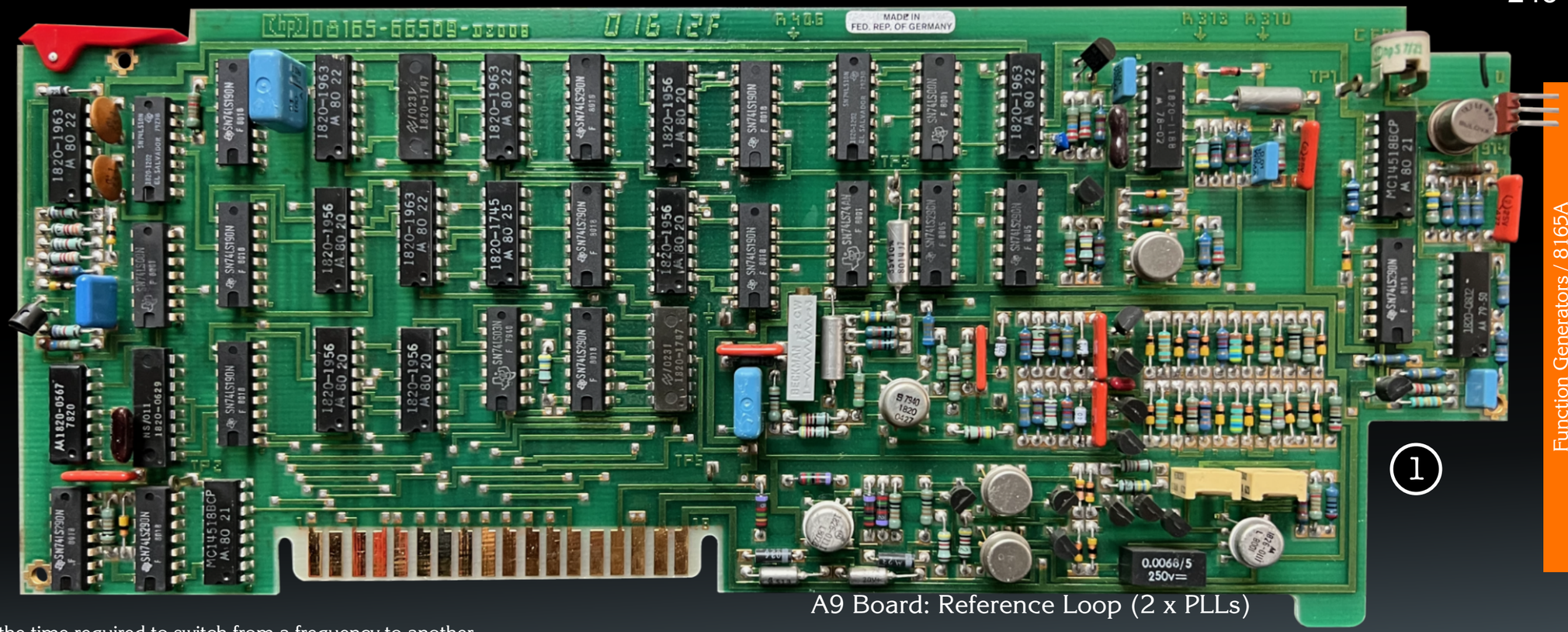
Frequencies between 1 kHz and 50 MHz are generated by using three PLLs controlling the main VCO, as we are going to explain. By itself, this VCO produces square and triangle waves, the latter subsequently transformed to sine.



Each board is identified by a color, so that it is less possible to mismatch them. The ideal should be to have extension boards, but with some tricks you can work however even without them.

Basic Phase-Locked Loop

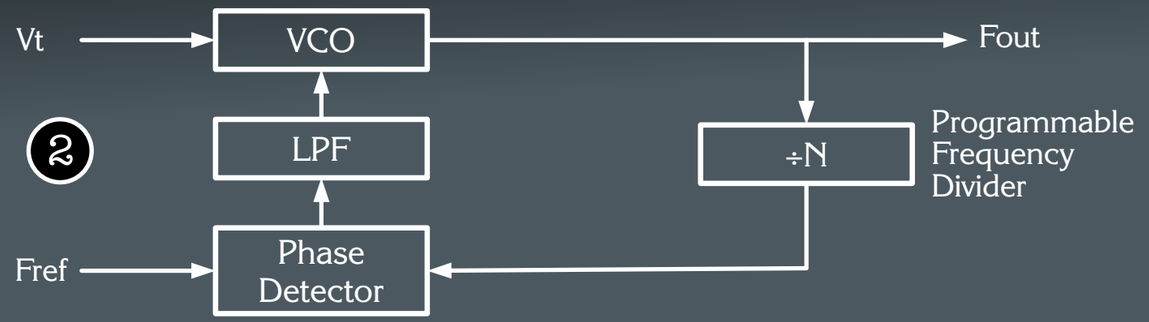
Phase-Locked Loop (PLL) method of indirect frequency synthesis has the advantage of transferring the accuracy and stability of a crystal source to the variable-frequency output. In a basic PLL frequency synthesizer (figure ❶ on the previous page), a Voltage-Controlled Oscillator (VCO) is tuned roughly to the required frequency by a tuning voltage. The output signal is compared with a stable reference frequency, and any phase difference appears as a voltage at the output of the phase detector. This signal is smoothed and applied to the VCO to correct the output frequency. Variable frequencies are generated by inserting a programmable ÷N divider between the VCO output and the phase detector.



A9 Board: Reference Loop (2 x PLLs)

Settling time

A PLL parameter that I did not consider too much before is the **settling time**, i.e., the time required to switch from a frequency to another, but, conversely, it seems it was a major concern for the 8165A's designers, as we are going to see. Certainly, it is important for the frequency modulation; I thought also for the sweep function, but in sweep mode the PLL is disabled at all frequencies. I could suppose that high ÷N values make the settling time worse, because every time you change the frequency you have to wait at least N pulses before any action is taken. I would like to know, if this multi-PLL architecture could also reduce the phase noise, not negligible in Integer-N PLLs.



❶ The 8165A A9 Board contains two PLLs and many parts of the main PLL loop, like the programmable frequency divider. ❷ The basic and traditional Phase Locked Loop scheme; Nowadays present everywhere, PLL was a novelty in 1978, thanks to the arrival of logic IC families.

Multiple loops

HP Journal 12/1978 describes the 8165A and gives us much interesting information about it. The 8165A uses two other loops in addition to the main reference loop for a total of three (figure ❷ on the facing page). The article explains that this reduces settling time by keeping the division factor smaller and loop reference frequencies higher, and that these extra loops effectively provide the ÷N function.

The output frequency, f_{out}, is divided by a factor **R** so that the main reference loop **operates only in the frequency range 1-10 kHz**; this also contributes to short settling times.

The divide-by-R counter output is applied to a **Ramp Generator** (RG) and a **Sine Shaper** (SS) to provide a sine wave that is mixed with the output of the first loop. The RG follow the pattern that seems so dear to HP designers, with a capacitor charged and discharged by constant currents. Only one capacitor is used and the front panel frequency setting modifies both currents at the same time.

The Journal says that using a sine wave instead of a square wave or ramp helps to keep small spurious products of the mixer, which might cause low-frequency jitter. This made the circuit sensibly more complicated, but I didn't understand why the other input to the mixer (from Loop1) is however a simple square wave.

The difference frequency is filtered from the mixer output and compared with the second loop's frequency. If f_{out} is accurate and the phase detector output is zero, then

- $f_1 - f_t = f_2$

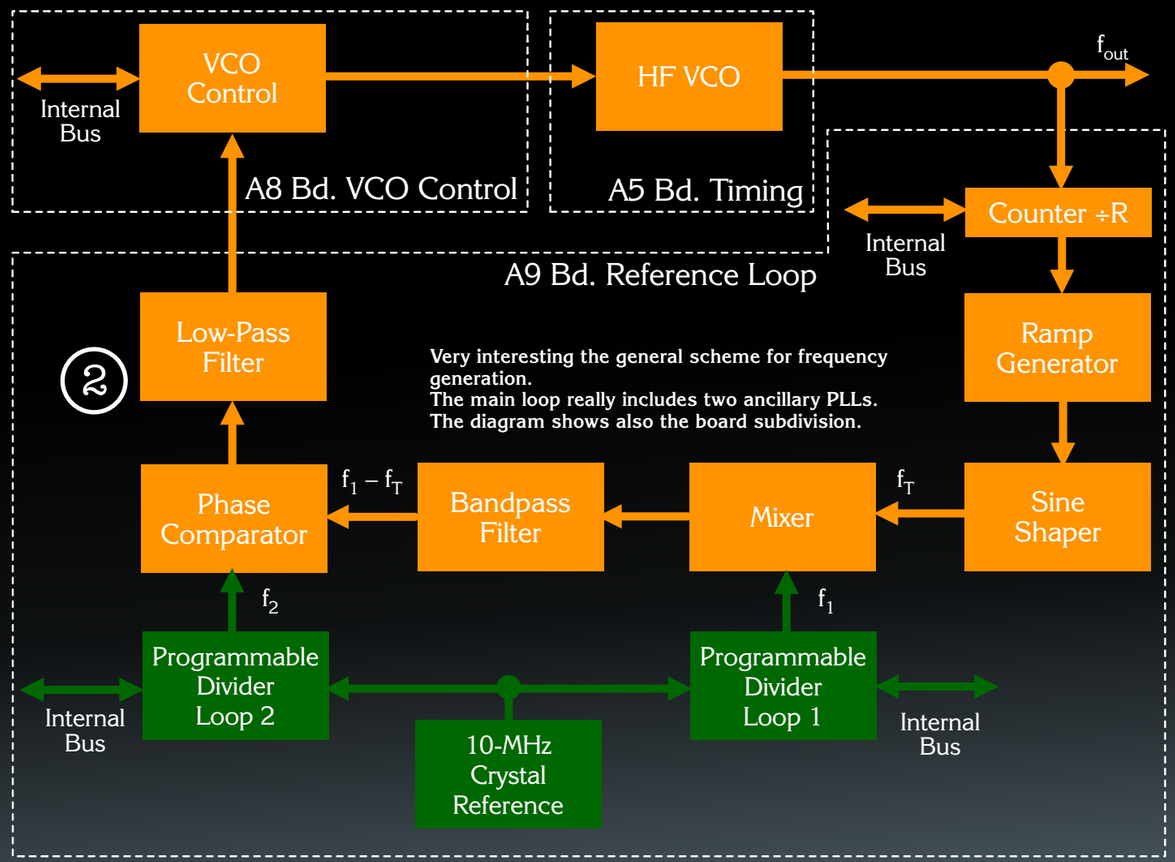
and hence

- $f_{out} = R \times f_t = R \times (f_1 - f_t)$

This means narrow tuning ranges for f_2 (900-801 Hz) and f_1 (1.9-10.8 kHz). At frequencies above 1 kHz, the PLL is disabled in GATE, TRIGGER, and BURST modes (so VCO's frequency calibration is important to have precise single pulses, but they are likely to be not very precise). In NORMAL mode above 1 kHz, the PLL is enabled and the control voltage to the main VCO is modified by the modulating signal so that the deviation is constant as a percentage of the output frequency.

Further explanations

I found these explanations not totally clear, so I studied also the Service Manual, which adds some bits of information that make things more understandable.



We have **three** PLLs: the main loop takes care of the **band** where the required frequency lies, i.e., exponent of the frequency, by mean of the **Counter ÷N** programmable divider.

The **other two** PLLs, take care of the 4-digit **mantissa**:

- f_1 is set to the **first two frequency digits** plus 0.9 kHz;
- f_2 is set to 900 Hz minus **last two frequency digits**.

Each of the two auxiliary loops are in duty to ensure their required frequencies, while the main loop ensures the final phase correctness (and thus stability) of the frequency resulting from the various mixings. The final phase comparison is performed by the CD4046 IC U201 with the Loop2 output

frequency f_2 and not directly with the reference oscillator; this doesn't seem wonderful to me, because in this way we add the unavoidable Loop2 phase noise to the output frequency.

As an example, suppose that an output frequency of 1.234 kHz is required, then:

- f_1 = 1.2 + 0.9 = 2.1 kHz
- f_2 = 900 - 34 = 866 Hz

Hence, f_1-f_2 =2.1 kHz - 866 Hz =1.234 kHz.

Remembering that

- $f_{out} = R \times f_t = R \times (f_1 - f_t)$

we have that R=1 and the output frequency is 1.234 kHz as required.



A8 Board: VCO Control

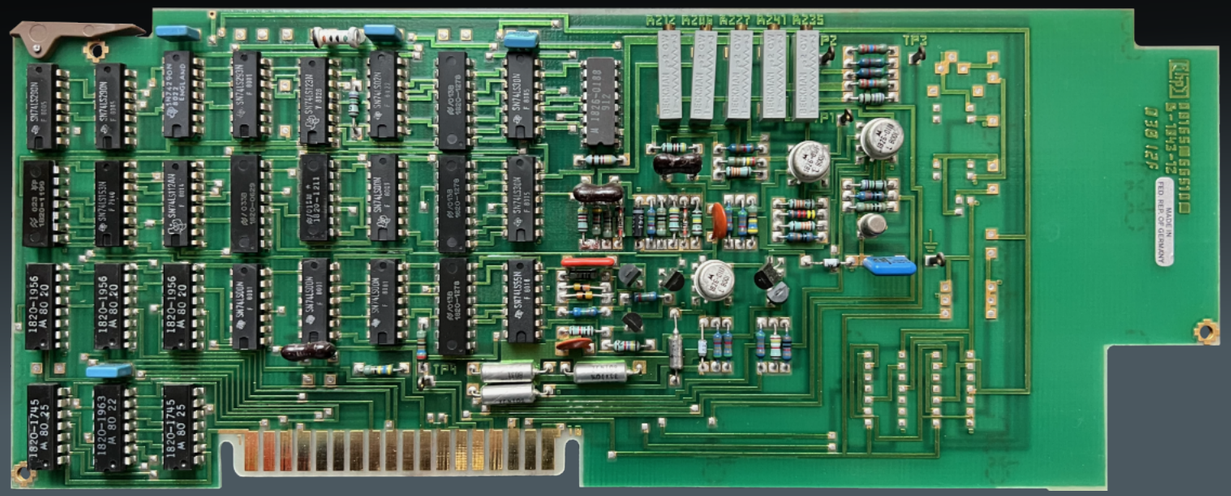
Frequency Generation below 1 kHz

Frequencies below 1 kHz are obtained by a very genial idea: by creating a triangle wave using a 9-bit up-down counter, directly connected to a 9-bit D/A converter. The VCO clocks the up/down counter whose count direction is determined by a flip-flop. At counter states of 0 and 500, the flip-flop changes its status and reverses the count direction. The 9-bit DAC output is obviously a perfect triangular wave, while the count direction bit is a perfect square wave. Note that the DAC chip is really an 8-bit 1408; the ninth bit is added using an opamp, similarly to the VCO control where even two bits have been added (see below).

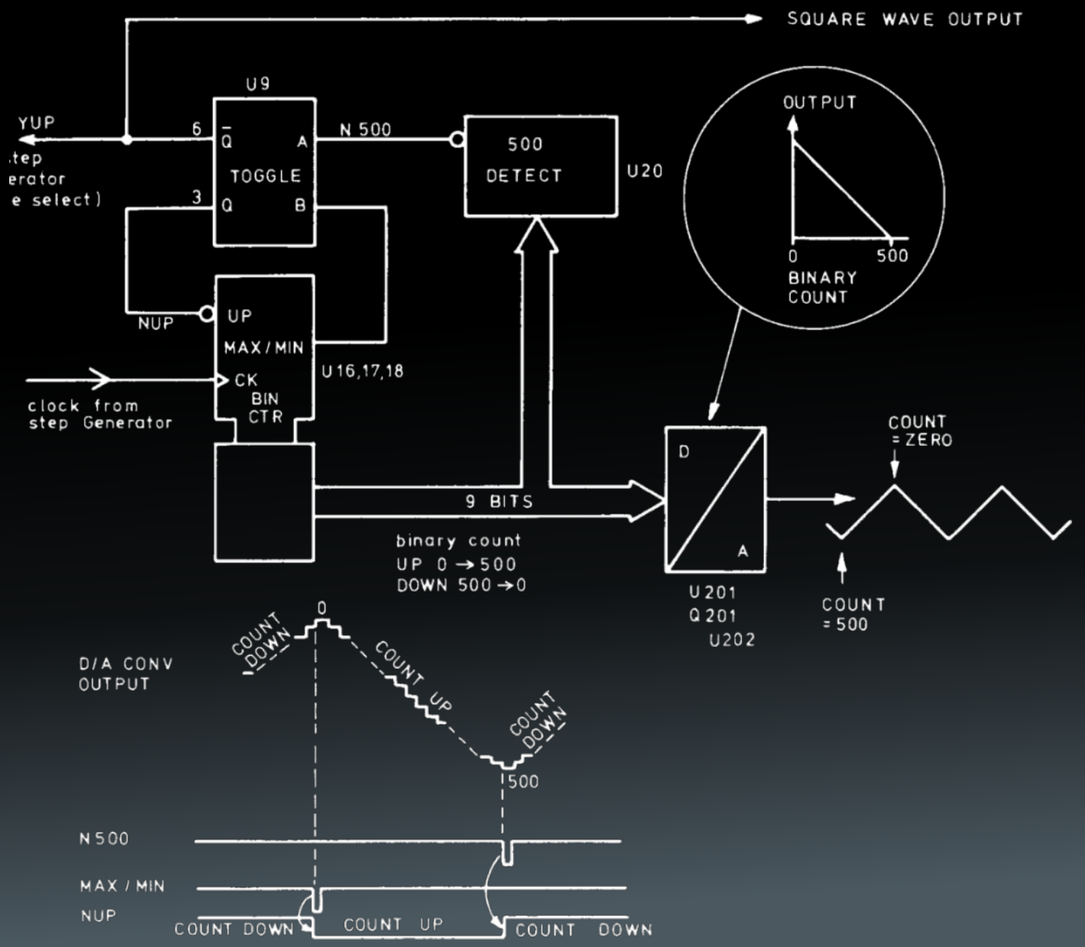
In the low-frequency range from 1 mHz to 999.9 Hz the 8165A's phase-locked HF VCO runs at frequencies 10^4 to 10^6 times higher than the output of the low-frequency generator. This guarantees high accuracy in the low-frequency output, much greater of any analog way (think that 1 mHz correspond to 1,000 seconds period).

Other features are provide to supply also 20 and 80% duty cycle output.

Should it be great to use the same method ever (LF and HF)? Certainly yes, but it would have led to very high frequencies for the VCO and very fast DAC converters. It was not yet the time for that.



A10 Board: Low Frequency Generation



The LF ramp generation scheme. Being completely digital, it is obviously extremely precise, at least for the triangle generation.

Current Sources

Used everywhere

Constant-current sources are used everywhere in 8165A, like in previous 8015A, 8012B; you can go back to them for their description. In the 8165A, new forms of constant-current sources are used, and thus we need to add some information before going on with the 8165A VCO.

Then is not today

Someone writes today: *"…constant-current sources figure prominently in circuit-analysis exercises and network theorems, then they seem to more or less disappear . . . unless you're an IC designer. Though rarely encountered in typical PCB design, current sources are ubiquitous in the world of analog ICs. This is because they are used 1) for biasing and 2) as active loads…"* (Robert Keim, All About Circuits).

I would add *"…or unless you are a time-waster lover of vintage equipment…"* to the above statement…

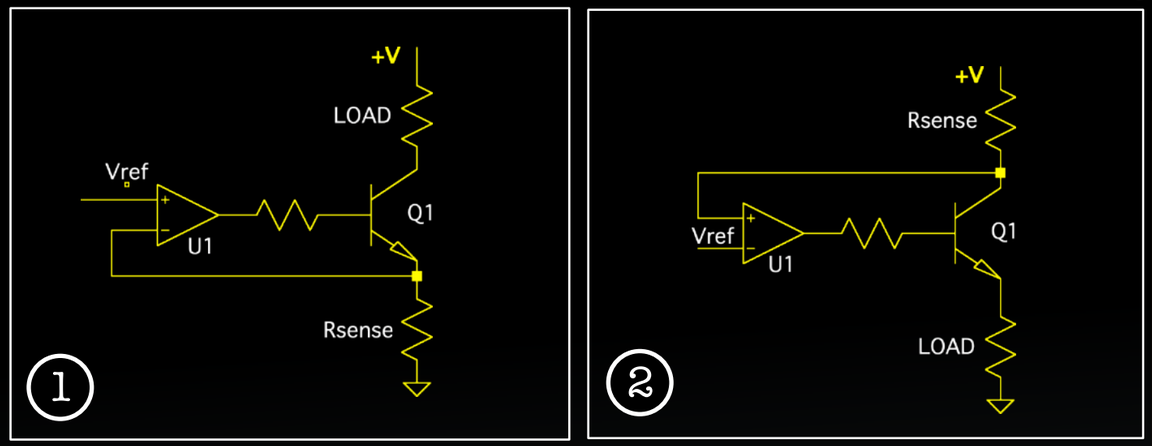
Opamp current sources

I suppose that the new availability for operational amplifier ICs excited HP designer who could with them build-up better current sources. We are going to see two basic schemes, frequently used in the 8165A.

Opamp negative constant-current sources

The circuit in figure (1) maintains a current through a floating load LOAD (i.e., neither end is connected to ground), with current origin from a negative or ground potential toward a positive power supply. The key to the circuit's operation is in placing a current sensing resistor Rsense in the op amp feedback loop. The current delivered to the load RL is

- I = Vin / Rsense



How does the circuit work? Three simple functions help this circuit accomplish its goal (remember, no current flows into the op amp's input terminals). The opamp automatically adjusts its output (Q1's base drive) to bring its negative input equal to the positive input. This means that Vsense = Vin. A simple application of Ohms law now tells you the current in Rsense: I = VRsense / Rsense

Q1 delivers the current, and because Q1's currents are related by Ic ~ Ie, the same current that is developed through Rsense must also flow through LOAD. (http://www.ecircuitcenter.com/Circuits/curr_src1/curr_src1.htm).

Opamp positive constant-current sources

The circuit in figure (2) is similar, but it maintains a current through a floating load RL (i.e., neither end is connected to ground), with current origin from a positive or ground potential toward a negative power supply. Don't be surprised, as I was, because the feedback goes to opamp + input: it is not a positive feedback, because the transistor invert the sense of the reaction.

❶ Negative constant-current source.
❷ Positive constant-current source.

Voltage Controlled Oscillators

Three VCOs implementations

We learnt that the 8165A doesn't have just one VCO, but three. As stated, two of them are named **Loop1** and **Loop2**, and we will call the third **HF VCO**. We already tried to describe their outer working and their relationships. Let's now pass to examine their implementation, starting with the 1 and 2 loops, much easier than the HF.

Really, the two additional loops run at:

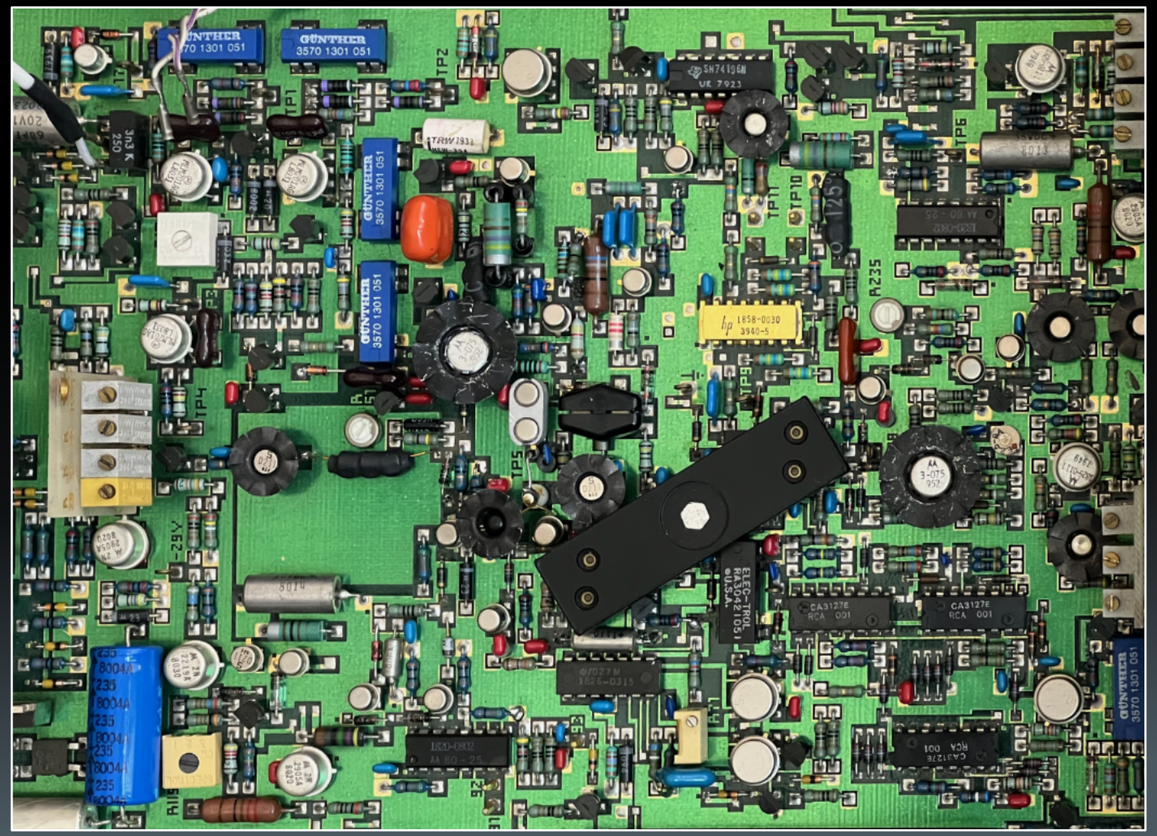
- **Loop1**: 95-540 kHz, then divided down to 900-801 Hz;
- **Loop2**: 8.01-9 MHz, then divided down to 19-10.8 kHz.

It is interesting to take a look to the schematic diagram (sheet 5A), to see that **Loop2** is implemented by using a normal 4046 CMOS integrated PLL (A9U208), both for the phase comparator and the VCO. For **Loop1**, the 4046's frequency limit made it not suitable, so a 4024 VCO CMOS chip (A9U708) was used, together with a normal dual flip-flop (A9U707) as a phase comparator.

HF VCO

The HF VCO is much more complex indeed, because probably, at the time, when the 4046 was still a novelty, no integrated solution was available capable to reach 50 MHz, and the CD4046 was used only as phase comparator. This VCO is based on the constant current capacitor charge/discharge. I hope I can describe it rather well, because I had to study it deeply trying to fix it.

A5 Board: VCO and Sine Shaping

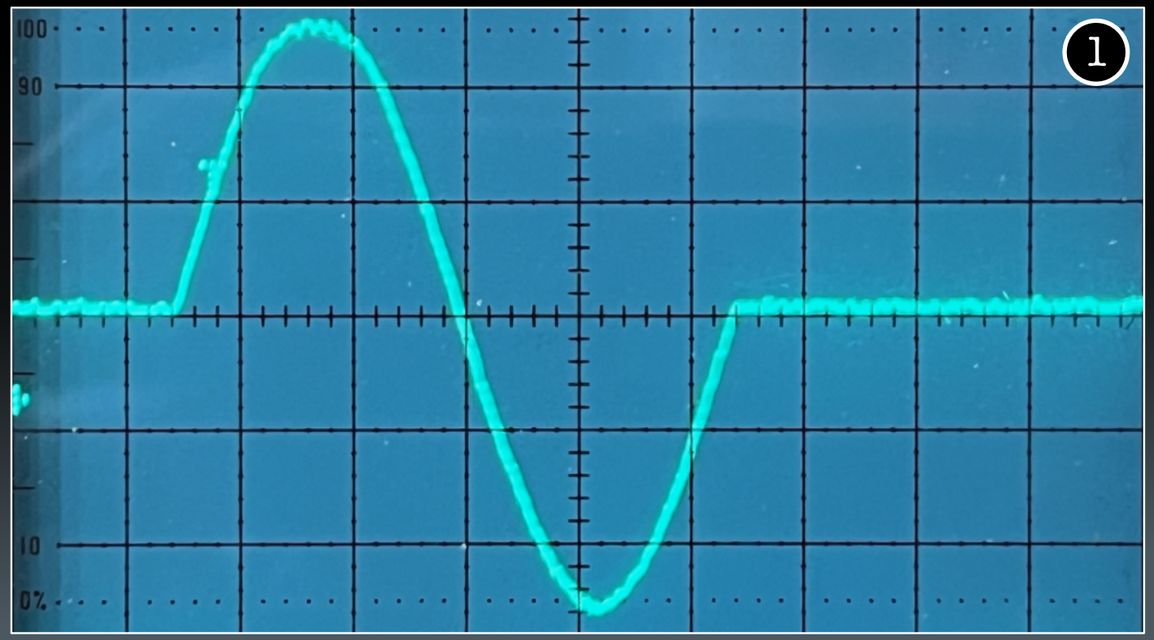


The VCO is entirely contained in the A5 board, together with sine generation and other circuits. The A5 Board is the motherboard, where most of the other boards are inserted. Here in this photo, you can see only the effective A5 circuits area.

Why this solution?

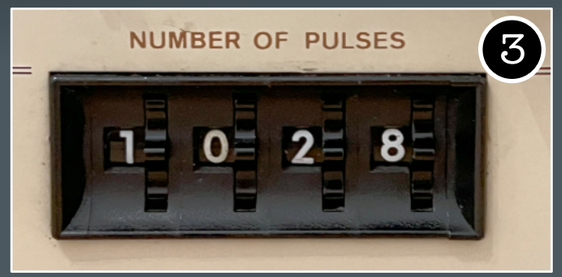
Probably I was right thinking that there was a better way to build-up a VCO, but in this case the choice of the ramp generator also had a different origin. In fact, in the 8165A we have, not only the NORMAL mode, where a continuous wave is produced, but also other modes, like TRIG and BURST, in which you need to produce, for example, exactly 6 pulses, as shown here in these photos. With this kind of ramp-based oscillator, that is relatively easy, much easier, for example, than with a normal free-running oscillator, but the accuracy is not controlled by PLL and completely relies on VCO calibration and stability, as we already noted.

Below 1 KHz, as we saw, signal generation is completely different. In this range, the output is generated digitally by mean of a DAC, and the VCO is made to run continuously at a frequency 10-times higher, and PLL stabilized.



❶ TRIG mode single pulse generation. ❷ BURST mode (Option 002) 6-pulse generation. Both of them are very interesting, but require an external source to start, or to press the MANUAL button (no generator is provided to start automatically), exactly like the 8015A, even when with the burst option). ❸ 8015A's number of pulses hardware setting switch. ❹ 8165A's number of pulses setting is performed in software.







Generating Ramps: an Overview

The 8165A's HF VCO is clearly an evolution of the 8015A's and generates a triangular voltage in the range 1 kHz to 50 MHz by **charging and discharging a capacitor at a constant rate** (❶).

This is done using a **switchable** positive current source, **Ix** (named **2 I_0** in the manual), and a smaller negative current source, **Iy** (named **I_0** in the manual). When the positive current source is on, the capacitor charges with Ix-Iy current. When the positive current source is off, the capacitor discharges with Iy current. We underlined "switchable", because, as we are going to see better next, the positive current is not switched off to discharge the capacitor, but in reality diverted on a different rail (green in the picture). As a consequence, the negative Iy current is almost constant. Both current generators are driven synchronously by another current generator to set the oscillator frequency.

The positive source is switched by a pair of transistors (U7A and U7B) controlled by a Schmitt trigger driven from the ramp voltage itself. Frequency is determined by the time taken for the ramp voltage to reach the Schmitt trigger thresholds. Consequently, it is dependent on the ramp **capacitor value** and the **charge** and **discharge currents**. All of them (capacitors and currents) are varied according to the desired frequency range and the selected output frequency. As it is intuitive, **trigger's thresholds** must be very precise, because the oscillation frequency depends much on them. If you have to trip higher, more time is required and signal's period increases.

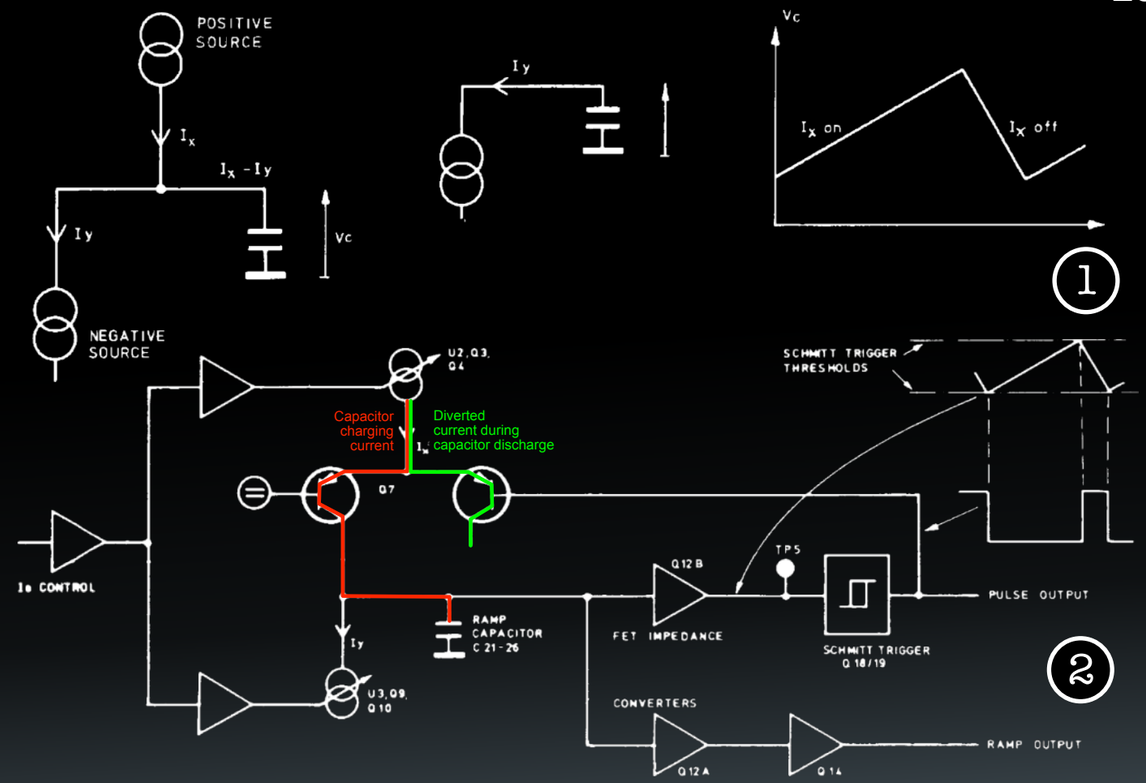
Signal symmetry depends on the ratio of charging current (Ix-Iy) to discharging current (Iy). In the range 1 kHz to 19.99 MHz, the symmetry is selectable (20%, 50%, 80%). At 20 MHz and above it is fixed at 50%. This means that the duty cycle variation is not performed digitally but with current ratios; in other words not very precise, even less after 45 years…

In figure ❷, you can see a principle schematic of the ramp generator, with its capacitor (C21…C26) and its current adjustable sources (U2, Q3 and Q4 for Ix and U3, Q9 and Q10 for Iy). Q7 is used to switch Ix on and off, on trigger's command (Q18 and Q19).

Beware TP5!

TP5 is a good place to watch what is really happening, if you are curious or, like in my case, you need it, **but only at low frequencies**. Despite the FET decoupling stage, at frequencies of some MHz, even a good 10-Mohm oscilloscope probe alters completely circuit behavior.

❶ Ramp generation principles. From the left: The positive current prevails and the capacitor charges. The positive current is removed and the capacitor discharges. ❷ A better representation of the real 8165A circuit.



Covering the Full Range

The full frequency coverage is ensured by mean of four ranges with different size capacitors:

- band a: 1 - 9.999 kHz;
- band b: 10 - 99.99 kHz;
- band c: 100 - 999.9 kHz;
- band d: 1,000 kHz - 50 MHz.

Like in the 8015A, the fastest band is very wide, and, without the PLL, it would be very difficult to keep its stability. Furthermore, we can expect that the phase noise (jitter) in the high band can be rather high.

Looking closer at the Circuit

Did they pay for transistors?

After having showed VCO's big picture, let's now take a closer look at 8165A's schematic diagrams. Initially, you might be confused by them, and suspect that HP didn't pay for transistors… only in schematic sheet 2B, one of the two composing A5 Board, I could roughly count more than 50 of them. Thus, decoding the circuit behavior is not always so easy for unexperienced guys like me…

Yes I am not completely unexperienced, but, technically, I was born later, and used very few transistors in my projects, typically for the digital real-world interfaces only, not enough to decode this semiconductor-Kamasutra, and I forgot many years ago what I studied at university. But when I succeed understanding these intricate tangles, I don't know why, I feel gratified.

My analyst says that human medicine is still helpless against this kind of diseases…

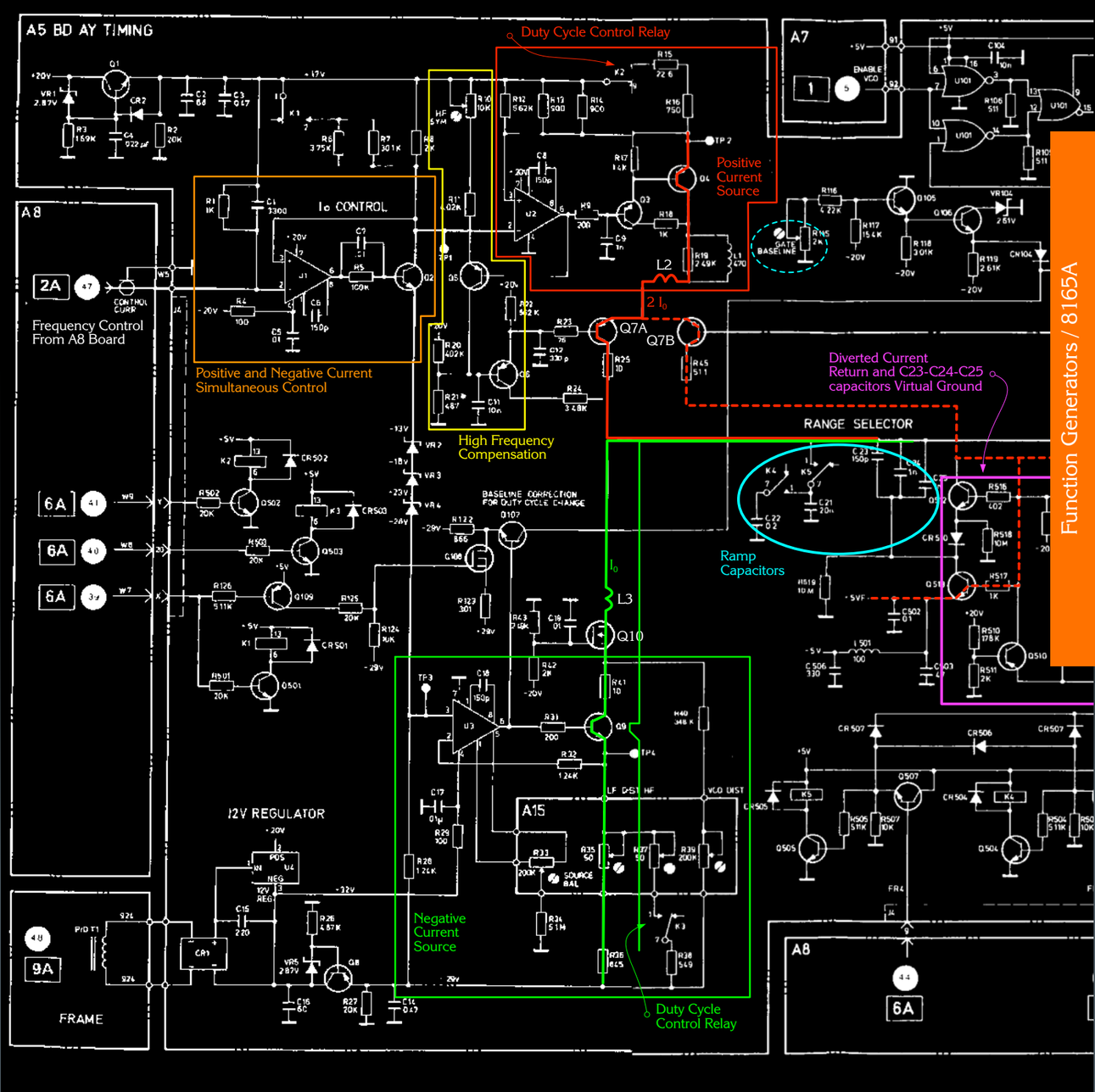
Ramp Capacitors

Before seeing the currents, let's identify "what" we are going to charge with them, i.e., the ramp capacitors (in cyan on the schematic diagram). At maximum speed (band a), only C26 is used. Then C23, C24 and C25, wired in parallel, are added by mean of a special static switch (band b), while the larger C21 and C22 are added simply by mean of two relays (band c and d).

Currents Control

In light of what we have already seen about current sources (see above and 8012B), you can identify three opamp-based current sources in the schematic diagram on the facing page:

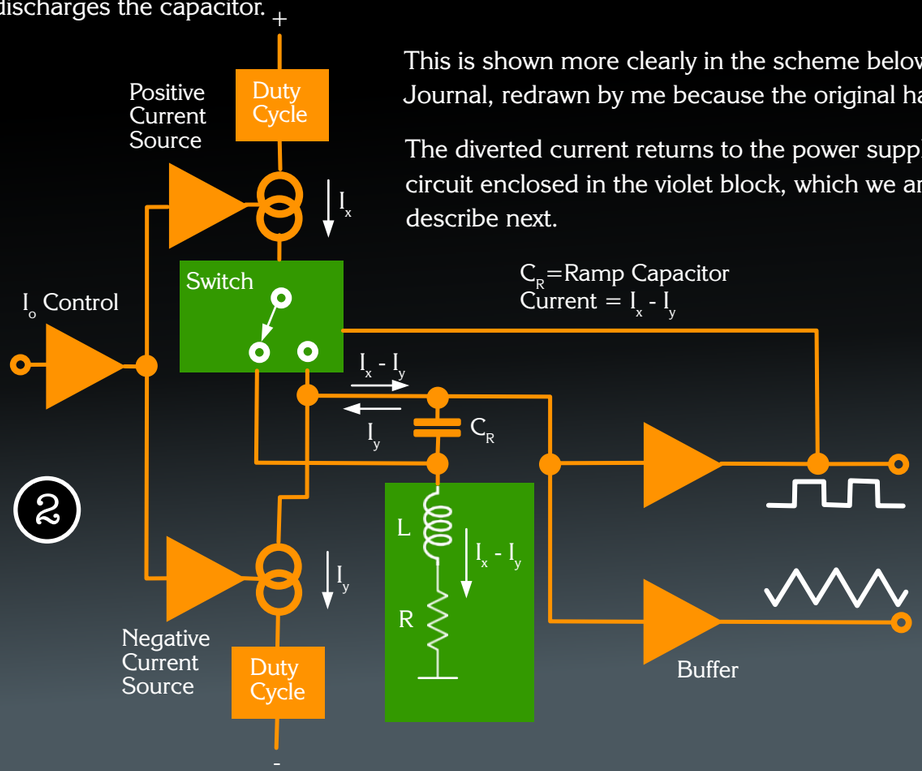
- in red: the positive current source, producing 2 I_0 ramp capacitor(s) charging current;
- in green: the negative current source, producing I_0 ramp capacitor(s) discharging current;
- in orange: the current source that synchronously controls the two above, upon the command of the A5 VCO Control Board to set the VCO frequency.



Note that the positive current source uses two transistors instead of one as amplifier, being twice the negative one. Note also, on top and bottom, the two relays that change the ratio between the positive and negative currents to produce 20% or 80% square wave duty cycle or positive and negative ramps.

Current Diversion

Something that we can often note in the 8165A is that normally currents are never switched on and off but "diverted", using the typical differential circuit like that shown here and composed by Q7A and Q7B transistors. The positive current 2 I_0 used to charge the ramp capacitor(s) flows through Q7A, but when Q7B is activated, it takes the dashed line; the negative current source prevails and discharges the capacitor.



This is shown more clearly in the scheme below from the HP Journal, redrawn by me because the original had too low quality.

The diverted current returns to the power supply through the circuit enclosed in the violet block, which we are going to describe next.

C_R=Ramp Capacitor
Current = I_x - I_y

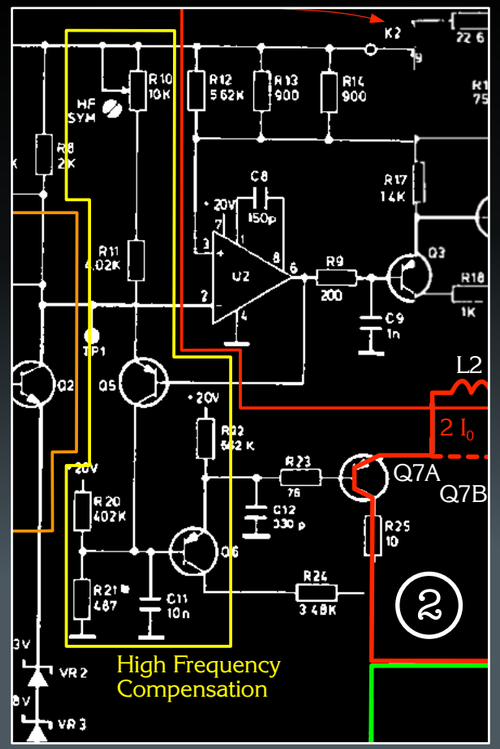
❶ Ramp capacitors and current diversion implementation. ❷ Schematization of the ramp circuit. Note the common I_0 control for both positive and negative currents and the trigger we are going to describe thoroughly.

Capacitors reference ground

The violet block in the scheme on the previous page required me some effort to be understood and even an LTspice simulation, but it is not so terrible as it seems. About that, the HP Journal reports some explanations but they seem to me not very correct or at least not very clear. Perhaps you can understand this better from the simplified diagram here on the right.

Of the six ramp capacitors, one (C26) is very small and obtained directly from the PCB. C21 and C22, respectively 20 and 200 nF, are big enough that the parasitic capacitance of the relay contacts can be accepted. But for C23+C24+C25 (220 pF + 1 nF + 1 nF = 2200 pF) a relay is too much. So they are inserted or excluded from the circuit by mean of a transistor (Q513).

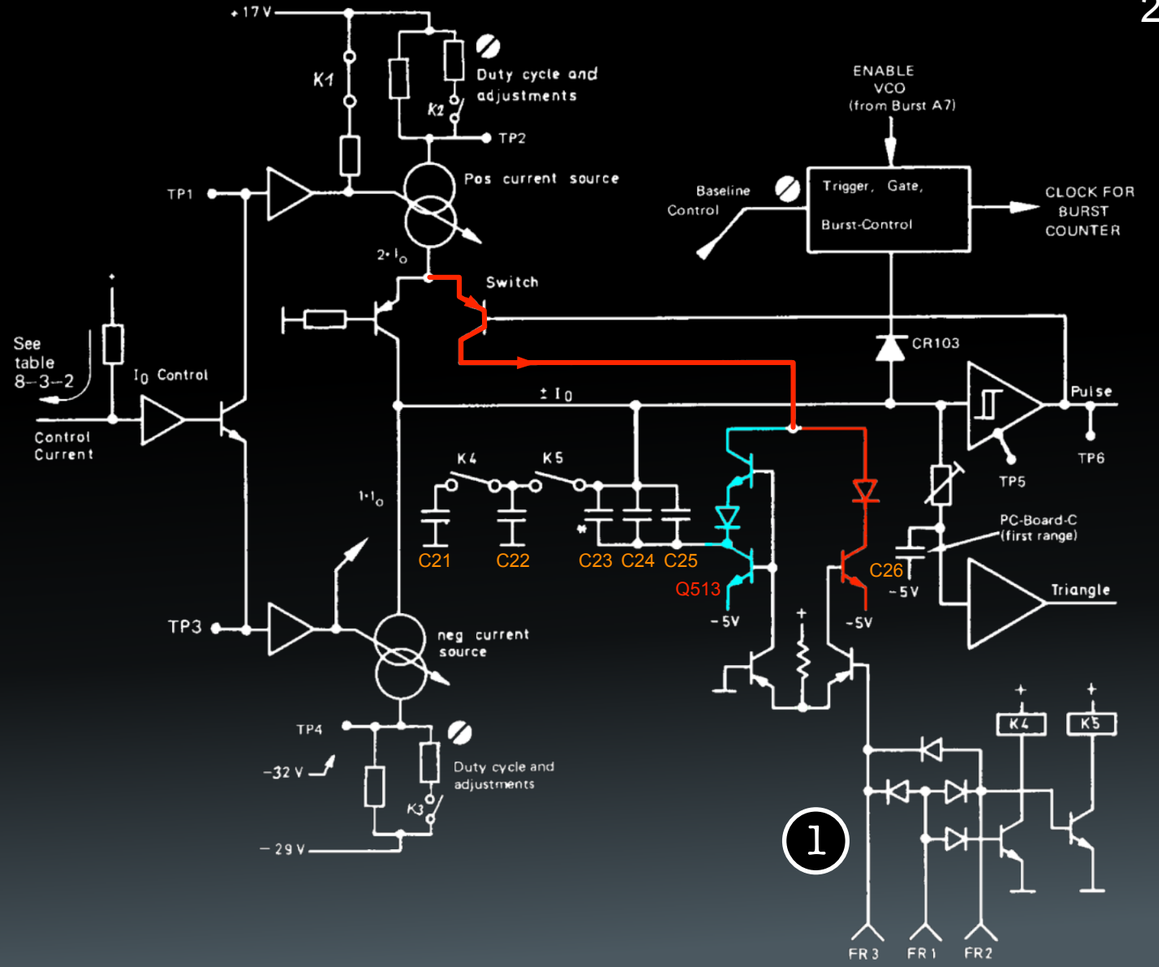
However, this way has a drawback, because, Q513 is saturated, it adds a “step” of about 200 mV that finish to create a step on the ramp. So, when C23+C24+C25 are used, the red diverted charging current (figure) takes left cyan path and “moves” the ground reference voltage of the capacitors of the required amount in the opposite direction (in the HP Journal they call this “a virtual ground”), by leaving them “pre-charged” in the end of the discharge ramp. The switch to this cyan branch instead of the standard red one, is decided by FR3, a digital line from the microprocessor. Nothing is ever simple in the 8165A…



HF compensation

I am not sure I understood the circuit in the yellow block but I can tell you that it is used to set the ramp amplitude at 50 MHz.

Q6 base changes its voltage according R10 setting and Positive Current setting, via U2/Q5. When Q5 drive rises, also the voltage at Q6 base increases. This reduces the current in Q6 which acts as an automatic gain control to avoid that at high frequency the ramp amplitude becomes too high.



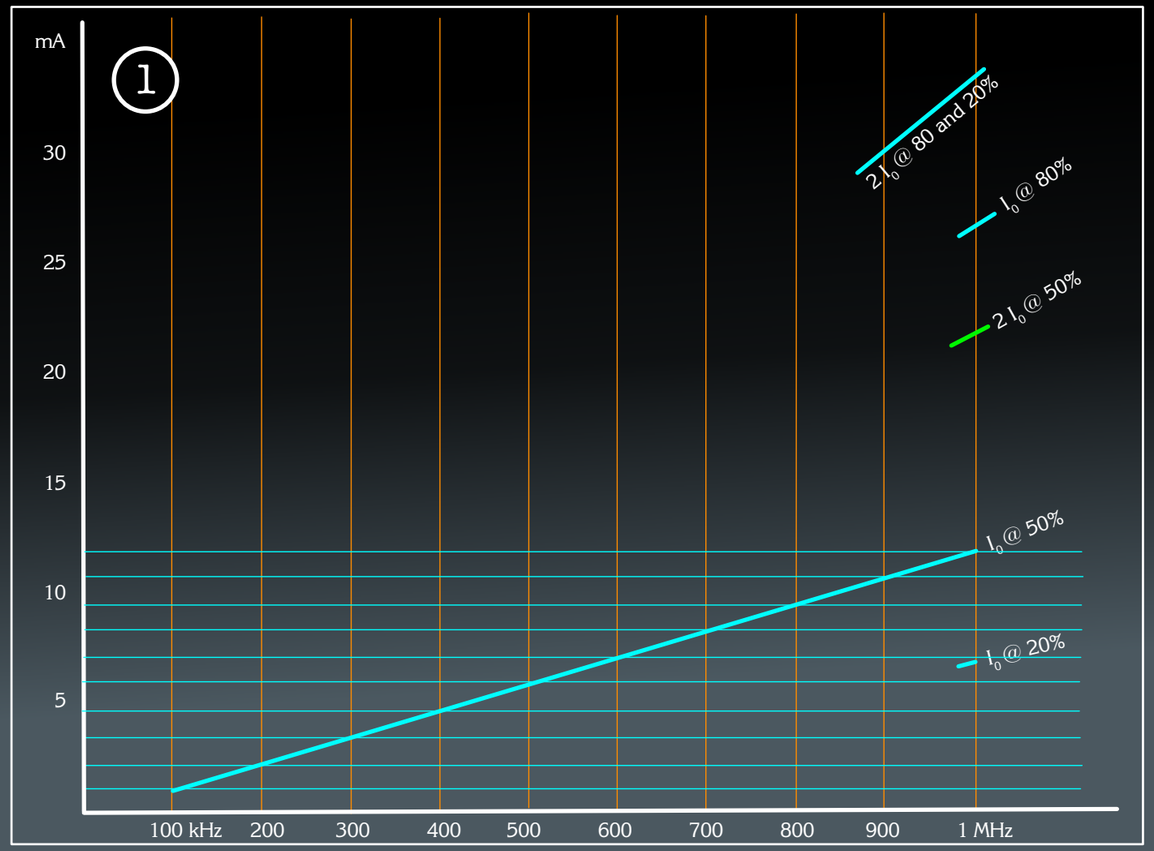
❶ In red, the circuit that allows to set correctly the reference ground for capacitors switched by transistor instead of a relay, to compensate for transistor Vbe. Red path is used in other cases.

❷ The high frequency compensation circuit described in the text is adjusted during calibration @50 MHz.

FRQ range	FR1	FR2	FR3	K4	K5
1 kHz – 9.999 K	1	0	0	ON	ON
10 kHz – 99.99 K	0	1	0	OFF	ON
100 kHz – 999.9 K	0	0	1	OFF	OFF
1 MHz – 50 MHz	0	0	0	OFF	OFF

Checking Currents

This instrument is strongly based on the currents; so, it is important to be able to check their value. Luckily, the manual suggest a way to do this measurements: just disconnect L2 (or L3) and strap it to ground by mean of a milliammeter. Two diagrams are supplied with the expected values, but their quality is definitely poor, so I tried to restore them to improve their readability, in the 50% duty cycle zone, which you probably want to check first, cleaning the other lines.

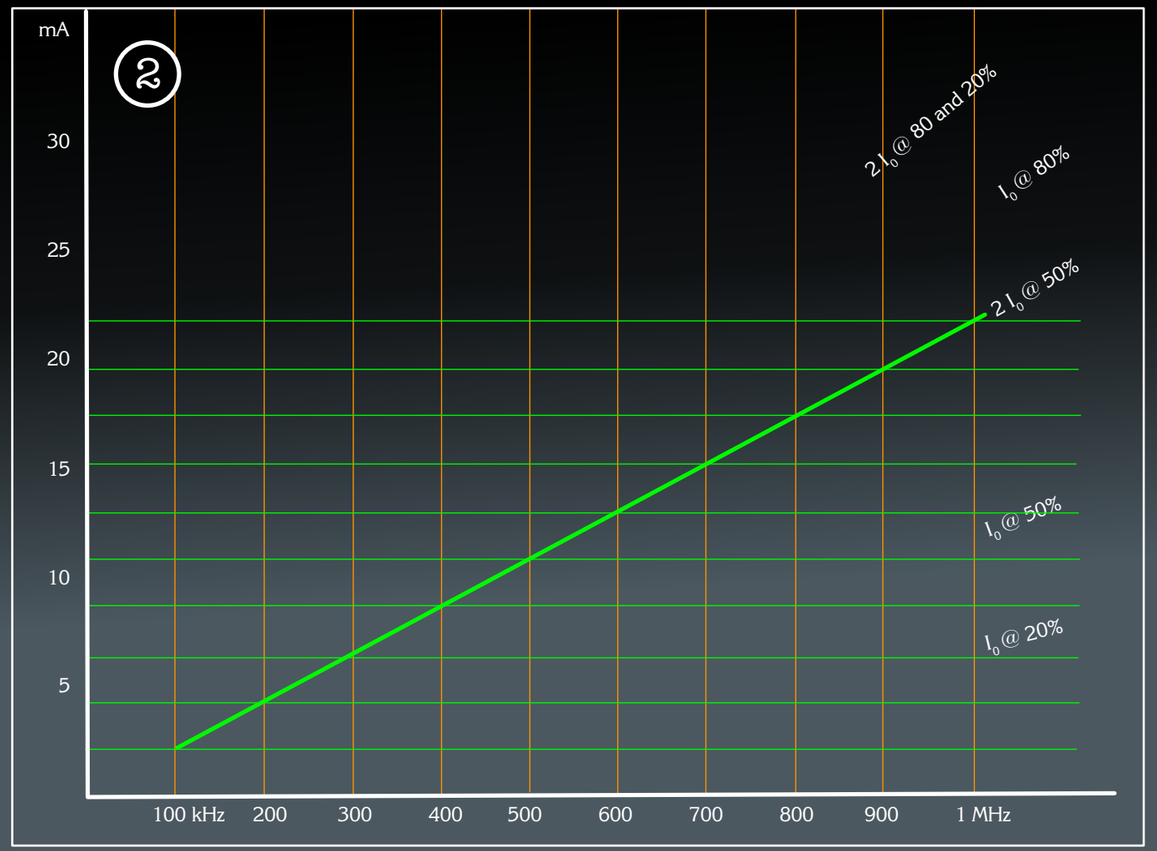


Remember that charge and discharge currents are “static”, i.e., they have a fixed value for each frequency set on display.

These diagrams are very important for the 8165A’s restorer. I redrew them from the original ones in the manual because they are not very readable, at least in my copies. They describe the ramp capacitor currents in the range 100-999 kHz. The diagrams in the manual reports the currents in all the possible conditions. I left only the lines for 50% duty cycle, the most useful, separating them in two diagrams.

❶ Capacitor discharge current.

❷ Capacitor charge current.



VCO Trigger

Basic trigger scheme

We have already dealt also with the basic transistor trigger circuit, like that in figure (1) talking about the 8012B pulse generator, and you can go back to it for further details or you can see the several web pages on this topic, starting with Wikipedia. Now we need to study the 8561A VCO modified version of trigger which, as we will see, it is not eventually so different.

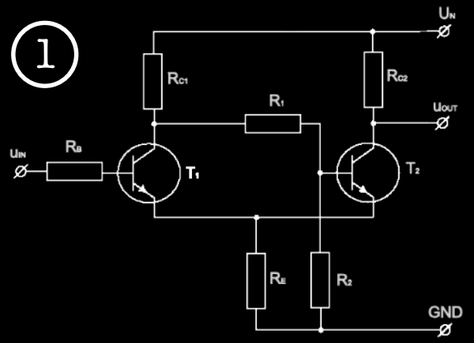
Modified trigger circuit

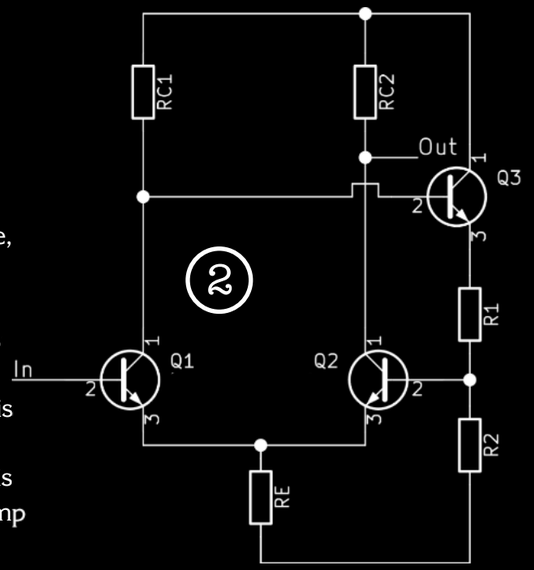
The trigger used in the 8165A does not follow exactly the base schematic like (1) from Wikipedia, but it is more like the one shown in figure (2).

Steady states

Let first analyze the steady states:

- **During capacitor charge**: Q1 is inhibited and the trigger input is increasing (the ramp capacitor is charging). Meanwhile, the base of Q3 is very positive, so Q3 is saturated and pulls up the base of Q2, keeping it on. RC1 larger than RC2; this is a basic requirement of any trigger. Thus the current in RE is "higher" and the Q1-Q2 emitter voltage is "lower".
- **During capacitor discharge**: Q1 is on and so Q3 is open and the base of Q2 is held low by R2. The current in RE is "lower" and Q1-Q2 emitter voltage is in the "higher" state. Trigger input is decreasing (ramp capacitor discharging).





Transients

Let's now see state changes.

- **Upper threshold**: when the base of Q1 becomes 0.6V more positive than the emitter, we reached the upper threshold, and Q1 starts to conduct. As a result, Q3 base begins to decline, and so does Q2 base, and Q2 starts to open. Being the current in Q2 higher than that of Q1, the opening of Q2 determines the Q1-Q2 emitter voltage decrement, and this increases the growth speed of the difference between base and emitter of Q1, making the process regenerative. This is make faster also the opening of Q2.
- **Hysteresis**: The distance we took with the fall of the current in the Q1 branch allows us the luxury of going down a little with the input level; in this case, just Q1 current decreases because we are now in a (relatively) stable status. We need to reach the trigger lower threshold to reset Q2 in the on state, as we see next. This dual threshold operation is called hysteresis and is the reason for which we use the trigger.
- **Lower threshold**: now the trip voltage is the one resulting from the new (lower) current level in Q1. The input needs now to go below Q1 emitter voltage plus 0.6V, so that Q3 no longer remain open and begins to close. The base of Q2 rises and makes Q2 conduct; the emitters current rise again and we return in the other stable status.

As we will se better later, the transition between the states is slightly different: The emitters voltage drop is almost immediate when Q2 switches on, while follow the input when Q1 is on.

The third transistor

OK, you convinced us that it can work… but why did you add a transistor to the basic trigger scheme? This scheme is not very different by the basic one, and, IMHO, Q3 has only the purpose of amplifying the voltage differences on Q1 collector; according someone, it makes the circuit more stable with higher hysteresis. The basic circuit will work with a small hysteresis but will eventually become less stable when the resistance or RC/RE is too high. However, HP designers surely had their good reason to follow this model. But how do R1/R2 affect circuit behavior?

❶ Standard transistor-based trigger circuit, from Wikipedia (by Audrius Meskauskas - Opera propria, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=633382)

❷ The modified trigger version with the third transistor added.

8165A circuit

Those HP designer didn't lose the opportunity to make the circuit much more complicated. first of all they, added on trigger's top and bottom sides two additional circuits:

- on top, they added a voltage stabilizer which produces about 15 volts;
- on bottom, they added a current regulator, capable of producing an adjustable current in the range 23-30 mA.

For now, let's forget them, we will reverse engineer them later.

The trigger itself

On the facing page you can see the trigger itself. When you depurate it of the input impedance converter, the top voltage regulator (cyan block) and the bottom current regulator (yellow block), which, as we said, will be discussed later, you remain with the trigger itself painted in green, red and orange, which resembles closely the three-transistor trigger that we described earlier. We observe that:

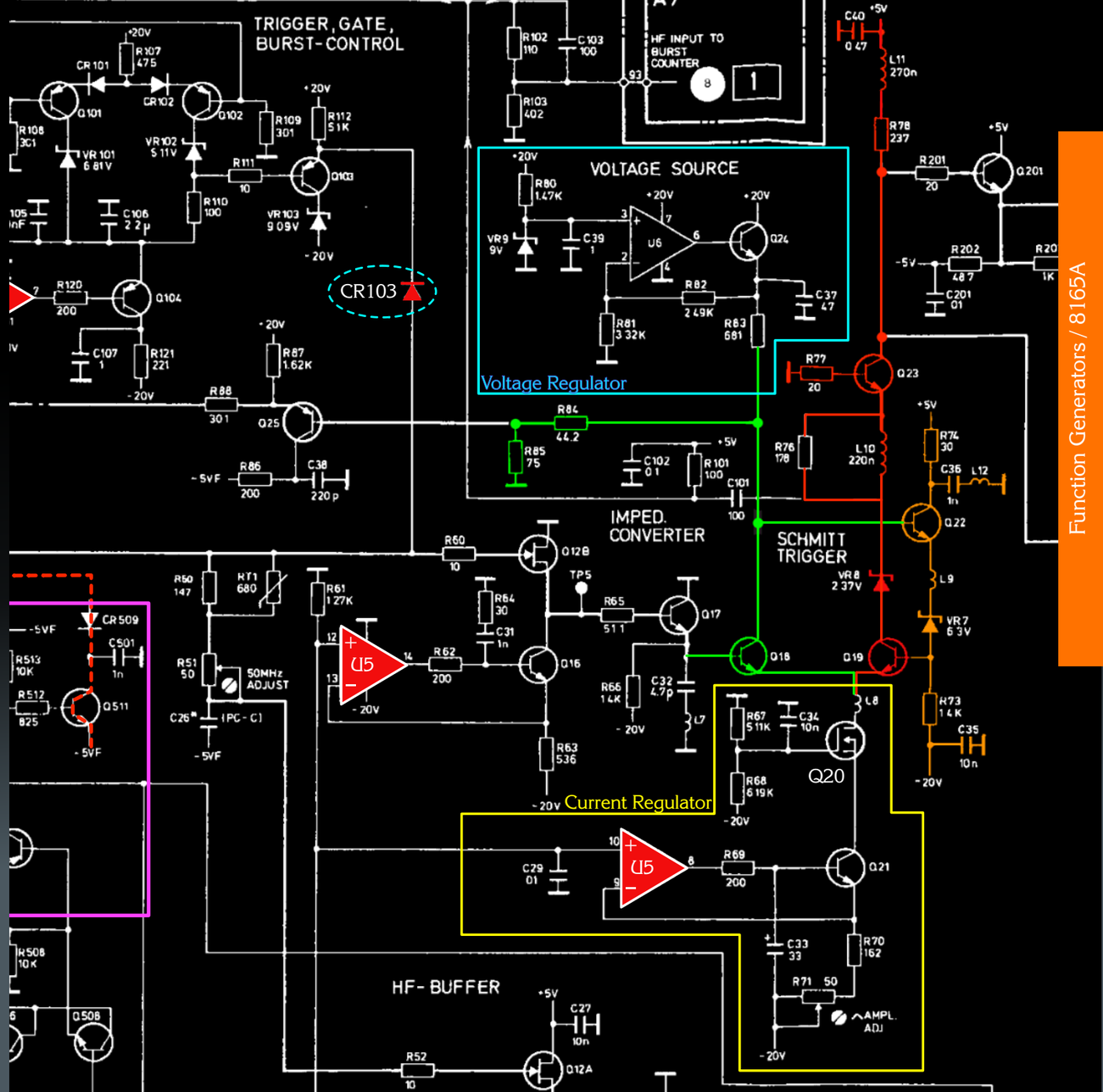
- resistor R1 has been replaced by a Zener VR7;
- resistor R74 has been added;
- on the right branch, a Zener VR8 and a current regulator Q23 have been added.

Thus, the circuit is substantially the same. I wanted to see if practice coincides with theory, and I must say that things are not so bad. Let's look back at the steady states and the transients we already saw with the 3-transistor trigger, with the confirmation of the oscillograms taken on the real circuit.

Charge: Q18 is inhibited and charging of the capacitor begins. Meanwhile, the base of Q22 is very positive, so Q22 is saturated and pulls up the base of Q19, which, given the circuit, should be at around -2V. Since the emitter of Q18-19 is at -5.5 (figure ❶ on the next page), Q19 is completely saturated, its base being about 1.5 volt above the emitter (yellow vs. orange trace). I expect the collector of Q19 to be almost at the emitter potential and therefore the output in the negative zone (collector of Q23).

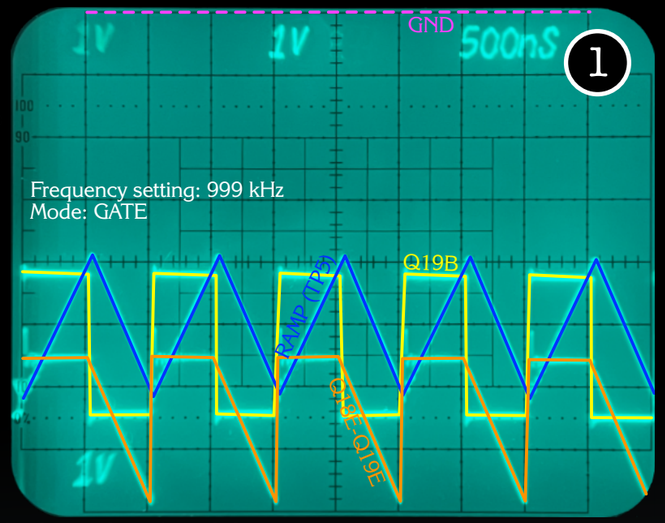
Discharge: during the discharge, Q18 is saturated, so Q22 does not conduct and the base of Q19 would like to go to -20 but is "held back" (to understand why) and does not go below -6.5V. However, it is below the emitter and Q19 remains open, so the output (collector Q23) goes to the positive zone.

The trigger circuit sets the charging and discharging of the ramp capacitor. Its precise operation is the base of 8165A's performance. If you consider only the trigger itself, the circuit is rather conventional, but in this case, considered its relevance, additional circuits contribute to its perfect behavior.



Much more difficult to understand the thresholds.

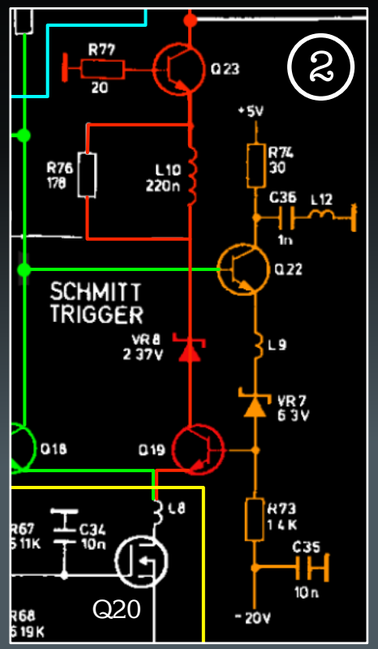
Start of descent: when you reach the top of the ramp, the base of Q18 becomes 0.6V positive with respect to the emitter, Q18 starts to conduct. As a result, Q22 base begins to decline. But Q18 emitter also drops (orange track), because the current in Q18 branch is, by design, lower than that of Q19. This increases the growth speed of the difference between the base and the emitter of Q19, making the process regenerative. This explains the trend of the orange track: there are two current levels: that of Q18 (lower, therefore higher voltage) and that of Q19 (inverse).



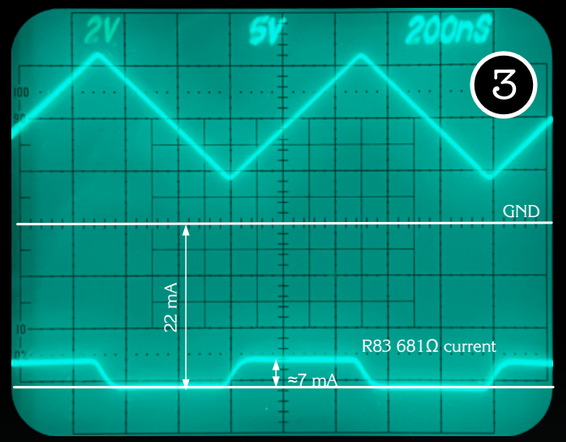
So the distance we have taken with the fall of the current in the Q18 branch allows us the luxury of going down a little with the input without the process reversing and is the basis of the hysteresis.

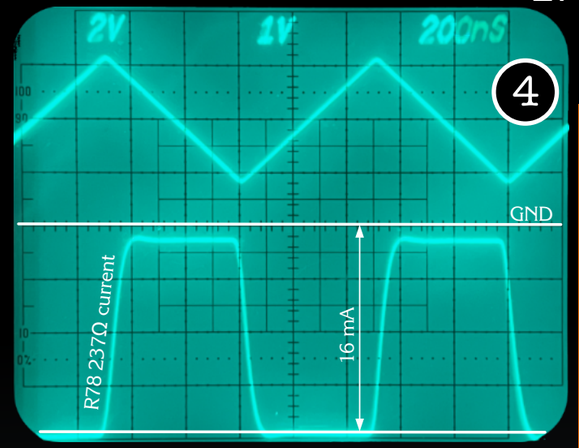
Start of increase: now the trip voltage is the one resulting from the new current level. When Vin drops below 0.6+Ve, Q18 can no longer remain closed and begins to open. The base of Q22 rises and makes Q22 lead and with it Q19, which makes the current rise (this is the greediest branch) etc. etc.

So I would say that an higher emitter current will produce a greater amplitude of the ramp, and this is confirmed by the experience: when on R71 is at minimum resistance, the ramp is more ample.



❶ Relationships among Q18-Q19 emitter voltage, Q19 base voltage and the capacitor ramp. ❷ Q19 trigger branch. ❸ The current in R83 (Q18 trigger branch). ❹ The current in R78 (Q19 trigger branch).





Current regulation

It's now time to see the lower current regulator, composed by two parts: U5/Q21 and the Q20 MOSFET.

The former follows exactly the basic scheme we already saw earlier, with the addition of a 30 uF capacitor that makes U5/Q21 a slow, coarse regulator.

I have more problems understanding Q20, whose base is held at about 9V by R67/R68. Surely it is faster. During normal operation, its source stays at -12 V while its drain moves in accord with the trigger operation (see picture ❶ for Q18-Q19 emitter voltage). During the ramp charge it stays at -5.5 V while during discharge, it follow the input signal, as shown in the oscillograms. I suspect that it has also some temperature compensation purposes.

Simplified current regulators

Another current regulator is Q23. For the basic transistor current regulator (see "Current sources" in the 8012B description), we said that I = (Vz + Vbe) / R1.

In some cases, we can save the Zener diode. An example is A5Q23, where the base is simply strapped to ground, because R1 (R78) is connected to +5V, so it is like having a 5V Zener diode between R1 top and Q1 base. This leads to i=24 mA. In reality, the current in R74 is greater (27 mA), probably for R201 and R207 (not visible in the schematic here on the right).

VCO Control

Obey my orders

It is interesting to understand how the VCO receive its orders. If we are not going to exploit the PLL (open-loop operation), we just need:

- to set the frequency band (this means mainly to chose the proper capacitors for the ramp);
- to set a proper command voltage to its input. A voltage to current interface provides to linearly set the VCO according the voltage value.

This voltage is produced by an 8-bit Digital to Analog Converter (DAC) U302, but this gives us only 256 possible values that are non enough for the 8165A; for this reason two other bits are added, under uP control, reaching 1,000 possible values (1024 really, but only 1000 are used).

Checking the DAC

This voltage can be tested setting the frequency value on the front panel and at checking the voltage at A8TP3, which should swing from 1 to 10V (see table (1) below). Be sure you disabled the PLL, by selecting GATE mode and applying 2-3V at the the front input BNC. Two trimmers are provided to set the exact voltage at 255 and 256 DAC values (R313 and R318).

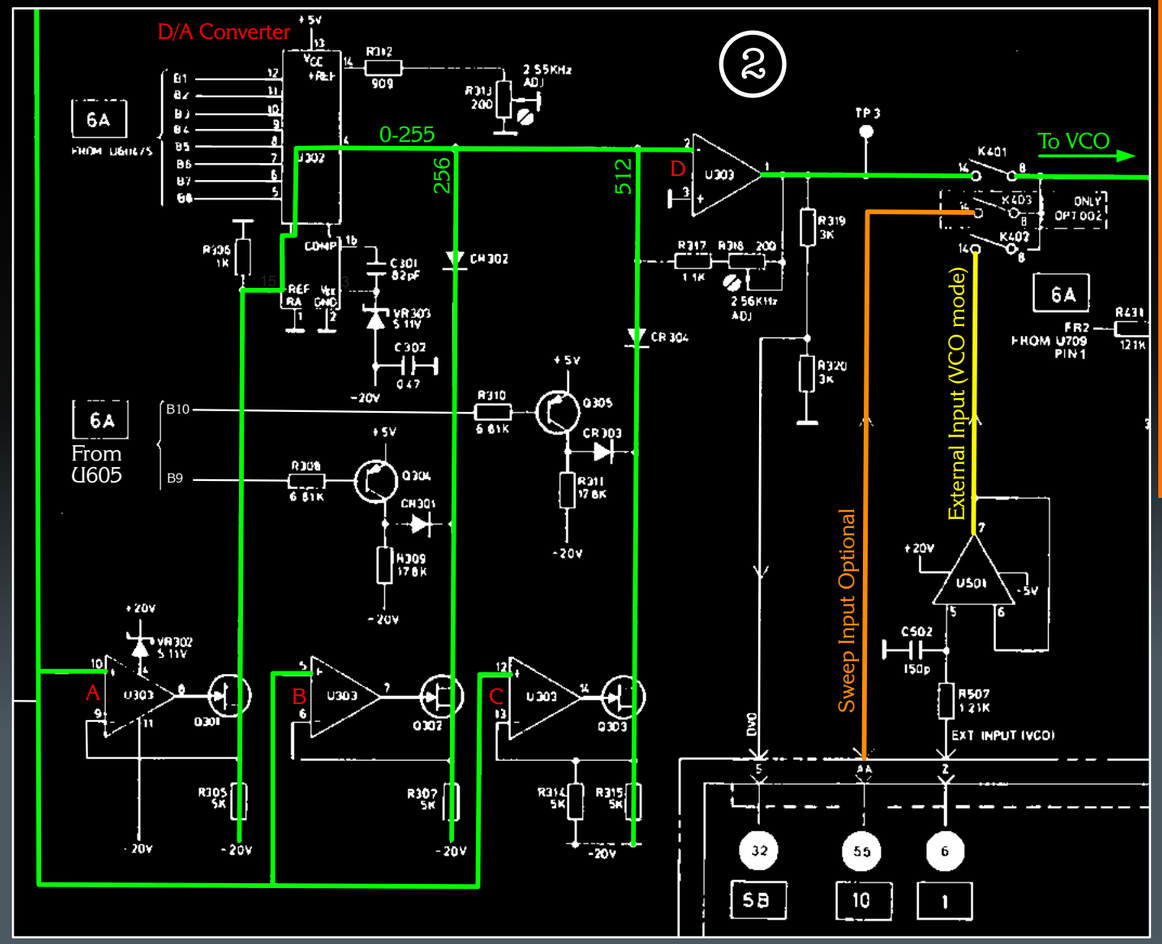
Table 8–3–1. FRQ Display to Voltage

Display (3 digit)	D/A Conv. U302 10 9 8 7 6 5	4 3 2 1	A8 TP3
1.00	0 0 0 1 1 0	0 1 0 0	1.00 V
1.50	0 0 1 0 0 1	0 1 1 0	1.50 V
3.00	0 1 0 0 1 0	1 1 0 0	3.00 V
5.00	1 0 0 0 0 0	1 1 0 0	5.00 V
7.50	1 0 1 1 1 0	1 1 1 0	7.50 V
9.00	1 1 1 0 0 0	0 1 0 0	9.00 V
9.99	1 1 1 1 1 0	0 1 1 1	9.99 V

Direct VCO control

You can control directly the VCO from an external DC source connected to front panel BNC input by pressing the VCO button. The manual says 10 mV to 10 V for 3-decade sweep (but you must however set a frequency value to select the range).

❶ FRQ display to voltage at A5T3 table. ❷ DAC area. Note the relay to select the input to VCO: the DAC, the external input in VCO mode, and the optional Sweep input (Option 002).



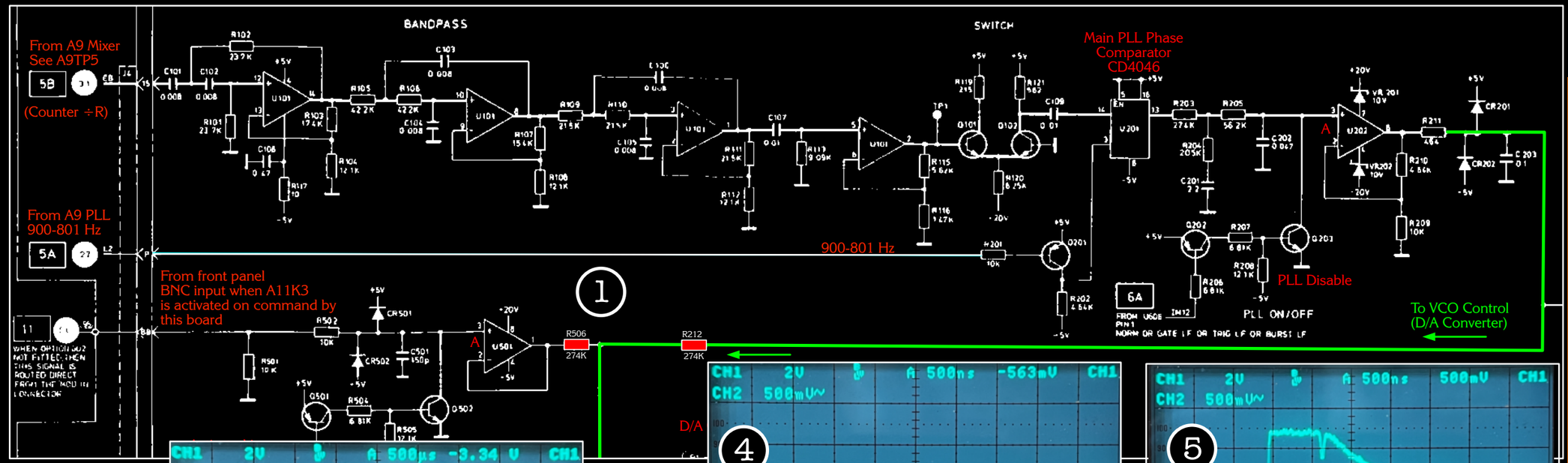
Closed Loop Operation

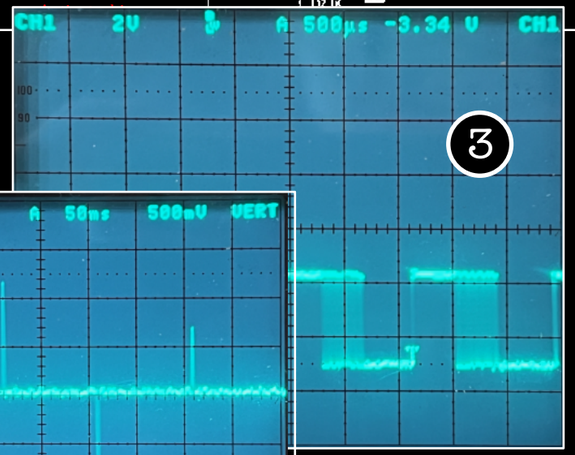
We just saw the open-loop VCO operation we activated with the GATE mode (and a voltage applied to the input BNC). In this way, the frequency accuracy and stability is that of the VCO oscillator itself, i.e., non exceptional. But just press the NORMAL button and, if your 8165A is good, the output frequency will be locked to a reference 10-MHz crystal oscillator, with accuracy of 0.001%n and stability of 1 x 10^{-6}.

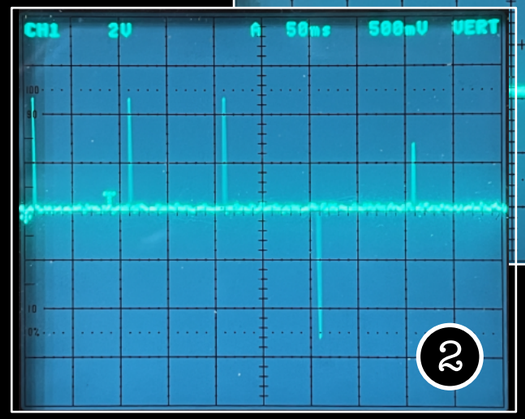
In the facing schematic diagram, you can see the main PLL phase comparator section. With reference to the previous descriptions, it compares

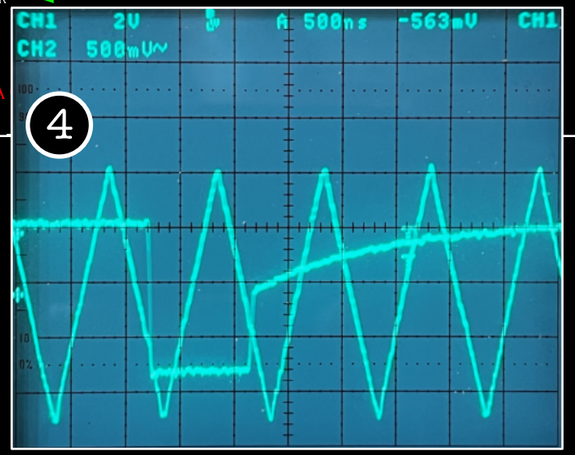
- the frequency coming from the mixer which joins the produced output signal with the Counter ÷R;
- the frequency from the Loop1 PLL.

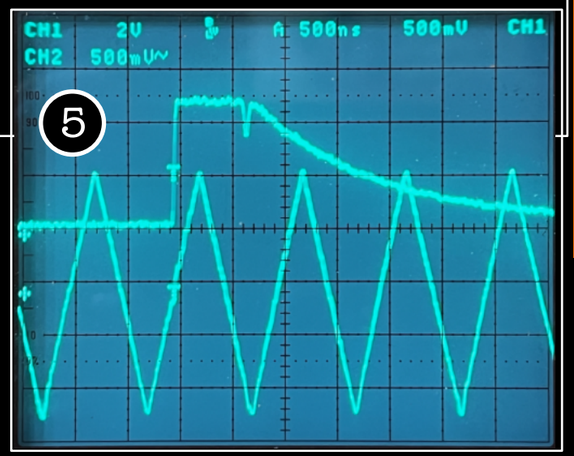
The signal coming out U202-A when the PLL is locked (pin 13 of U201 CD4046) is shown in figure ❷. It is normally at zero, but it contains some spikes, toward plus or minus, to keep the frequency locked.











When U212 pin 13 is zero, it means that the output frequency is perfect; when it is positive, it means that the frequency is too low, when negative, we are going too fast. Figure ❹ and ❺ show an enlargement of these pulses, and the convergence to the right frequency is made more evident.

Photo ❸ shows a situation in which the PLL is disabled and the frequency is almost correct, just a little too high, and it was taken using the envelope function of a Tektronix 2431L oscilloscope.

Electrical connections

The output of the Phase Comparator amplifier and level translator (202-A pin 6) is joined by mean of R212 with the signal from U501-A pin 1 via R506, used for frequency modulation (both resistor enhanced in red in the schematic). This signal is used to modulate the DAC current to adjust them (and the frequency) according the PLL needs.

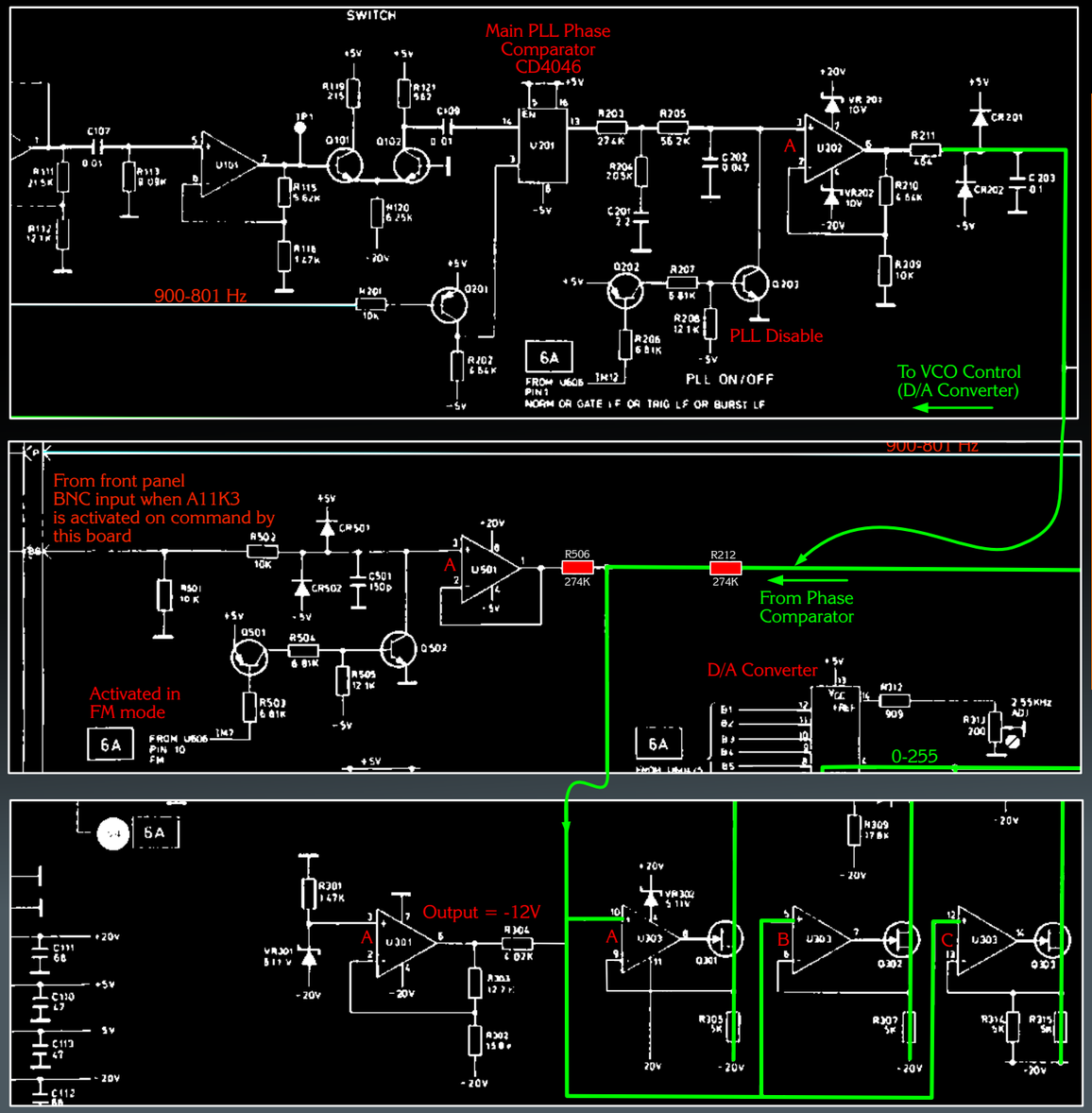
Another fault

Here also I found a fault: the PLL could not be disabled, because U606, another CD4042, was broken. It is used to short to ground (by mean of Q203) the input of U202A. I had not well understood, the circuit and I also changed U202 (LM324), but I am not sure now it was really defective.

Phase Noise

Looking at photos 4 and 5 on the previous pages, I believe I eventually can see an important concept. In those photos, you can see that, at a certain moment, there is a “brisk” VCO control voltage step and thus a phase change, which, I suppose, has the effect of jitter, in time domain, or a greater phase noise in the frequency domain.

We are going to see that the marvelous **3325A**, described later, will introduce an important improvement in PLL-technique, named **Fractional-N Phase Locked Loop**, which overcomes this problem.



General Sine Shaping

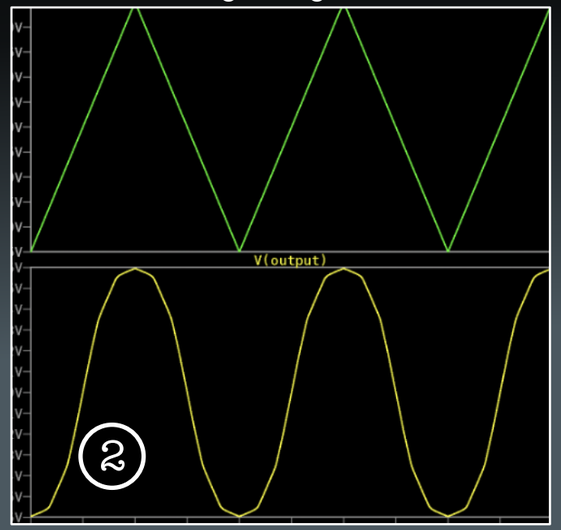
I.e., Not All Crazy People Are in the Asylum

Studying old electronic equipment and writing books that probably few people would ever read is perhaps not literally insane, uhm, but let say… uhm "original"? So it comforts me to know that I'm not the only crazy person outside the asylum, and someone else loses his time studying vintage instruments. But let's go in order.

Diode Sine Shaping

HP Journal 12/78, describing the circuit that transforms the triangle wave in sine, starts saying that diode shapers were not suitable for the 8165A, because they are valuable only in the frequency range up to 10 MHz, and even the use of diodes with very low storage times cannot increase the frequency range significantly.

I had never heard of **diode shapers**, so I decided to start studying them, before affording the 8165A itself. Searching the Internet, I was surprised to find an article Reverse-engineering the waveform generator in a 1969 breadboard by Ken Shirriff (the other "crazy one", whom I thank - find his address below in ❸) who analyzed the HP 3300A Function Generator, and in particular the sine-wave shaper. I found fascinating the theme and well written the article, so I tried to study a diode shaper with the help of Ltspice (❶ facing page).



I was initially scared by so many diodes, but the circuit is very simple when you understand how it works.

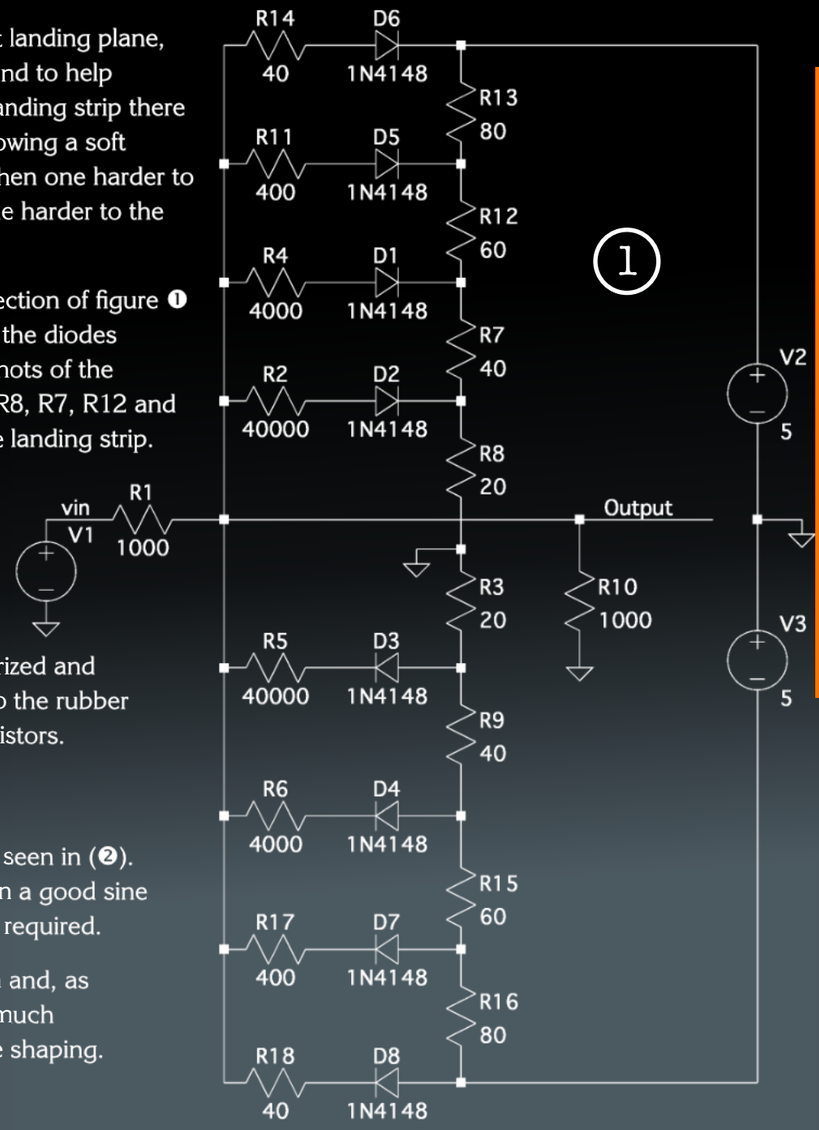
❶ Ltspice circuit simulating a diode sine shaper.
❷ The simulation results. At least 6 diodes would be required to make a good sine wave. In addition, the resistors should be calculated correctly.
❸ The web site with the referred article: http://www.righto.com/2022/03/reverse-engineering-waveform-generator.html

Rubber bands

Suppose you are on a too fast landing plane, and you have some rubber band to help stopping it. On a side of the landing strip there are some pillars. You start throwing a soft rubber band to the first one, then one harder to the second and so on, until the harder to the last pillar.

Looking only at the positive section of figure ❶ (the negative is identical, with the diodes reversed), the pillars are the knots of the voltage divider composed by R8, R7, R12 and R13, being R13 the end of the landing strip. The rubber bands are R2 (softer), R4, R11 and R14 (harder).

As the triangle wave rises, diodes D2, D1, D5 and D6 are progressively directly polarized and conduct, providing foothold to the rubber bands, i.e. the the R2-R14 resistors.



Results

The simulation results can be seen in (❷). According the article, to obtain a good sine wave, 6+6 diodes are at least required.

But all that is just a digression and, as anticipated, doesn't help too much understanding the 8165A sine shaping.

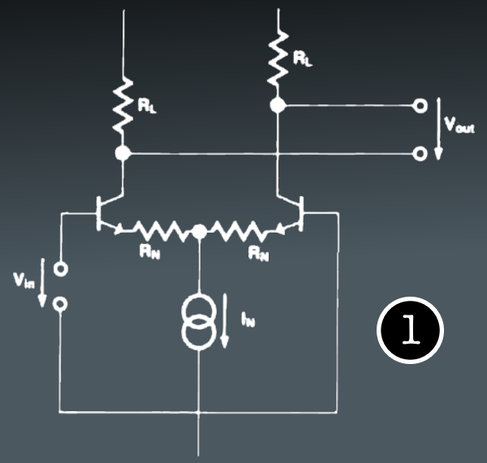
8165A Sine Shaping

A different Circuit

As anticipated, the sine shaper concept used in the 8165A, therefore, is different, even if the descriptions contained in the manual and in the HP Journal were not sufficient for me for a complete understanding.

HP Journal says…

The basic cell used in the 8165A for the sine shaper is shown in 1. It consists of a differential amplifier whose gain is determined only by the resistors R_L., which constitute the "rubber bands" of the previous example. The breakpoints (i.e., the "pillars") are determined by the current I_N. The shaper circuit consists of five cells connected in parallel (i.e., N = 1,2,3,4,5). An advantage of this approach is that the gain is determined by resistors and is therefore independent of temperature variations. However, the input amplitude and offset must be very stable, since an amplitude drift would cause odd harmonic generation, and an offset drift would cause even harmonic generation. In TRIGGERED mode an offset drift cannot be compensated. At high frequencies and continuous waveforms, automatic compensation is switched on.

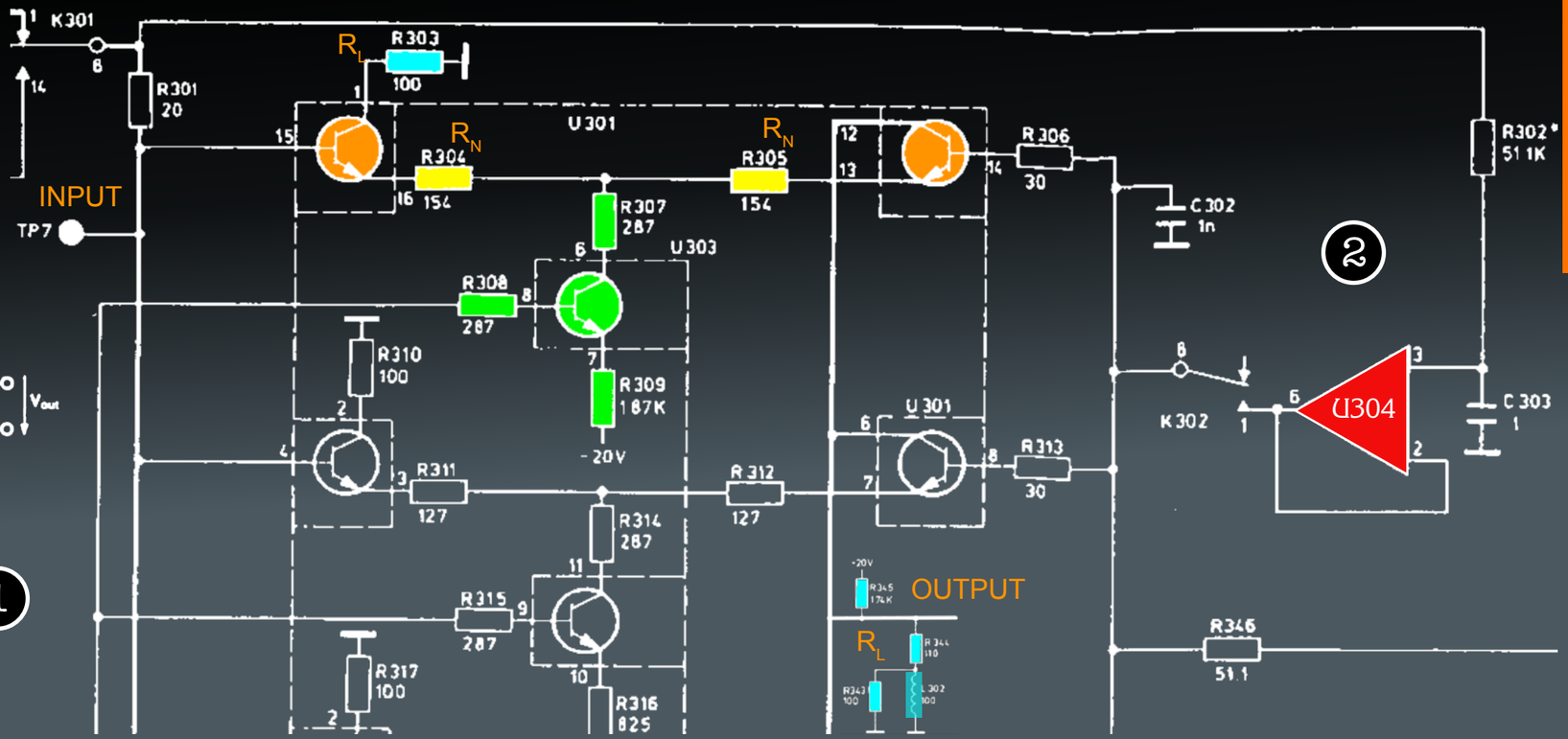


❶

The Edited Diagram

I tried to match the above description from HP Journal with the 8165A schematic diagram. In diagram 2, you can see in green the constant current source (each cell has different values, as expected), the R_N resistors, in yellow, and the R_L resistors in cyan (the output resistors have been copied from other part of the diagram for space reasons). Also the latter have different values for each cell, as expected.

❶ An 8165A basic cell closely resembles an operational amplifier. ❷ The 8165A Sine Shaper circuit seem intricate and it is. Additionally, automatic level correction is applied via U304 (enhanced in red) and relay K302. It is enabled at frequencies above 1 MHz in NORM, VCO and SWEEP modes) and, for frequencies below 1 kHz, via A10U203a on Service Sheet 3 (see signal 12).



More on Sine Shaping

With reference to the schematic diagram on the previous page, in sine operation, a triangle is fed via K301 from the VCO (signal 7) or LFG (signal 16) to the sine shaper (U301, U302, U303). This feeds the sine amplifier (Q303), thence to the buffer (Q401) and to the output driver (U401) via K401. The sine shaper consists of five differential amplifiers in parallel, each of different gain and threshold.

Net gain is input-amplitude dependent such that a sine wave is produced from the applied triangle.

Sine wave baseline (DC level) is zeroed by the preset baseline adjustment (U401a, Q403, Q301, R350) which applies a de to each amplifier of the sine shaper. Additionally, automatic level correction is applied via U304 (enabled at frequencies above 1 MHz in NORM, VCO and SWEEP modes) and, for frequencies below 1 kHz, via A10U203a on Service Sheet 3 (see signal 12).

For optimizing distortion, the gain of the sine shaper can be regulated by the preset adjustment (R340, U305).

Sine wave amplitude is controlled by the preset adjustment (R360) of the sine amplifier (Q303). Symmetry is adjusted by the sine offset (R243, U402b, Q212). The sine amplifier is enabled when signal 30 is high.

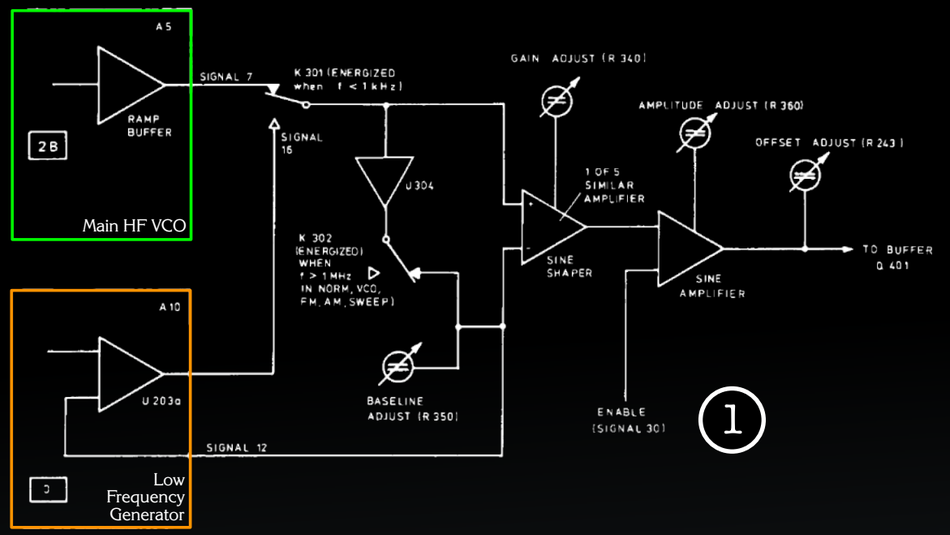
My Sine Shaper

The 8165A Sine Shaper was another point were I remained stuck for some days. Eventually, I discovered that the circuit was operating rightly and the bad sine produced was simply due to the low amplitude of the VCO ramp.

As we will see in the Calibration section, the Sine Shaper requires some adjustments.

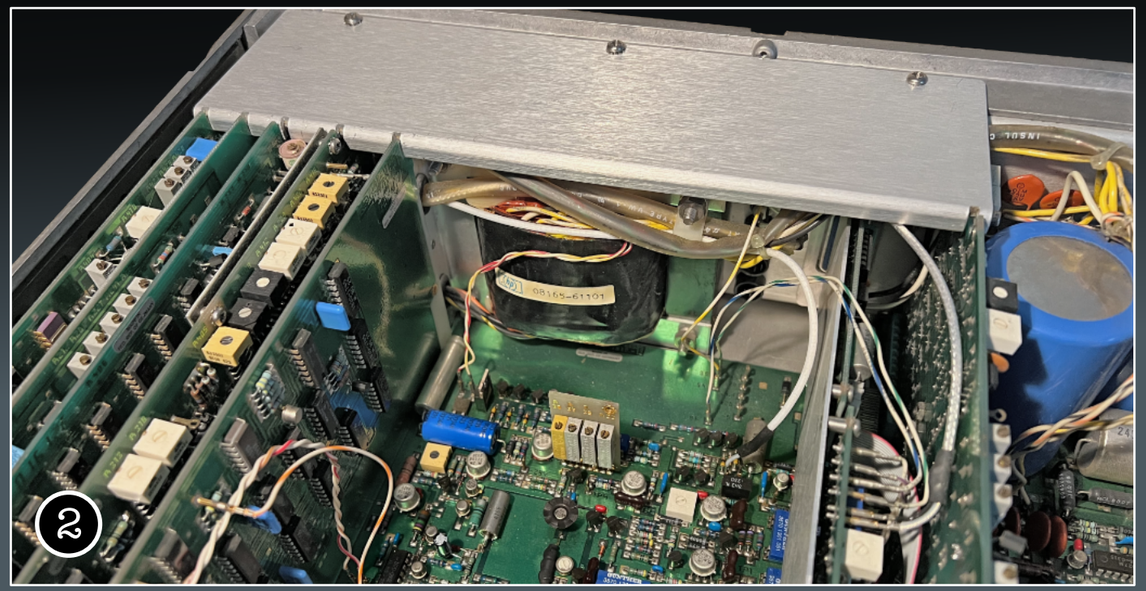
Yet Another Failure

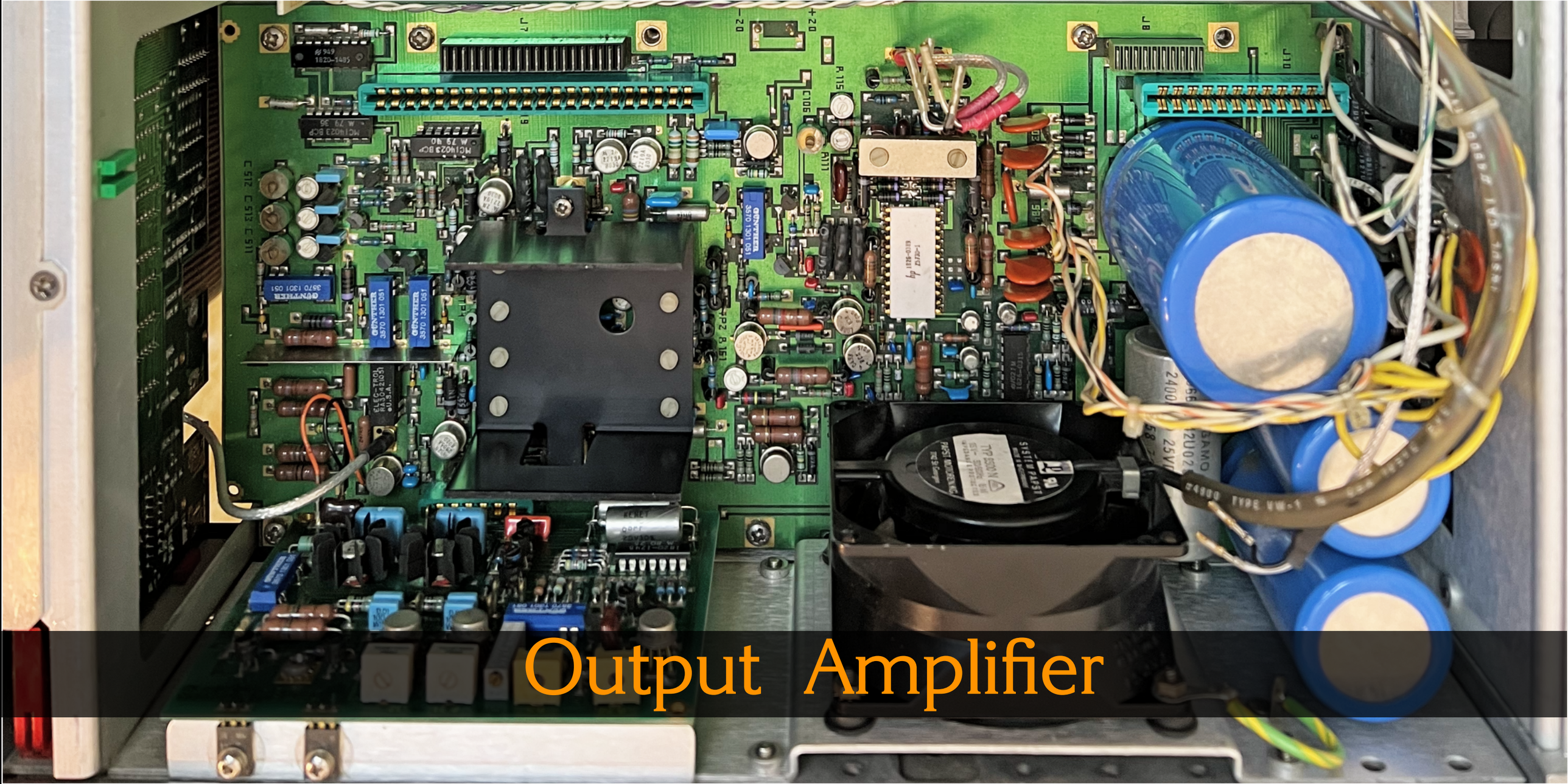
During the tests, I discovered that relay K401, which selects the input to the output stage of A5 board between triangle/sine or square wave didn't move. The problem was in transistor A5Q515 which I replaced.



❶ Inside the 8165A there are two different devices: Main HF VCO, from 1 kHz to 50 MHz, based on the ramp generator, and the Low Frequency Generator (LFG), almost full-digital.

❷ Daughter-boards are kept in position by mean of an an aluminum bracket. Note the big transformer, cause of most of the equipment weight.

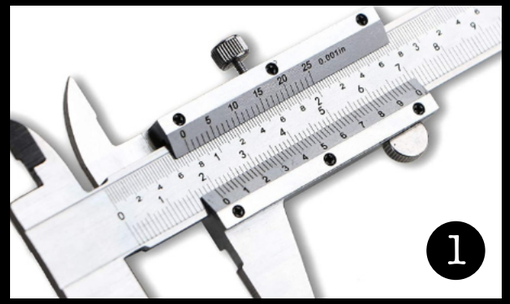



Output Amplifier

The Output Amplifier

The Output Amplifier amplifier comprises four main functional sections:

- Active Vernier
- Power Amplifier
- Attenuator
- Offset generator



Verniers

A **vernier scale**, named after Pierre Vernier (1580-1637), is a visual aid to take an accurate measurement reading between two graduation markings on a linear scale (said “nonius”) by using mechanical interpolation, thereby increasing resolution and reducing measurement uncertainty by using vernier acuity to reduce human estimation error. It may be found on many types of instrument measuring linear or angular quantities, but in particular on a vernier caliper, which measures lengths [from Wikipedia].



By extension, the term has been used to indicate an auxiliary device designed to facilitate fine adjustments or measurements on precision instruments. In our world, every precision rotating control is named a **vernier**.

Old electronic equipment used to have wondrous verniers, extremely precise, like, for example the glorious WW-II BC-221 Frequency Meter

Pseudo-Verniers

Thanks to the “extension”, we accepted to use the vernier term even when no nonius was present, but HP took advantage of it a little too much, and called “vernier” also for the horrible linear 8015A potentiometers.

8165A Verniers

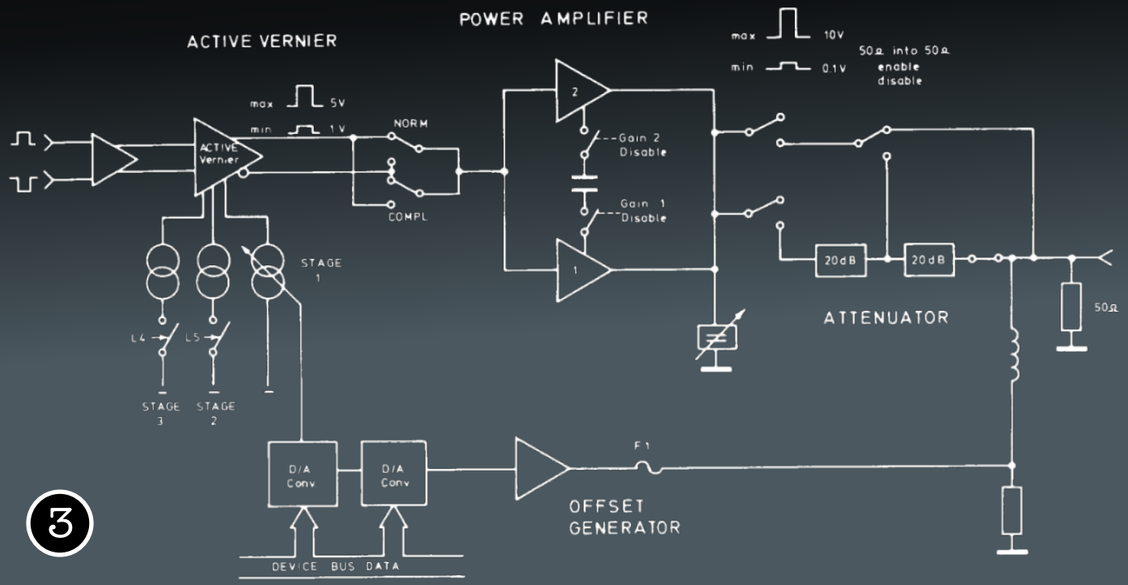
With the 8165A, professional generators return back to the good times gone by, in digital version; finally (and again) you can set a precise setting also for the amplitude, without another instrument to check it.

The 8165A output **active vernier** comprises 3 attenuator stages in parallel, each stage consisting of two attenuating elements, one for normal and one for complement output.

❶ Daughter-boards are kept in position by mean of an an aluminum bracket. Note the big transformer, cause of most of the equipment weight.

❷ The old, good BC-221 was a heterodyne frequency meter from WW-II. After more than seventy years it remains rock-solid stable and perfectly aligned with its frequency tables. A high-quality vernier is the base of its operation.

❸ 8165A Output Amplifier and its main components.



Digital Verniers Basic Cell

As figure 1 on the facing page shows, each attenuating stage is a differential amplifier connected so that the signal current flows into (or out of) the common emitters. The output current is taken from one of the collectors and then converted to voltage.

When I first saw it, I remembered I already had to fight with something like that; needless to say, it was the wicked 8015A. It is time now to understand more about it, or, at least, to try. The manual is incredibly imprecise and surely contains mistakes that I tried to amend, but I am not sure that my corrections are correct, so take what follow witch caution. The schematic diagram, from the 85165A manual, has been redrawn to correct the errors and also to use a special font, where capital letter "i" can be discerned from number "1" etc.

I understand that this circuit is basically a **differential amplifier**, where the current flowing in each collector is proportional to the potential difference between the two bases (yes, it has been drawn not conventionally, but, if you look carefully, you can almost recognize it in the left green part).

Inner working

Thus, without considering for now the orange part, by varying Vy on the base of one of the transistors, the current Iout can be controlled, and the input signal controls the share of current source I which flows through each input transistor Q5 and Q6.

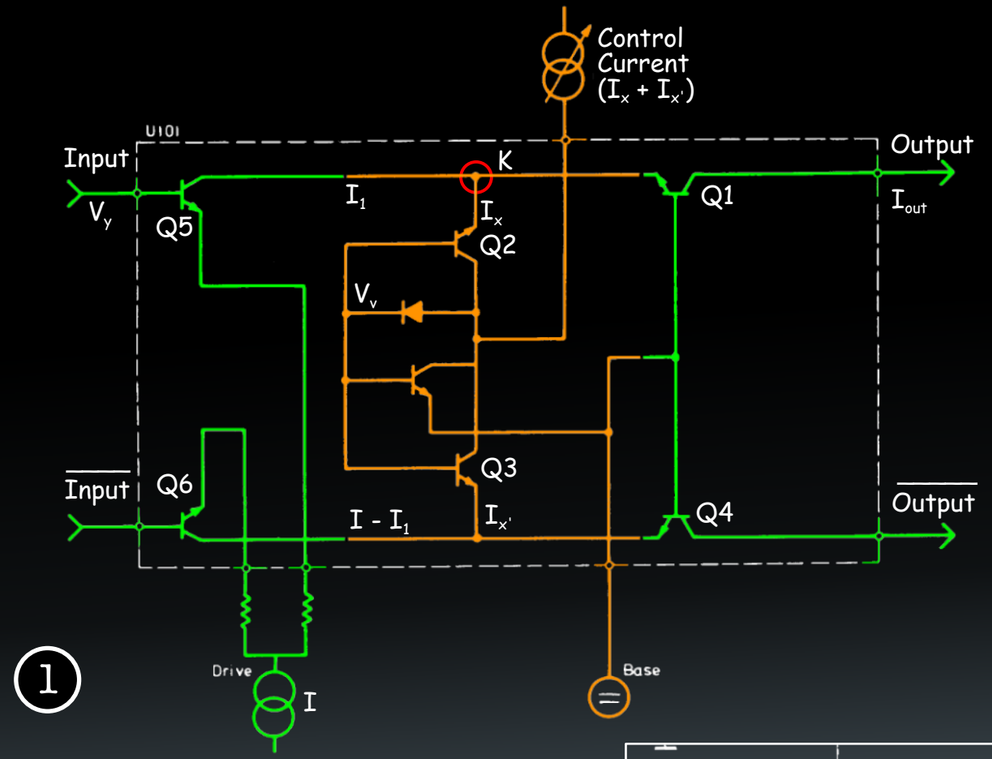
Consider now the orange part and specifically the "K" knot, where the sum of I1, Ix and Iout currents must be null (and the same on the branch below). For a better understanding, we use a font where the vertical characters are clearer.

Example 1: if I = 1 mA and Vy is set so that the current in Q5 and Q6 is equally distributed, to have a reduction ratio of 0.5 (2:1), we have:

- I1 = (I-I1) = 0.5 mA
- Ix = Iy = 0.25 mA

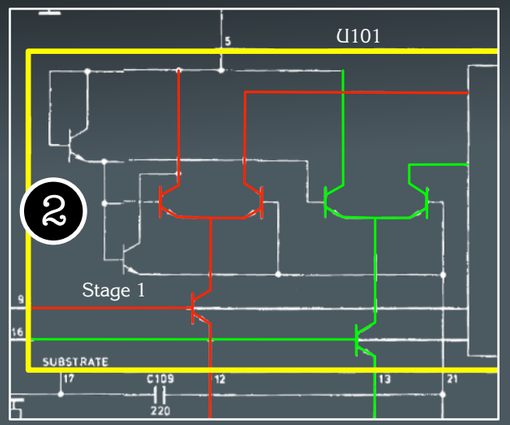
Example 2: if I = 1 mA and Vy is set so that I1 = 0.2 mA and (I-I1) = 0.8 mA, to have a reduction ratio of 0.5 (2:1), we have:

- I1 = 0.2 mA; Iout = 0.1 mA; Ix = 0.1 mA;
- (I-I1) = 0.8 mA; /Iout = 0.4 mA; Ix' = 0.4 mA.



The sum Ix+Ix' remains constant, and the orange part "steals" current from the differential amplifier; the reduction factor is the ratio between I and (Ix + Ix') currents.

Three circuits like this are contained in a single chip (U101).



❶ 8165A digital vernier basic cell.

❷ In the 8165A A4 schematic diagram, the circuit described in these pages is depicted in a way that you could find more understandable: each transistor of the first differential amplifier drives another differential amplifier.

A Bigger Picture

We learnt how the digital vernier basic cell works, but the complete picture is much more complicated.

Following a scheme similar to that we already saw for the VCO control, an 8-bit DAC converter is “extended” by adding a 9th and a 10th bit (stages 2 and 3), and, in consequence, three digital vernier basic cells are required, each of them being contained in U101. Microprocessor-derived signal L4 switches stage 3 on and off; L5 switches stage 2 on and off. Control current source for stage 1 consists of one current source driven by the D/A converter U801, to calibrate the lower attenuation point, and another current source to calibrate the upper attenuation point.

Each attenuator stage of the vernier IC has its own control current source (U802-Q801, U901-Q906 and linearity correction U802-Q803, Q804 for 1st stage, U901-Q907 for 2nd stage, U901-Q910 for 3rd stage) to calibrate the required attenuation of the stage.

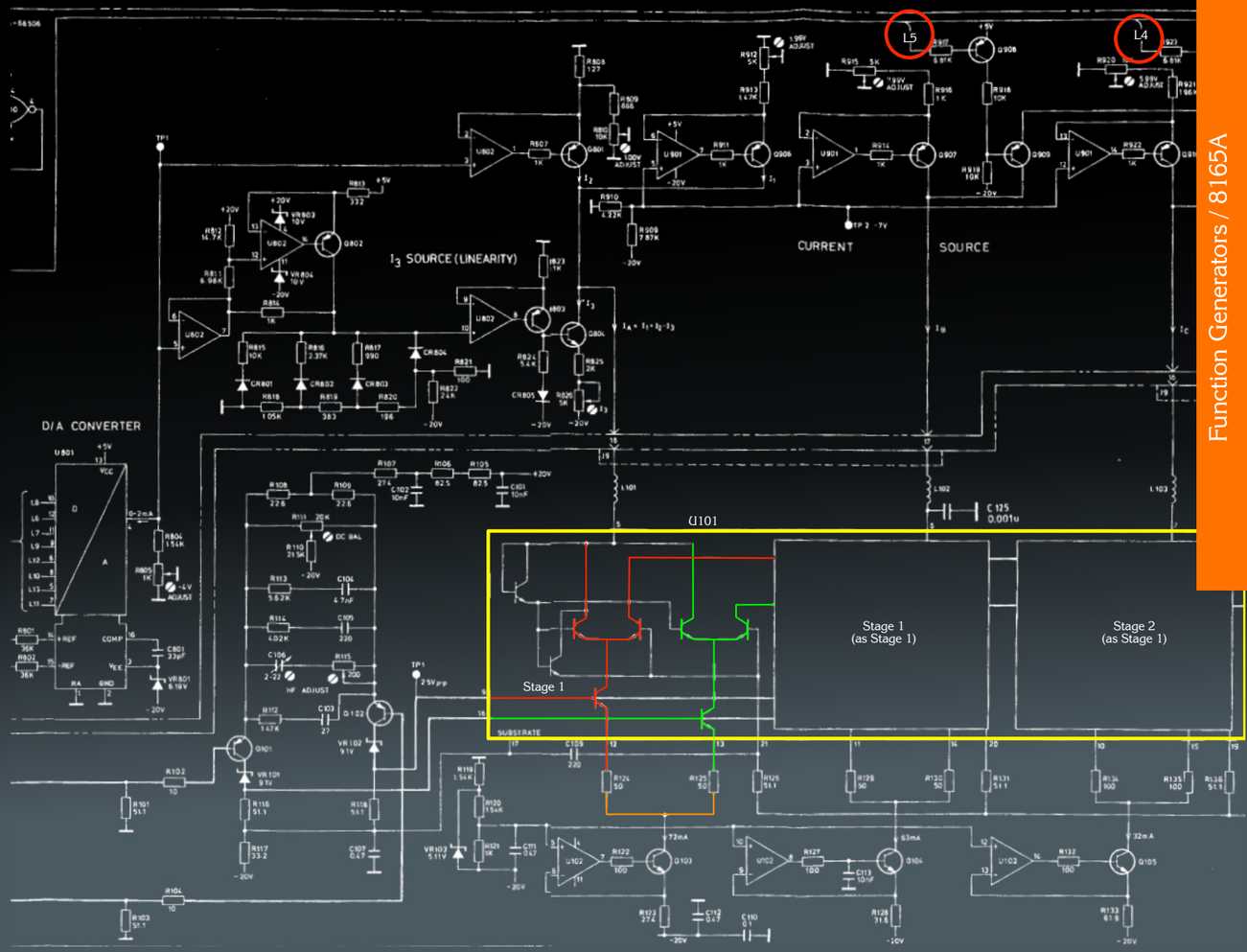
Stage 1 acts as the variable part of the vernier attenuator, and the maximum output from the total vernier is 5 V. With stage 2, the signal is attenuated to 50 % of maximum amplitude, and stage 3 attenuates the output signal a further 20 %. Stage 1 (variable part) also provides 20 % attenuation with 8-bit resolution.

I will not insist on constant-current sources, we already talked often about them.

Checking and repairing

With the help of the troubleshooting section of the manual (page 8-89), it was rather simple for me to check the correct operation of the digital vernier and find another fault in L4/L5 signals (circled in red in the upper part of the schematic here), driven by U707 CD4042 chip. Not having a replacement chip on hand, I replaced its outputs with switches and had the confirmation of the problem, which I later repaired.

This poor 8165A was very unlucky; to restore it into operation, I had to replace one transistor, two CD4042, one LM324 and one LM348.



Other sections

As mentioned, the Output Amplifier amplifier comprises other three sections: the Power Amplifier, the Attenuator and the Offset generator. Until now, I had not to repair them, so I add their description only for completeness, without going so much in detail as I did for the verniers.

Power Amplifier

Power Amplifier is described in Service Sheet 4B.

A block diagram of the power amplifier section is given here, in which it can be seen that the power amplifier comprises two amplifiers connected in parallel.

In normal operation, the Gain 2 amplifier is switched on and off via signal L3 at NAND gate U502. When switched off, total amplification (input to output) is unity, while switching on provides a total gain factor of 2 (Note: with a change in amplitude setting, both amplifiers are switched off momentarily (~ 5 ms) by the action of monoflop U503. A change in L1, L2, L14 or L15 causes L16 at U502/Pin 4 to go high, so that the next CLV clock pulse triggers the monoflop and the amplifiers are disabled).

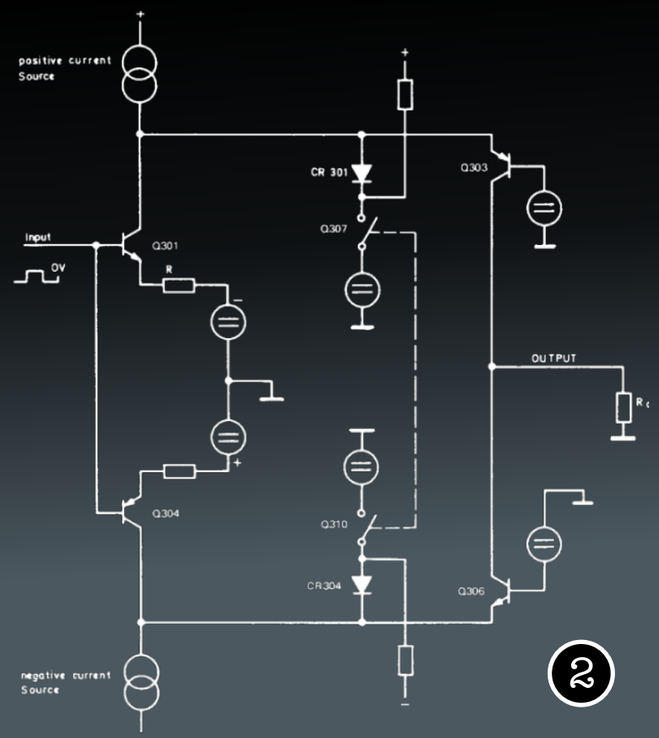
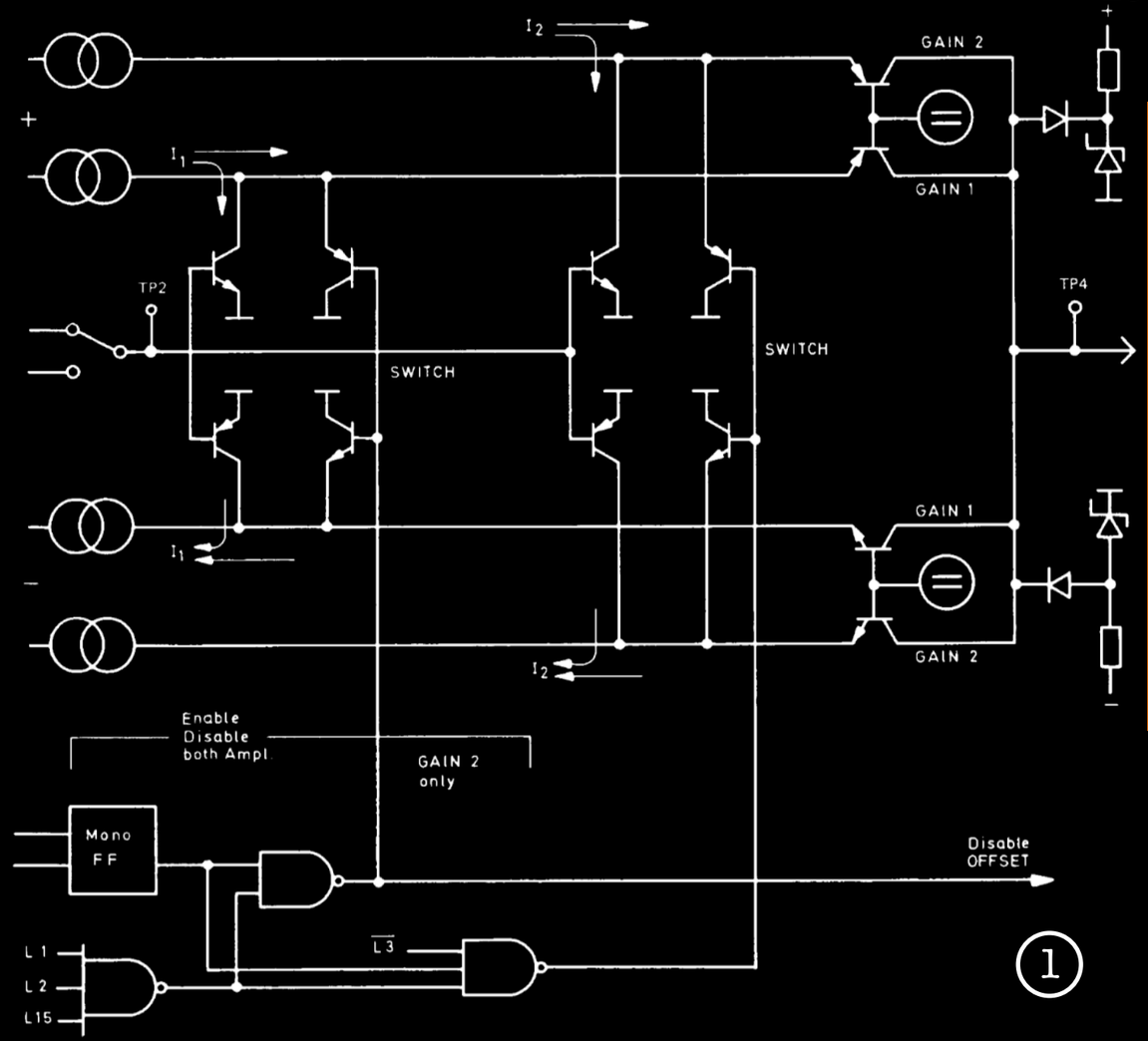
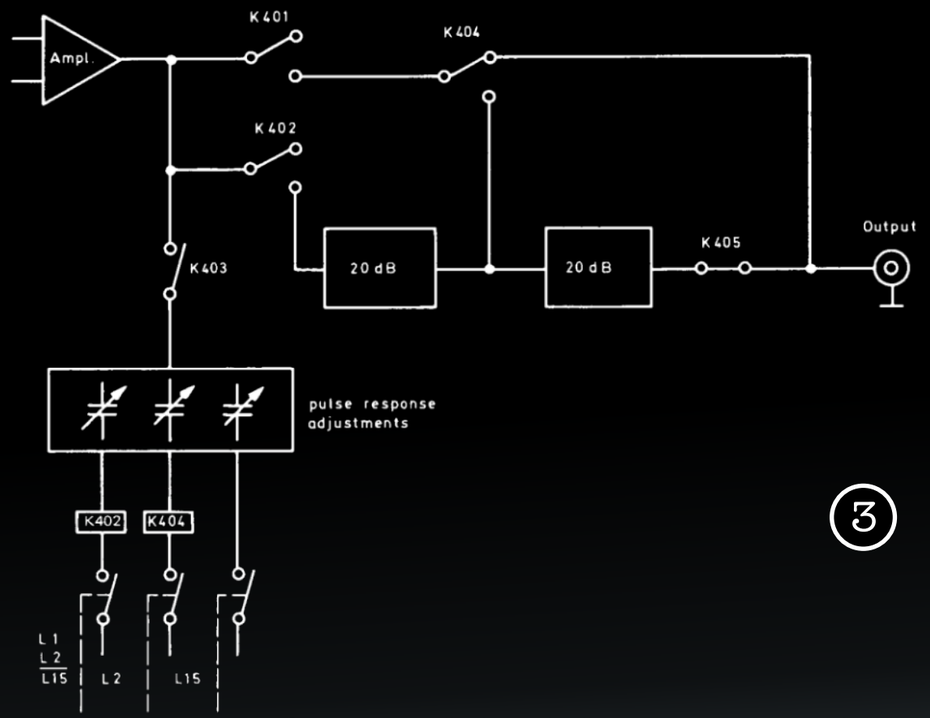


Figure 8-4-6 illustrates the operating principle of the switchable amplifier, the only difference in normal operation between this and the 'Gain 1' amplifier being the switch function. The amplifier consists of 2 complementary cascode stages working in push-pull mode (complementary cascode = NPN and PNP transistor connected in common emitter/common base configuration to provide high input impedance, high output impedance and high gain).



The positive cascode stage comprises common emitter transistor 0301, common base transistor Q303 and the positive current source; the negative cascode stage comprises common emitter transistor Q304, common base transistor 0306 and negative current source. 0301 and Q304 operate as voltage-controlled current sources, the input voltage to their bases determining which is more heavily



3

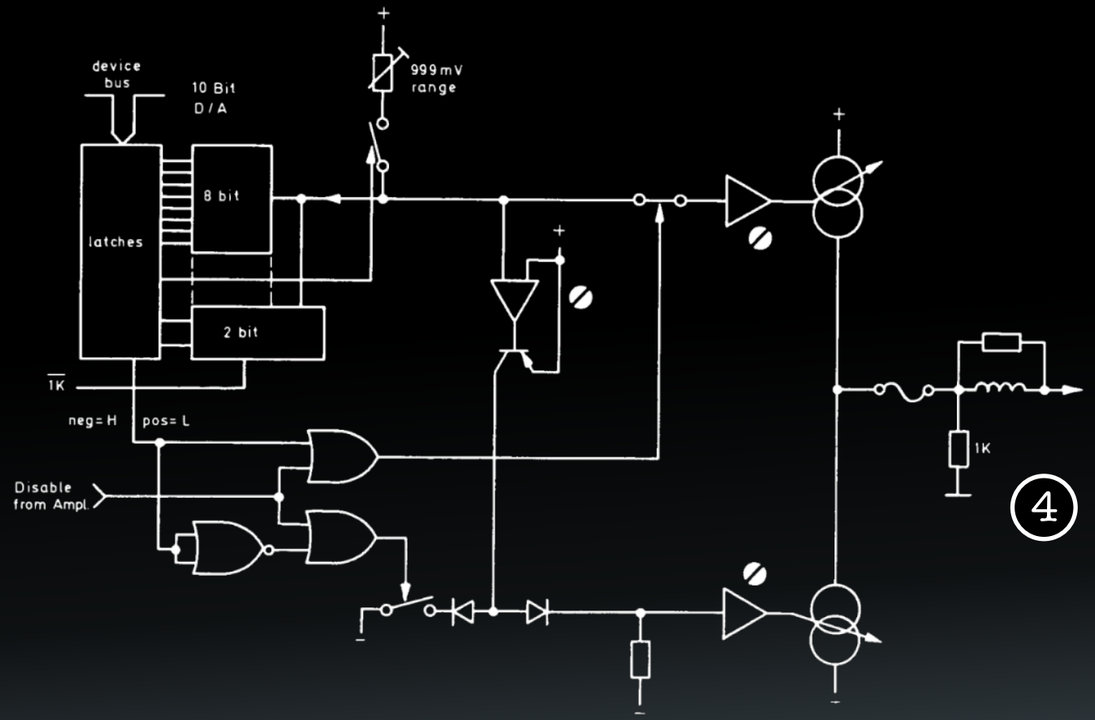
biased (the minimum bias current flows continually through all 4 transistors due to it being a linear amplifier).

To switch the amplifier off, transistor switches 0307 and Q310 are switched on, so that all current flows through diodes CR301, CR304 into the voltage sources.

Attenuator (Service Sheet 4B)

Two 20 dB resistive attenuators are located between the power amplifier and the output BNC connector.

The first 20 dB attenuator is switched in by the action of relays K401, K404 and K405 i.e. in 8165A amplitude range 100 mV - 999 mV. The second 20 dB is switched in (to make a total 40 dB) by K402 i.e. in 8165A amplitude range 10 mV - 99 mV.



4

Offset Generator (Service Sheet 4C)

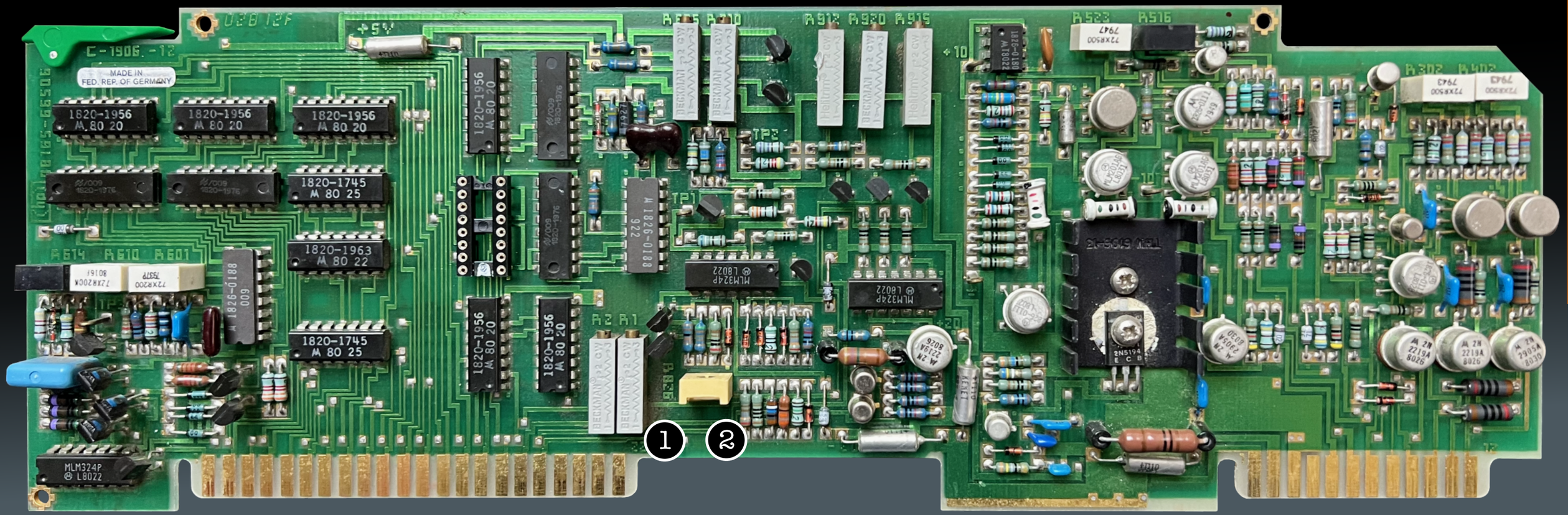
A block diagram of the offset generator is given in Figure 8-4-8. Depending on the desired output offset, the microprocessor transmits the necessary digital information to the 10-bit D/A converter, which in turn controls a positive and negative current source.

To keep capacitive loading to a minimum at the 8165A output, a filter (L1, R35, C9, R37) decouples the offset generator from the output amplifier.

During a change in the 8165A's output amplitude, the offset generator is momentarily (~ 5 ms) switched off via signal 24 at NOR gate U1, pin 12 and pin 6. When this signal is high, transistors Q3 and 09 are switched on thus disabling both current sources.

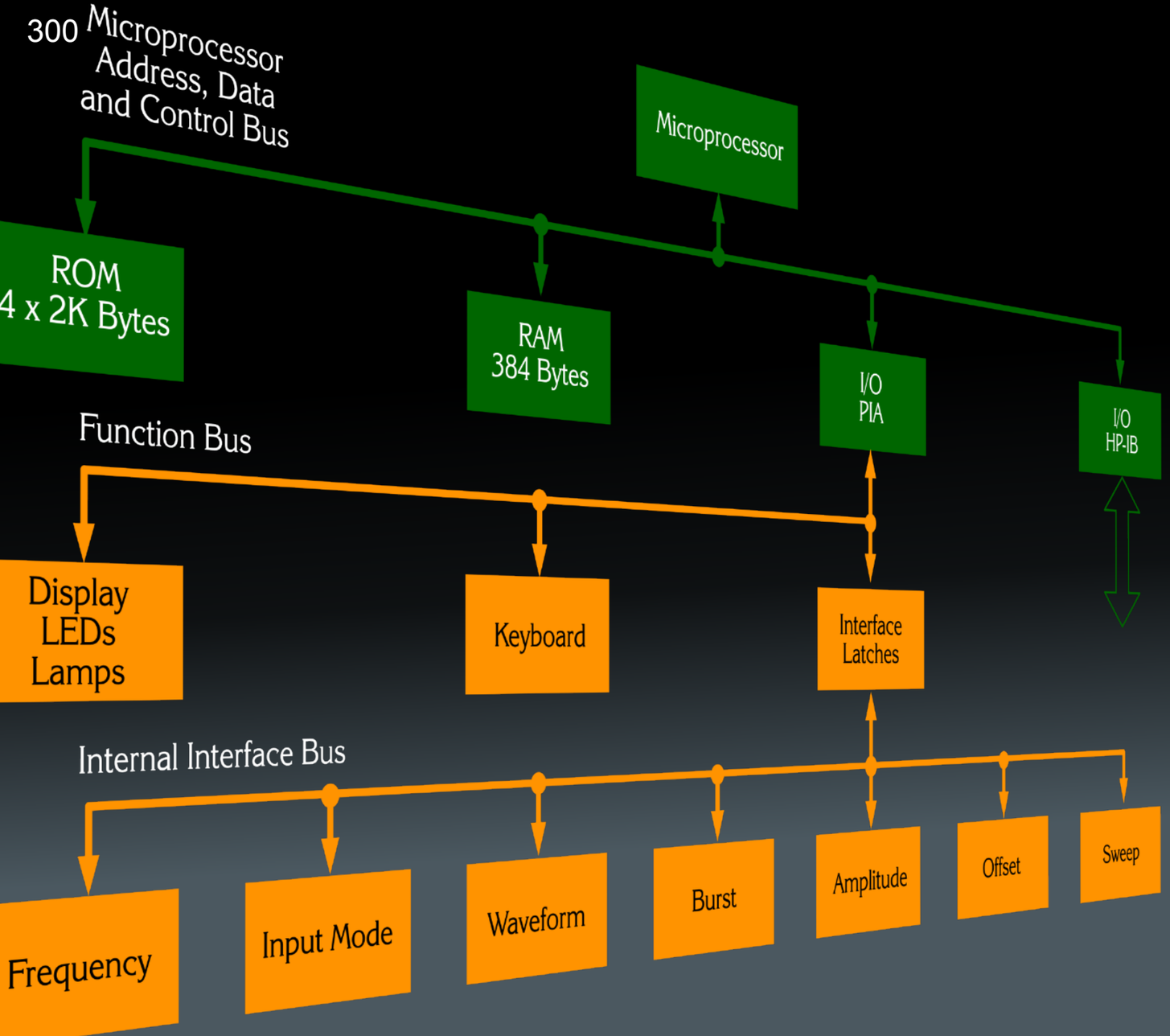
Control & Power

A6 Board: Control & Power



A6 Board contains parts of the power supply and some digital interfaces. Note the missing chip: the socket you can see is ready to receive U707 CD4042 faulty chip described in the text above.

Microprocessor



As usual

Arrived here, I realized I neglected, as usual, the microprocessor section of this 8165A, because it is the part I can understand better, and thus I find less exciting. I already underlined the wonder of software control introduction in a traditional instrument, so we limit here to technical aspects, again reviewing the trace of HP Journal, which is far too generous with information on this point, the most appealing novelty at that time (while I would have preferred to know more about the analogue part, like the output amplifier).

Microprocessor Control System

Like Tektronix did in several instruments, HP chose, for the 8165A, an 8-bit M6800 microprocessor, very popular at that time, as the Intel 8080 and the Zilog Z-80 were (the latter had been released last and was much more powerful than the others). The uP code was stored in a rather large 8K ROM, but was equipped with only 384 bytes of RAM. I can imagine the developers efforts; they had to manage the HP-IB interface as well, in a space that nowadays were not enough for an icon!

uP Tasks

Typical tasks handled by the 8165A's uP, included manual data entry via the keyboard, preparation of data to set up the generating circuits, data checking, data reporting, and, as told, remote data entry via the HP-IB. Data is stored by the microprocessor so that information about operating states or errors could be recalled or sent over the HP-IB.

8165A's microprocessor system is based on Motorola MC6800 and was one of the first used in a HP instrument. Among its big novelties, a HP-IB interface, which allowed to program almost every function of this generator.

Acceptors

A strange scheme was adopted to communicate with the various internal peripherals. Instead to simply implement output ports from the bus, they recreated a low-speed, 16-bit, address/data bus, using a MC6820 PIA, a dual 8-bit parallel port complementary chip of the MC6800 family. It's not clear why the decided for this approach; perhaps to reduce EM emissions?

This 16-bit multiplexed address/data bus was used to send data to **acceptors**, which, even then, we would call simply **output ports**. Most of the traffic in the 8165A is unidirectionally outbound to control analog circuits. The large figure on the previous page shows the microprocessor's kingdom structure. An acceptor has the function of storing just the information intended for its particular analog circuit, and to do this, each acceptor has a unique address.

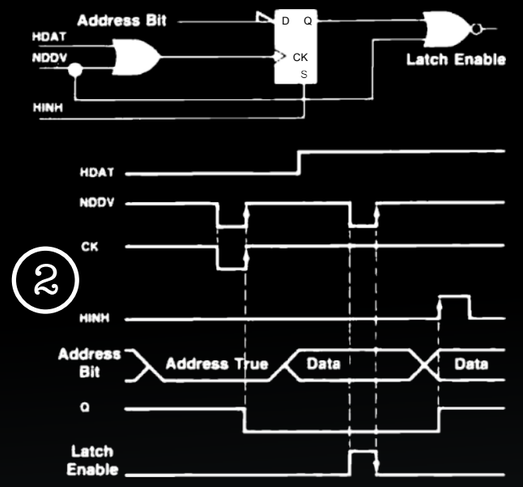
How the bus works

The internal bus consisted of 16 data/address lines and three handshake lines. The handshake lines defined whether data or an address was being transmitted and coordinated the information transfer.

- The **HDAT** (high data) line was high when data was transmitted and low when an address was transmitted.
- The **NDDV** (device data valid) line provided a positive transition to signify that the data or address on the bus was valid.
- The **HINH** (high inhibit) line goes high to terminate a transmission.

A typical acceptor consists of a latch and a latch-enabling circuit, the latter reacting when the appropriate address appears on the bus. I would say all this definitely conventional, once you accepted not to use the uP buses.

Circuit configuration and timing of a typical acceptor are shown in figure ❷. The flip-flop, normally with Q high, was clocked by NDD when HDAT is low. If the latch's address bit was active (low), Q will then go low and permit the next NDDV pulse to enable the latch. When the data was terminated, the HINH pulse returned the flip-flop to its normal state. Data transmitted over the line used by the address bit had no effect on the flip-flop when HDAT was high. If the data for the acceptor consisted of more than one 16-bit word, the words are transmitted serially and stored in a corresponding number of latches. Separate enable signals for each latch were generated by a master/slave flip-flop arrangement.



HP calls "acceptor" a simple port multiplexing. Besides the keyboard, in the 8165A, most microprocessor functions are "output-only".

Possible Addresses

Again with reference to the same figure, there were seven different addresses for the seven functions: **frequency**, **input mode**, **waveform**, **burst count**, **amplitude**, **offset**, and **sweep start-stop frequencies**.

Some acceptors in the 8165A used two address bits: in these cases the appropriate lines are applied to an OR gate to supply the flip-flop's D input.

The poor M6800 microprocessor with 4x2K-byte read-only-memory (ROM) and the ridiculous 384-byte CMOS read/write random-access memory (RAM) controlled the input/ output section including the HP-IB interface.

Operating the 8165A

A disadvantage of many digital instruments (including the 3325A we are going to examine next) was volatility of data after a power interrupt. The 8165A's CMOS RAMs with battery backup are able to store the data approximately four weeks. When the instrument is switched on, the output is automatically disabled to prevent possible damage to a device under test. A complete error test is also performed. Ten registers are provided to store ten complete operating states. This is very convenient on the bench as well as for systems applications, when rapid and repetitive changes of parameters are required.

An important design goal was to give the user maximum flexibility in setting up. Data loading is simple: select the parameter, and enter the value followed by a delimiting unit key. Simple task push buttons (e.g., waveform, input mode) may be pressed at any time during programming. A complete error test is performed after the change of any parameter. The error routine starts by verifying over-range or under-range of entered data. It continues by testing the compatibility of existing data with data just entered. After this sequence, data is stored and processed and the instrument updated.

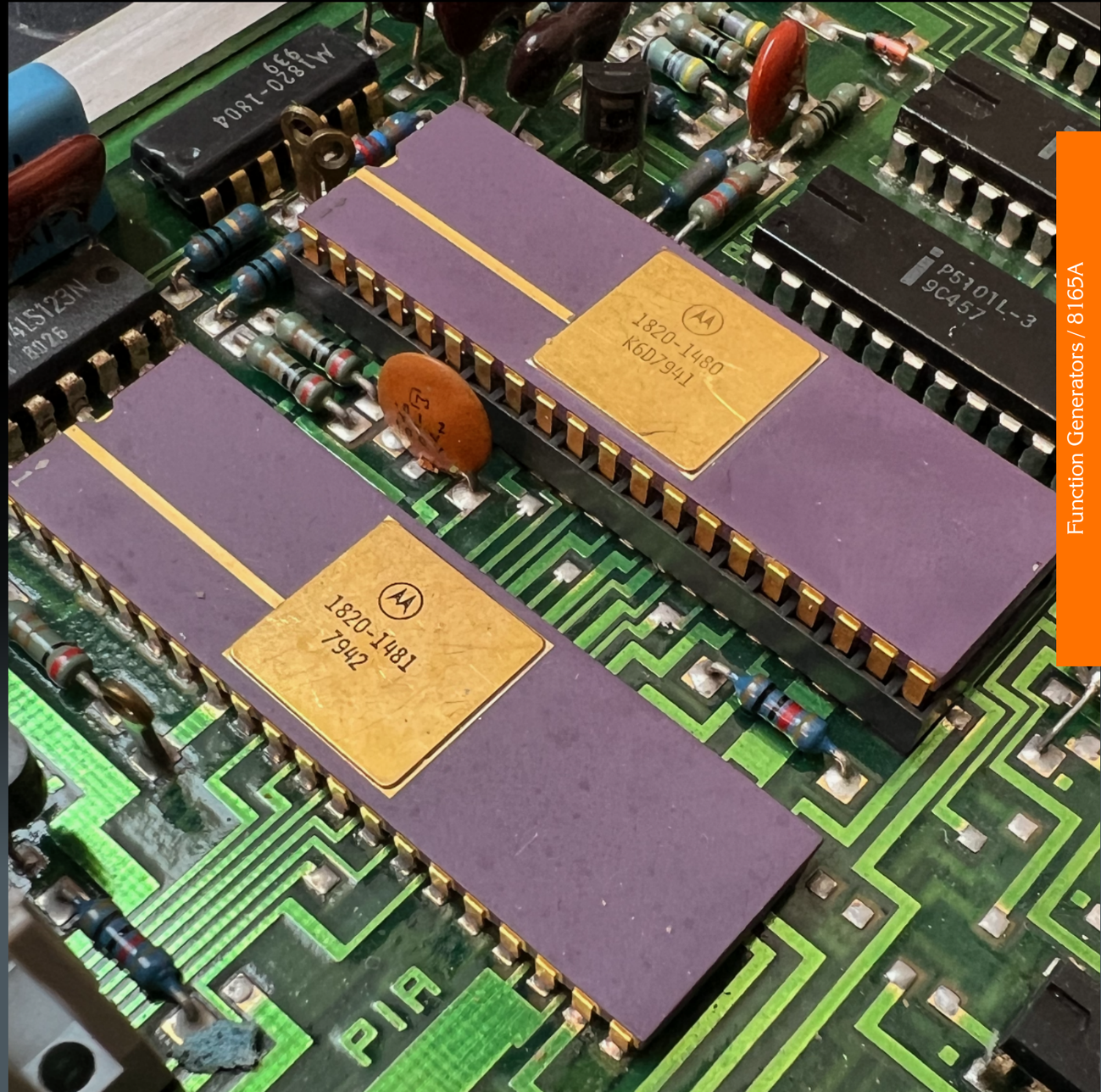
If an error occurs, the keyboard is locked so the only keys that will operate are those that allow the elimination of the error. As shown in the following photos, the keyboard, organized as an 8x9 matrix, is scanned serially by the processor. One-half of the PIA, in conjunction with a multiplexer and a demultiplexer, is responsible for the keyboard matrix. When a changing key status is recognized, key bounce effects are eliminated by reading the status again after a few milliseconds. If there is no further change, the new status is accepted by the control system.

Batteries

Batteries' advantages, as mentioned above, are consistent, but they are usually origin of problems to to us little restorers. We are talking about 45-years old instruments, and no battery survives so long. You are lucky if someone removed them before their acid leaks destroy PCB traces. In this case, someone did so, and PCB has only some corrosion signs. Modern lithium batteries are much safer from this point of view, but the 8165A uses rechargeable NiCd type, much worse.



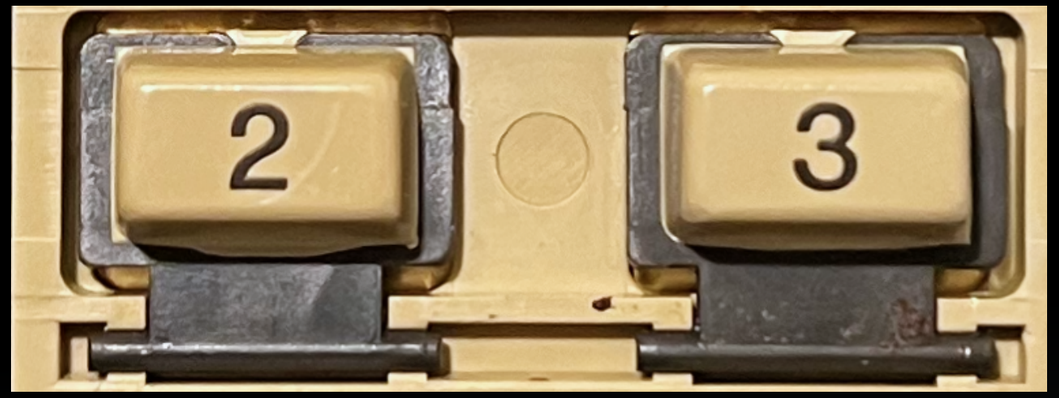
I bought from Amazon 6 inexpensive 1.2 V replacement batteries; the 8165A requires two of them, but 6-pack was more convenient. I was not careful, and I didn't realize their dimension, so, when they arrived, I remained surprised: they are huge (43x23 mm), so I had to find a horrible solutions to pack two of them in a sort of ball. I didn't want to discard my stock…

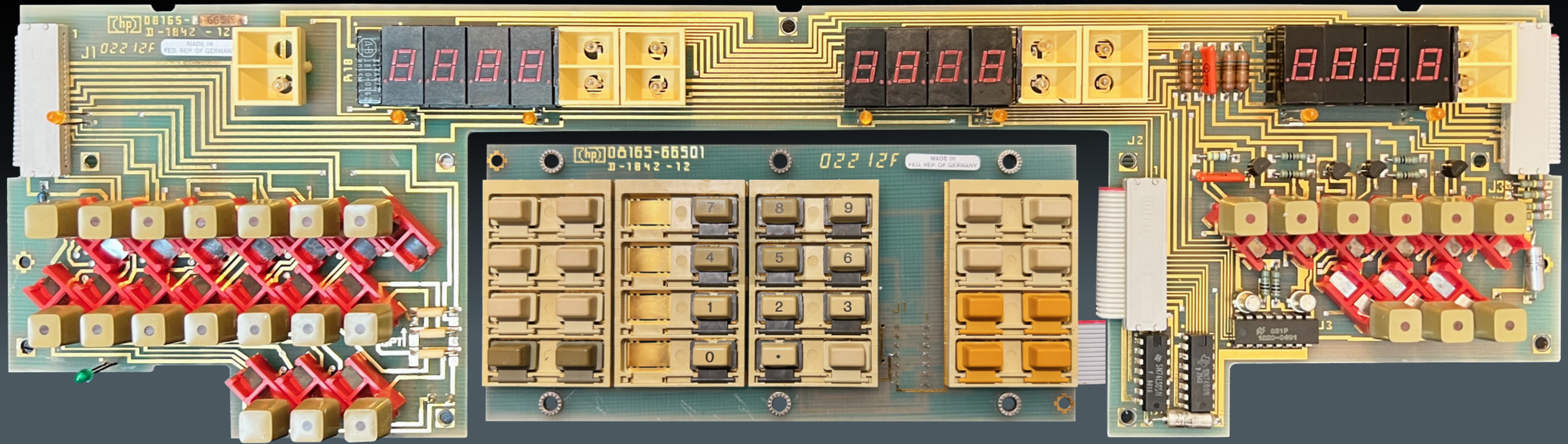


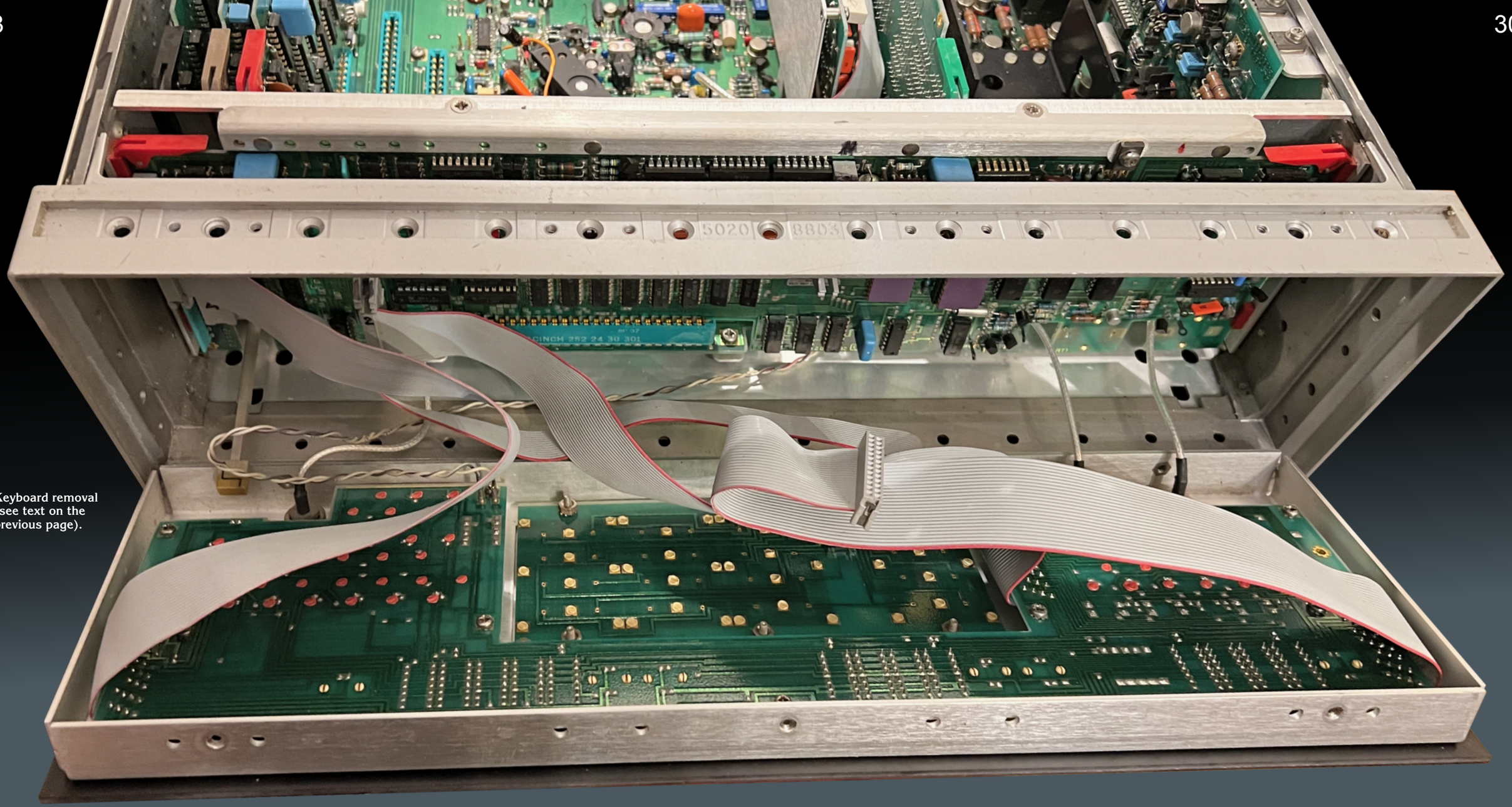
Glorious MC6800 microprocessor, disguised under the 1820-1480 HP name. 1820-1481 is instead the 6800-family PIA 6821 (Parallel Input/Output Adapter).

Keyboard(s)

The 8165A has two separate keyboards: one, which integrates seven-segment displays and LED, with large keys, the other with the same small keys used in handheld computers like the HP-35 or the HP-67 (see the detail above on the facing page). I like very much the large keys, used also in other HP instruments, like the 856x Spectrum Analyzers or the 3325A functions generator. In most of my equipment, these keys had a bad “clock” sound or false contacts, but just a spray of WD40C (note the “C”) cured them perfectly. To perform this operation, you must first dismount the PCBs. This is not too difficult, just remove the screws that lock the front panel, detach connectors and proceed with care. See the photo on next page.



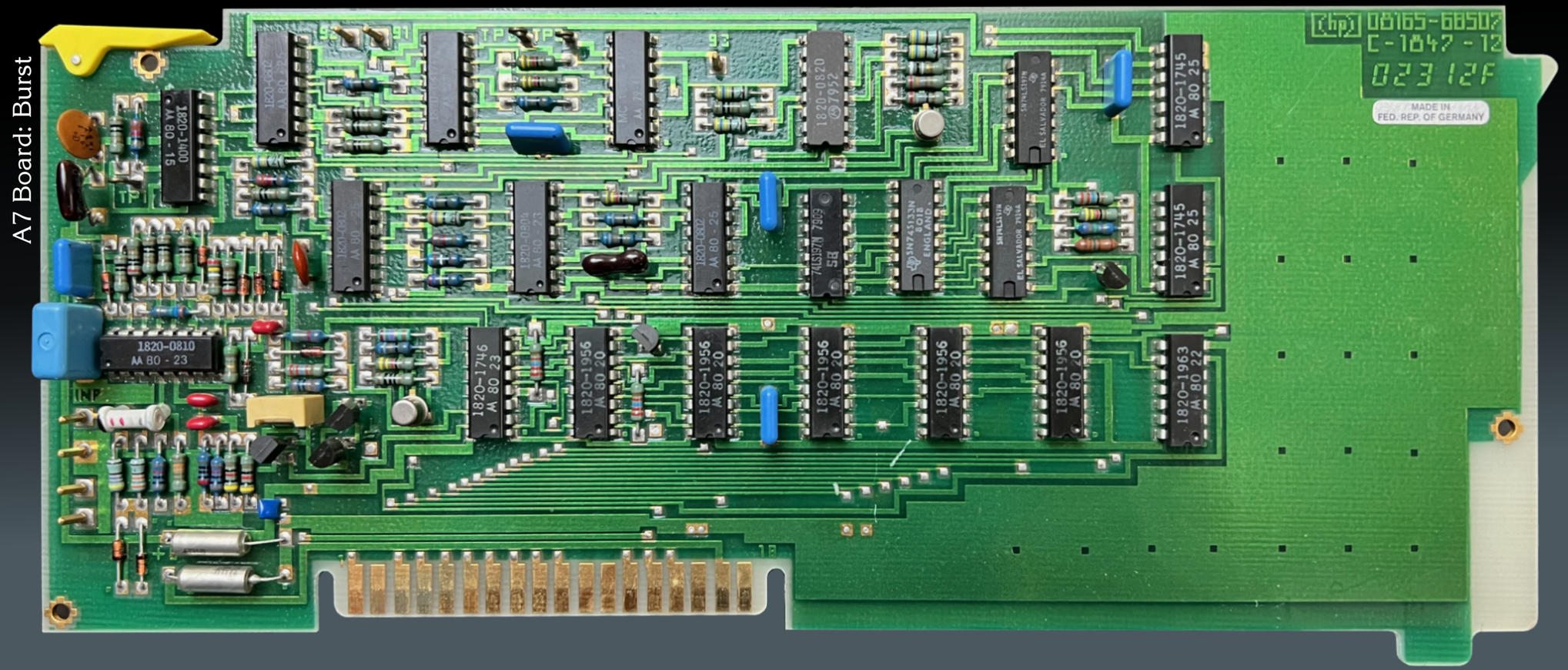




Keyboard removal (see text on the previous page).

Counted Burst

The 8165A has a counted burst capability, which means that, after a trigger signal is applied, a preprogrammable number of cycles are generated. The technical problem of designing a high-speed programmable counter with common ECL and TTL technology is solved in the usual way: a programmable up-counter is preset to a number Y-(N-1), where Y is the upper limit of the counter and N is the required number of output cycles. The counter is monitored, and when the state Y is detected, the next output cycle of the HF or LF oscillator is stopped. The value of N=1 is treated as a one-shot trigger, as in external trigger mode, and the value N=0 disables the trigger input and allows the 8165A to be used as a de source (signal off, offset variable). Thus the full range of 0 to 9999 cycles per burst is available.

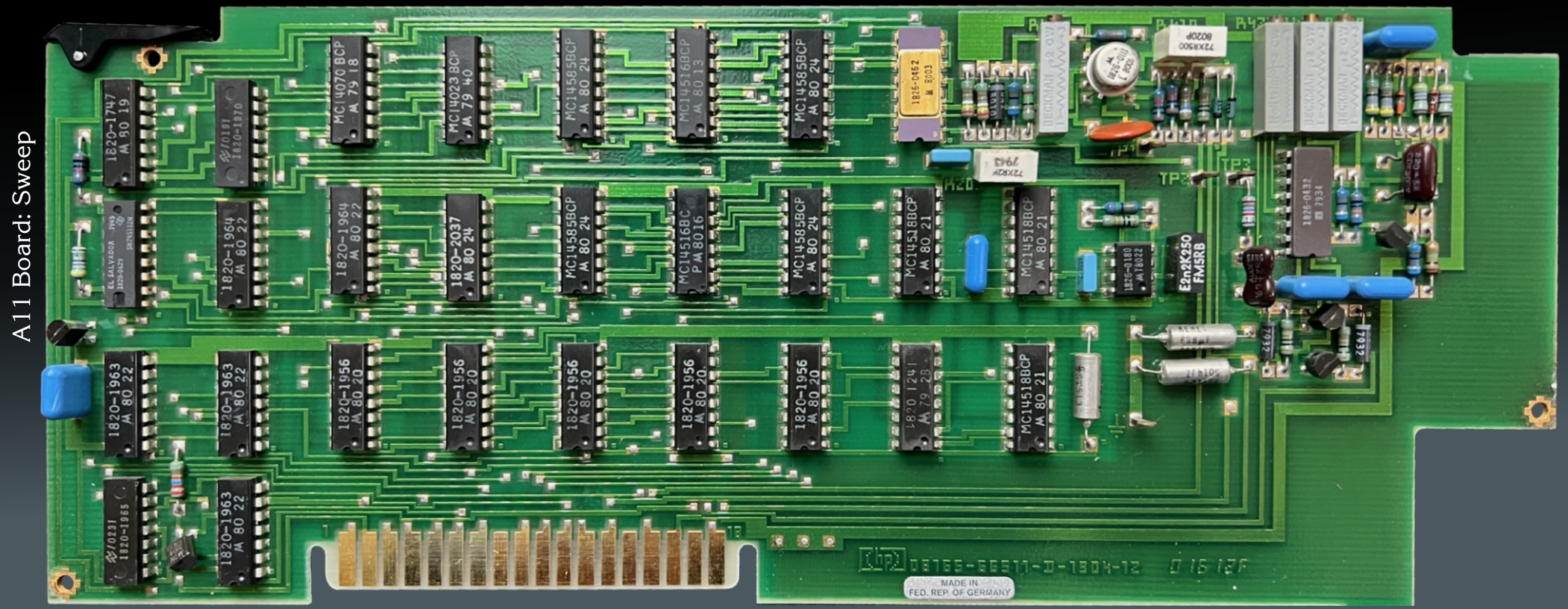


A7 Board: Burst

Sweeping

You can make the 8165A sweep by using the VCO input in VCO mode, with a triangle wave produced outside. The Option 002 provides the 8165A with logarithmic sweep capabilities (and, BTW, amplitude modulation). Logarithmic sweep output allows the user to sweep logarithmically between two frequencies, without any external equipment.

Start and stop sweep frequencies can be set by the front panel keyboard. The sweep time can be selected among preset values (0.01, 0.1, 1, 10, 100 and 1000 seconds) using dedicated button. Sweeping is implemented with the same technique we already saw more times, i.e., with a DAC cyclically producing a triangle wave. A range of three decades can be covered. Unlike some sweep circuits, a triangle instead of a sawtooth is generated. The advantage of this waveform is that there is no need for a blanking stage in an oscilloscope or for a pen lift circuit in an X-Y recorder. The sweep generator is based on an up/down counter and a digital-to-analog converter.



A11 Board: Sweep

The King of Faults

Seek on Arrival

I purchased this 8165A knowing that if was faulty. The eBay seller (IRSA, France) is very correct and well described its condition, but display and keyboard were operating and this was enough for me.

The King of the Faults

Nevertheless, as mentioned earlier, repairing it was very difficult and required more than four weeks of intense labor. I don't regret this; in this time, in which I performed a true partial reverse engineering of it, I learnt a lot, and, in addition, as you know, I classify it as amusement. But I also award this one as the King of Faults in my hobby activity related to vintage instruments and radio. Until now I never had to suffer so much to catch the bug (second in the standings: the 8012B).

Initial situation

The initial situation was the front panel full operative, but no signal produced. The 8165A signaled an initial ERROR message, but this was due only to batteries lack. Therefore, I had to start studying the original documentation which, as anticipated, was composed only by the manual and the HP Journal. I downloaded the free manual that I could find on the Internet, but it was of poor quality, so I bough also the Artek Manual version, but in this case they were definitely the same, and that forced me to a partial restore of some schematic diagrams that you can see in these pages (they are freely available in the complete form from my web page, should you need them).

Oscillations

My first concern was the main oscillator, and I started from there; I disconnected CR103 as suggested by the manual, and something appeared. Acting on the trimmers, especially R71, I could arrive to a rough oscillation, but:

- erratic frequency values, generally higher than expected when present;
- asymmetric shape of the triangle wave.

Even in VCO mode, when the output signal should be just controlled by a DC voltage, worked only in the upper part of each range. No lucky condition, like detached connectors, gave any hope, and trying to understand the inner operation was the only possible way,

Youtube does not help: it seems like no one has had this problem.

The approach

I am not sure that mine was the best approach, but the only way I know in cases like this is to study and document. These pages are only a summary of all the notes I collected and wrote down. This is the reason why I documented so much here the ramp generator and its trigger.

Anyhow, although I believe I understood most of the details of this area, I wouldn't have gotten anywhere without a little luck.

The magic 100 ohms

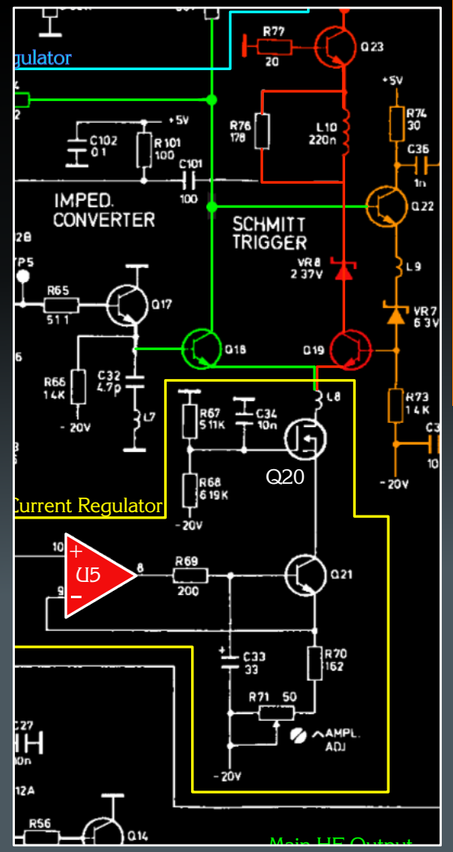
An important turning point was when I noted that things were getting better when the trimmer R71 (figure on the right) was screwed for the minimum resistance. So the current in the trigger is not enough, I thought, and decided to add a 100 ohm resistor in parallel to R70. That had a magical effect, and even the PLL in some occasions got locked. In parallel, the horrible output signal, started to seem more acceptable.

Thereafter, I doubled the energies studying the trigger, but… with very little results.

A digression

At this point, I decided to have a digression, studying the PLL. I was glad to see that Loop1 and Loop2 were operating correctly, and that sometimes the PLL worked rather well.

At this point, I discovered that many things operated well until I enabled the PLL (NORMAL key). But I discovered also that I



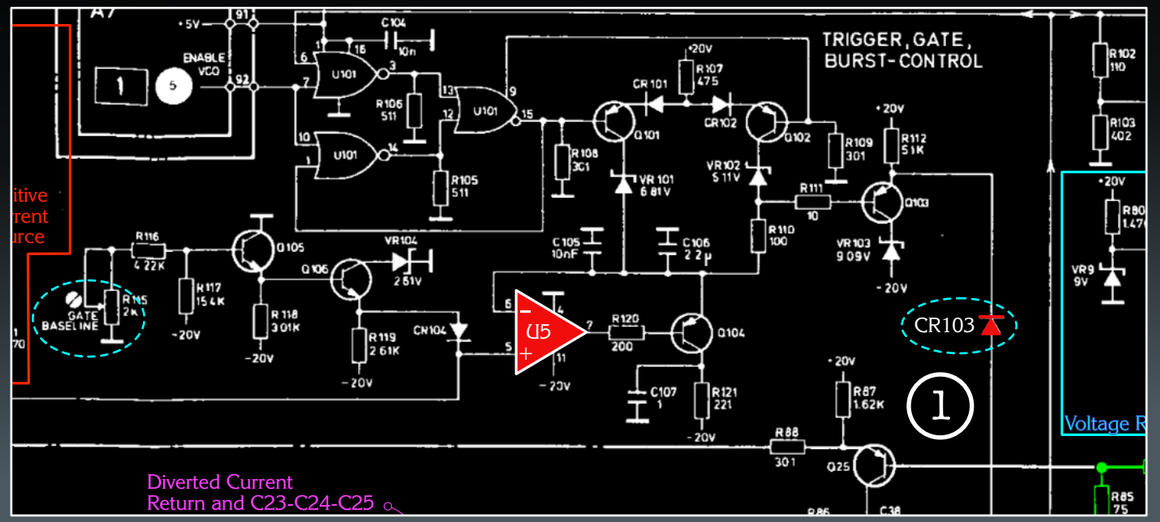
forgot to remount Q203, the only one that could really enable/disable the PLL operation. It seemed impossible, but the NORMAL key has no other effect.

The circle narrows

I observed also that detaching the wire 92 (see the figure here below), the NORMAL key had not anymore negative effects. So I focused on U101 circuit and, after several checks, I concluded that …it was impossible. This part of the circuit has inputs …but no outputs! Incredibly, removing Q103, the feeble signs of life disappeared. The only possible output was CR103, but it was not present. After other checks, I understood that U5 (enhanced in red here below) was shorted. Hence, a bold hypothesis… U5 is part of an LM348 quad opamp. Where are used the other three? In the trigger!

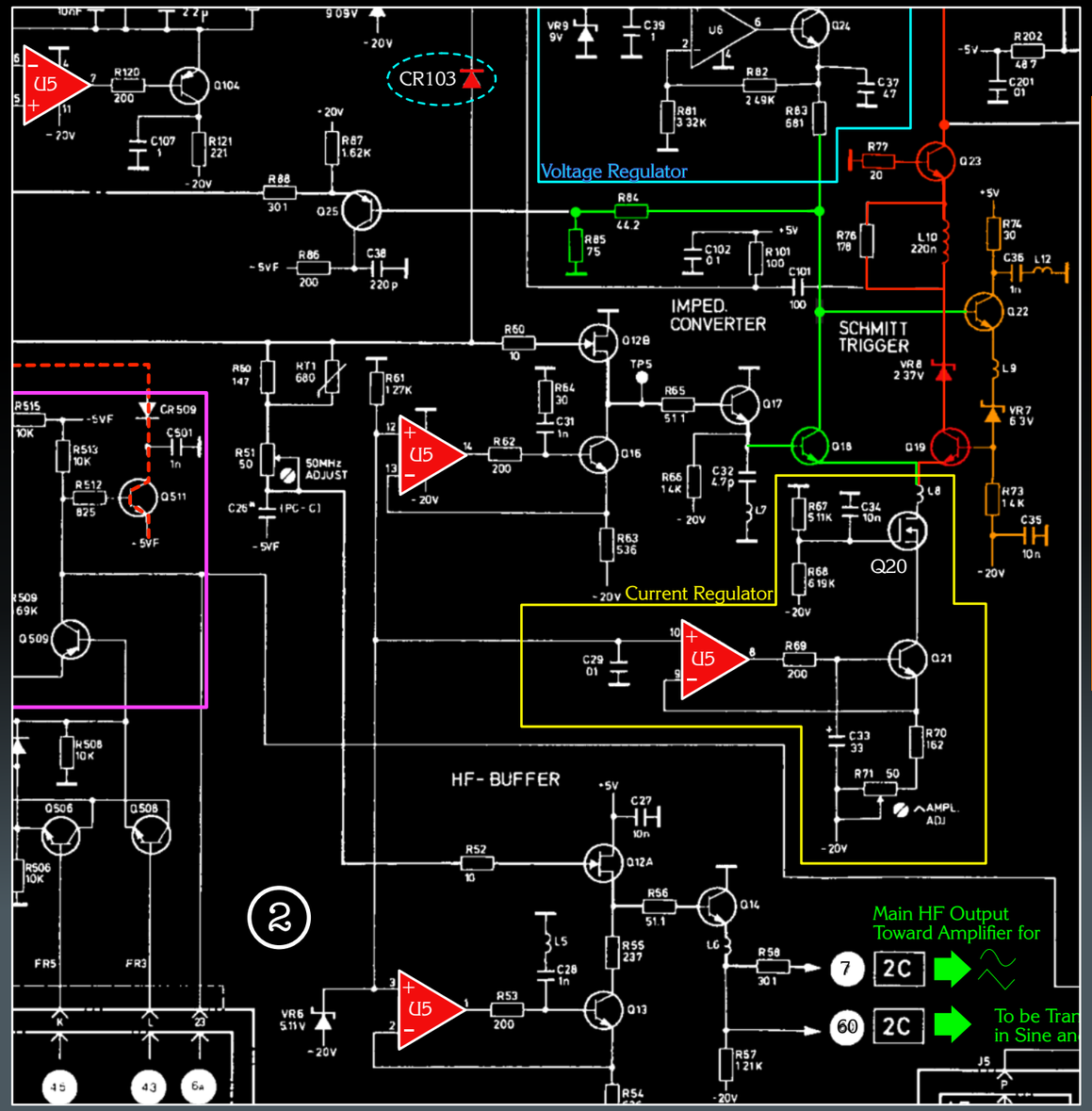
Finally, the solution!

On a Saturday, I removed U5 and placed a socket in its place, but I had to wait until Monday, and then for an intense labor day (the real work, not the hobby…) to get finally an LM348 and to see theory's confirmation: most of the functions got OK, including BURST and SWEEP. Wow!



❶ This faulty U5 LM324 (/Q104) determined unpredictable behavior of all the frequency generation, although not involved in the process itself.

❷ The reason is that the other U5 sections are used in VCO trigger, as shown here.

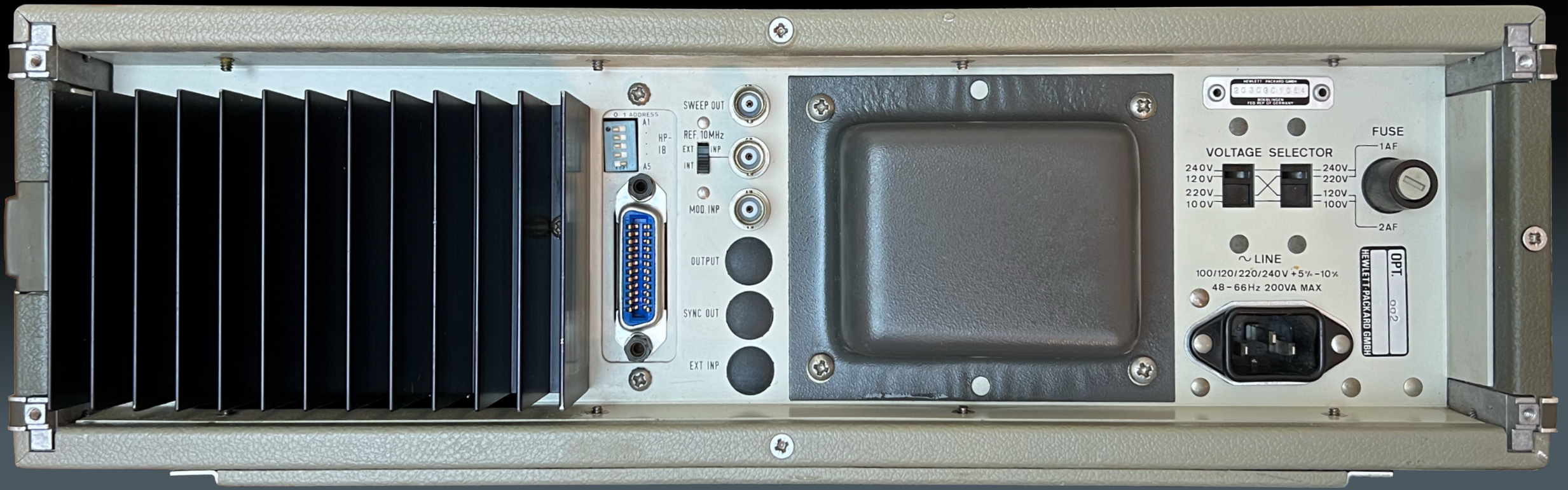


The B-side

8165A's rear panel follows typical guidelines of other HP equipment of that time. In this case, the most striking novelty is the HP-IB connector, forbidden on previous generation equipment.

The heatsink is there in addition to the internal fan, and only three BNC connectors are present: two are from Option 002 (Sweep Out and Modulation Input), the other is for using an external 10-MHz reference, to obtain greater frequency accuracy/stability. The internal reference is a simple crystal oscillator, without any thermal stabilization, but is however rather stable.

The other BNC are just placeholders, for Option 003, which allowed you to have front connectors on the rear. Note the sticker signaling the presence of Option 002 and the serial number 2030G01064, which tells us that it includes the first 22 changes but not the production year (from ICs, we can locate it in mid-1980).



Calibration Notes

My Less Preferred Operation

Calibration is the part of restoration that I like less, because it is too “analogical”, so, when not mandatory, I often prefer to leave things as they are. But in this case, it was necessary, because during the repairs I moved almost all the VCO related trimmers, and the good 8165A deserved it, having decided to return to life despite all the insults I had directed at him.

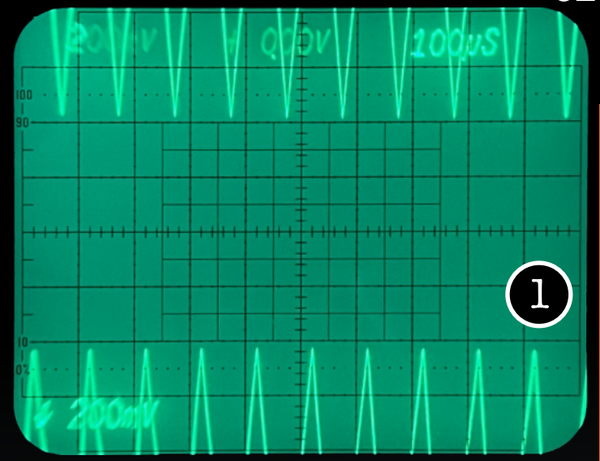
Some Notes

Also in this, the manual is not exceptional. Nevertheless, with some patience, it can be followed. I hope that few notes may help who wish to perform this operation (if any…) in the future.

- **OUTPUT DRIVER BALANCE** How to interpret the statement *“Set DVM to 10 V range or use a low pass filter for the 1 V Range. Connect DVM (dc, floating) between A5TP10 and A5TP11”*? I used a different method. I used the 7A13 differential plug-in, connecting TP10 and TP11 to its plus and minus inputs. In this mode, you can get something like figure (1), after setting the ground to the center. The correct setting is when the upper and lower trace are equally distant from the center.
- **TRIANGLE DISTORTION** Here I could not succeed following the manual. I have no explanation: the manual seems to be wrong when it require *“Connect the capacitor (0.47 F) between junction A5R50/R60 and ground”*. The junction A5R50/R60 is the ramp capacitor. As expected, adding that capacitor, no oscillation is produced. I proceeded without it.

❶ Use of a differential input oscilloscope plug-in for Output Driver Balance check.
❷ The frequency setting trimmers for the various bands and frequencies.

- **HF SINE DISTORTION** The suggested method to adjust the sine shaper and produce a good sine wave is very good. Using R340 and R350, you minimize the second and third harmonics difference when in normal and complement mode. I this way I could obtain a good result, which I could not obtain preceding by eye.
- **VCO CONTROL ADJUST** Be sure you are using a suitable oscilloscope, i.e., with enough bandwidth.

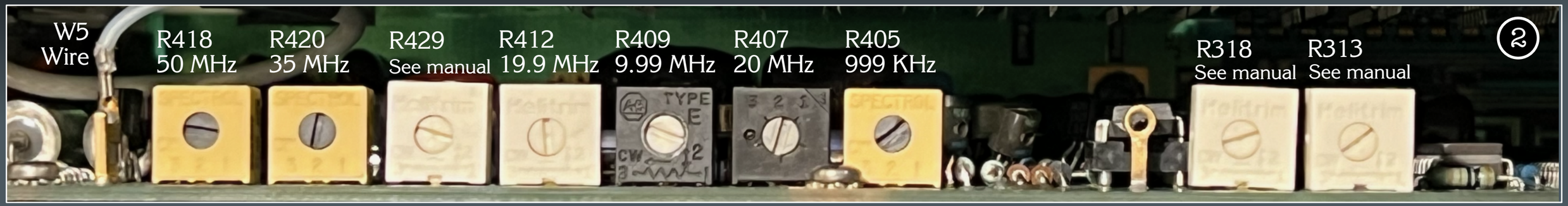


Frequency Problems

You need to set the oscillation frequencies in the various band by setting the GATE mode and applying a voltage to the front panel BNC input, to keep the VCO enabled and the PLL disabled. As intuitive, you must set the non-PLL frequencies to be as near as possible to the expected frequency, so that the PLL makes little effort to hook it (not more than 5% from the expected value).

Setting R418, R420, R412 and R409, I could not reach the target frequency in the related frequency bands. At high frequency (above 1 MHz), just C26 ramp capacitor is used, directly built in the PCB and very small. I imagined that even few pF could make the difference, and was right.

The problem had been created by me and was in the socket I added for Q513 (see the photo on the next page) and in solder residuals. Removed the socket and cleaned the PCB, the frequency still remains rather low, but with the trimmers I could however reach the required set points.



A Comparison

Time Does Not Pass in Vain

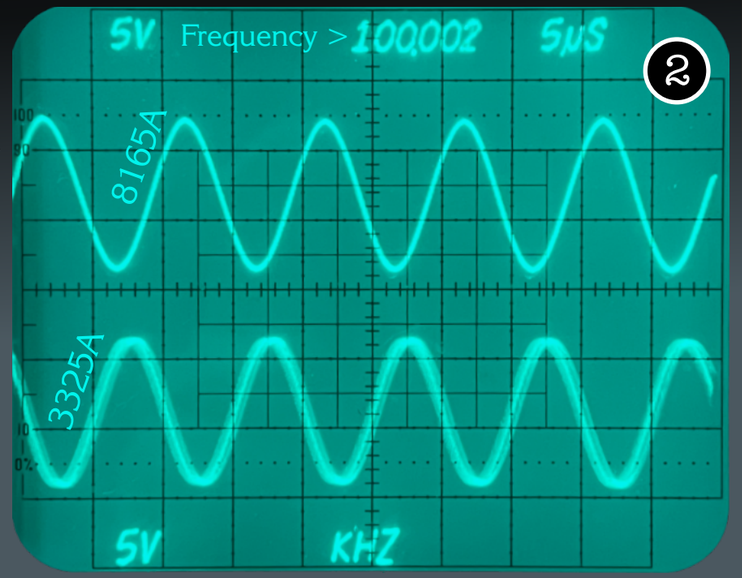
The photo below compares the 8165A, on the upper trace, and the 3325A Function Generator on the lower. The latter, which we will describe in the following, is more modern and uses the Fractional-N PLL, more precise, having not brisk phase changes like the “normal” PLL (said “Integer-N”). The 3325A allows to change the frequency very precisely; I could then adjust its frequency until I had a stable display of both the sine waves. Just one of them, the 8165A, triggers the oscilloscope. In this way, using the CRT storage 7633, I could record the small oscillation of the lower trace, which I attribute to the 8165A brisk phase changes.

This phenomenon is more evident at higher frequency and is probably greater for the multi-PLL 8165A’s architecture, which, as we expected, determines high jitter (or phase noise in frequency domain). In the photo, we are only at 100 kHz, as you can see thanks to 7D14 Frequency Counter plug-in of the Tektronix 7633 oscilloscope, much more accurate than many DSO “software” measurement.

It’s evident that the 8165A is producing, in this case, a signal of 100.002 kHz instead of 100.000, but we are still inside the specs: only 4-digit values are guaranteed.

As we will see, the Fractional-N PLL changes the phase “continuously” and represents a great improvement. Time does not pass in vain.





❶ This small socket for Q513 determined a reduction in VCO’s frequency due to parasitic capacitance, as described on the previous page.

❷ The oscillogram compares 8165A with the 3325A.

Conclusions

Beginning of Love?

The 8165A experience was very intriguing. As mentioned, working on it, I started to hate it less and even to love it a little, if only for giving me the satisfaction of the most difficult repair ever. Surely, it allowed me to learn a lot. Maybe that, in the future, I will rehabilitate also his friends 8015A and 8012B.

Complexity

Its circuit is very complex and someone could ask if this extreme complexity was really necessary. I can only guess that precisely this complexity made HP instruments so famous for their specifications.

Probably, the point **is not complexity**; good HP designers did their best to leave us extraordinary instruments. In most cases, the problems of my old stuff were not caused by a poor design, and an LM348 or a CD4042 can get broken everywhere, even more after 45 years. Even better, I must say that every component I checked was very precise since the beginning and perfectly maintained its 1% value even after all these years.

A Lesson from the History

All this teach us something that can help us even in our today jobs: the real problem is not the complexity by itself, but its **management**. You can design and produce complex equipment, but you must be prepared to manage it. As I told you, I consider myself rather unexperienced about these analog circuits, but probably the average service technician was not too more skilled than me.

In a short, I learnt from old HP generators, that, in general, the biggest problem is the **lack of information**. A better documentation would have been enough to make my repairer's work many, many times easier and weeks shorter; at least just few voltage indications, like those used in old tube equipment, would have been enough.

On the left: my preferred oscilloscopes are the CRT storage 7623A and 7633. Very useful the 7A13 differential plug-in, which allows to measure currents even dynamically, and the 7D13 precision voltmeter. Not shown in the photo, also a 2431L DSO helps me in my hobby works. Automatic measures and cursors are priceless.