Digitizing and Modernizing a HP141 Display

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March 15, 2025

[1]Submitted to the Department of Electrical Engineering at the University of Cape Town in partial fulfilment of the academic requirements for the qualification of a Bachelor of Science in Electrical and Computer Engineering.

Declaration

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Acknowledgements

When you ask God for a gift, be thankful if he sends not diamonds, pearls, or riches but the love of real, true friends.

—*Muhammad Ali*

To my supervisor, Dr Stephen Paine, thank you for pushing me to reach my full potential and completing this research project. I am truly grateful for showing me what it means to be a good engineer.

To Michael Inggs, thank you for providing the necessary information for starting the project. The technical data, notes and videos that you sent to me at the beginning of the project were a lamp on the path to completing the project.

To my teachers who shared their knowledge along my academic journey, thank you for the great work that you continue to do in opening doors to a brighter future.

Thank you to my friends Thato Makhubedu and Ditiro Nkuna for their help when I did not have a place to stay while writing this report. Thank you to Steve Jermy, whose advice allowed me to remain in the city long enough to complete the project.

To the Almighty God and my mother, thank you for applying the patience that was required to mould me into the person that I am today.

Abstract

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Abbreviations

ADC **A**nalog-to-**D**igital **C**onverter

AvM **A**verage **M**ode

CRT **C**athode **R**ay **T**ube

DFT **D**igital **F**ourier **T**ransform

EDA **E**lectronic **D**esign **A**utomation

FFT Fast Fourier Transform

FPGA Field Programmable Gate Array

HP **H**ewlett-**P**ackard Company

IF **I**ntermediate **F**requency

LCD **L**iquid **D**isplay

LO **L**ocal **O**scillator

PHM **P**eak **H**old **M**ode

RBW **R**esolution **B**andwidth

RF **R**adio **F**requency

RwM **R**a**w** **M**ode

SA **S**ignal/**S**pectrum **A**nalyzer

SDK **S**oftware **D**evelopment **K**it

VSA **V**ector **S**pectrum **A**nalyzer

Chapter 1

Introduction

1.1 Background

Designed and patented in the 1970s, Hewlett-Packard Company's (HP) high performance plug-in model 8552B and 8555A spectrum analyzers (SA), equipped with the 141T display, remain powerful tools for characterising signals in the frequency domain. The 8552B is particularly convenient for measuring spectra in a wide frequency range between 20 Hz to 40 GHz. Another advantage of these spectrum analysers is that a user can broaden frequency requirements by increasing the number of tuning sections. Additionally, the 141T features absolute calibration of amplitude as well as high resolution, sensitivity and a simple display output.

The shortcoming of the spectrum analyzer, however, is that it uses a cathode ray tube (CRT) display which is prone to degradation after extended periods of usage and is outdated compared to the display on most modern devices. In this project, a single board computer and a liquid crystal display (LCD) touch screen is interfaced with the 141T display unit, thereby, replacing the outdated CRT technology. This allows users to continue to exploit the advantageous capabilities of the spectrum analyzer, such as the wide frequency bandwidth, despite damage to the CRT display. In addition, interfacing a single board computer with the 141T offers improved software-based features for performing frequency analysis.

Specifically, this project aims to develop a new display for the high resolution 8552B intermediate frequency (IF) section equipped with the 8555A spectrum analyzer radio frequency (RF) section which can make frequency domain measurements from 10 MHz to 18 GHz. The broad scanning frequency bandwidth of this model makes it suitable for frequency domain analyses in engineering applications such as mechanical vibrations and EMC field strength analysis with a calibrated antenna [1].

The CRT display subsystem consists of a post-accelerator storage tube with a 9 kV accelerating potential and aluminized P31 phosphor for producing high trace brightness. When calibrated, the CRT screen can display frequency bandwidths of up to 2 GHz wide. To display the full frequency range with a maximum of 18 GHz, the CRT can be calibrated in 10 frequency bands using internal mixing. One of advantage of the 141T over other displays that were manufactured during that time is that more detail can be observed in the spectrum by progressively narrowing frequency width from 100 Hz/division to 2 kHz/division. Overall, the 141T consists of a CRT graticule which can plot the frequency domain representation of a signal on a 2D plane with 8 x 10 divisions.

For this project, the 141T is powered by a 220 V single-phase source at 60 Hz, requiring less than

225 W even when plug-ins are connected. To achieve the 9 kV accelerating potential for deflecting electron beams in producing the CRT display, the device uses a step-up transformer and transistorized oscillator. The main disadvantage of having to increase the accelerating potential in a CRT display system is that the performance of electronic voltage regulation components such as capacitors, diodes and resistors can degrade over time.

Another challenge of using a phosphor CRT display is the effect of persistence on the saccadic information transfer which can lead to bias in experimental results [2]. This effect of persistence on experimental results is of particular interest to frequency domain analysis since displayed signals include noise from the environment which can make it difficult to extract accurate frequency information from plots. For the Model 141T, the persistence varies from the natural persistence of P31 phosphor (0.1 s) to a maximum of 15 s when the device is operating in the maximum writing rate mode. Therefore, phosphor persistence in the CRT display can significantly affect the amount of time to acquire measurements as well as the precision of the data extracted from the display.

1.2 Objectives

The aim of this project is to design a new display with full functionality and computer-aided signal processing features such as signal normalization. The digital display has to be compatible with the voltage outputs that enable analog signals to be plotted by the 141T. The aim of digitizing the signals is to interface measures from the spectrum analyzer with a computer that can perform tasks and store data accordingly. Therefore, a survey of the 8555A RF section and 8552B IF section outputs and available single board computer and touch screen options must be conducted. Furthermore, the project aims to investigate basic XYZ replicas, performing digital signal processing algorithms, how to correctly display signal data on annotated axes depending on available instrument settings.

This report aims to provide:

- Characterization of the HP141 display inputs from the 8555A RF section and 8552B IF section
- Available options for single-board computer and touchscreens options and the most suitable selection for interfacing with the two spectrum analyzer sections
- A design and simulation of interface between the single-board computer which includes analog converter for digitizing outputs from the RF and IF sections
- Algorithms for processing the digital signals and performing operations on displayed spectra
- Results on the construction, unit tests and integration tests of the improved system for spectral analysis

1.3 Project Requirements

Before detailing system requirements, user requirements were used to scope the project in terms of objectives that are not related to functions and performance. In designing the upgraded or ‘new’ SA, selection of hardware components was conducted with the aim of formulating specifications that successfully fulfill user requirements. Table 1.1 summarises the user requirements and gives a short description of the objective.

Table 1.1: User requirements.

ID	Requirement Description
UR01	Display of the new SA must behave like the display of newer generations of SAs, such as the Field Fox. That is, the new SA must achieve more or less the same number data points as the Field Fox (801 points).
UR02	The SA must have the following display modes: (a) Peak hold mode (PHM) which displays the largest value seen and updated at each scan. (b) Average mode (AvM) in which each frequency bin's average is updated at each scan. (c) Raw mode (RwM) where the latest value is displayed until the next scan and overwriting each value during a scan event.
UR03	SA unit must have a suitable vertical resolution based on a 10 dB/division in the logarithmic scale.
UR04	Linear display mode must have low priority.
UR05	SA display subsystem must have setting markers, similar to the Field Fox analyzer.
UR06	Design must be capable of storing and recalling traces.
UR07	Users must be able to change modes by touching the screen and must be able to enter data using a keyboard.
UR08	All software must load on power up.
UR09	SA unit must use a single wall wart power source for the display subsystem.
UR10	Project must develop an HP141T display emulator of horizontal sweep, vertical sawtooth and pen lift state.

Table 1.2 details system requirements in terms of functions and performance. These requirements were developed after a review of the scope through the formalization of the user requirements in table 1.1 above.

Table 1.2: System requirements.

ID	Requirement Description
SR01	The system must digitize analog outputs from an HP141T 8555A model which performs frequency domain measurements between 20 Hz and 18 GHz.
SR02	Digitized outputs must be interfaced with a single board computer for performing signal processing tasks.
SR03	The system must include a signal conditioning box for debugging purposes and replicating the outputs of the spectrum analyzer during testing.
SR04	The system must be simulated using software.
SR05	The display must include new annotations that take instrument and operator manual inputs into account.
SR06	The system must include appropriate documentation such as tutorials and operational instructions when using the signal processor and screen.

In addition to the above mentioned system requirements, the project considers the basic configuration parameters that signal analyzers typically provide such as:

- Setting the minimum and maximum frequencies to be displayed based on a given center frequency

- Setting the reference amplitude for frequency responses and a span that is suitable for the spectrum analyzer
- Setting the frequency resolution according to the passband of the IF filter
- Setting the sweep time required to record the full frequency spectrum that is of interest

1.4 Scope & Limitations

The focus of this report is in the design and implementation of a digitized display for the HP141T that interfaces with a single board computer for storing and manipulating signal data from the oscilloscope. The scope is limited to selection of electronics that are suitable for converting the analog signals from the HP141T that are responsible for displaying signals. The scope only includes a survey of the HP141T circuits and outputs that directly affect how a spectrum is generated with respect to time domain and frequency domain analyses. The paper is not concerned with changing or improving the operational design of the device with respect to its power, amplification and filtering circuitry.

1.5 Report Outline

Chapter 2 initiates the report by establishing the general history and theoretical framework for the design and applications of spectrum analyzers in engineering. The same chapter details the previous techniques for converting the output of a SA to digital values that can be manipulated by a processor. Finally, designs of displays are explored in literature to establish an approach to representing the processor output on a LCD screen.

Chapter 2

Literature Review

The aim of this chapter is to conceptualize the operation of spectrum analyzers and establish a theoretical foundation for the frequency analysis techniques applied to produce the correct output. This conceptualization is then integrated with a broader review of digitizing and modernizing the display of spectrum analyzers.

In circumventing design limitations of spectrum analyzer displays, it is prudent to survey the most suitable hardware components. This is particularly true for the case where electronic components are required to perform in a broad frequency bandwidth. For example, for high frequency signals, the Nyquist theorem indicates that the ADC is required to have a sample at a frequency that is more than double the frequency of the output signal. Furthermore, the challenge of presenting signals in the frequency domain using electronics exists due to the fact the input signal to the ADC holds information about frequency in the time domain. Therefore, the investigation of literature that is presented in this chapter aims to provide a motivation for the design decisions taken in digitizing and modernizing the HP141T display.

The chapter begins with an evaluation of the frequency domain analysis theory that is applied in the operation of signal analyzers. Then, the different principles that distinguish different types of analyzers are explored to form the basis understanding the expected behaviour of a spectrum analyzer with specific settings. Following descriptions of the operation of spectrum analyzers from literature, the chapter includes a review of the investigation into different techniques for digitizing analyzer displays. This also includes a review of the different electronic components and techniques for digitizing frequency information in order to survey available hardware options that can be selected for a cost effective implementation. Finally, a broad discussion is included on different types of displays for analyzers in literature and a critique of the literature is provided to outline the purpose of the proposed design.

2.1 History and Fundamentals of Spectrum Analysis

2.1.1 Brief History of Spectrum Analyzers

2.1.2 Frequency Domain Analysis of Signals

2.1.3 Classifications of Spectrum Analyzers

2.2 Digitizing Spectrum Analyzer Outputs

2.2.1 Output Voltage Regulation and Preparation for Frequency Analysis

2.2.2 Transforming Spectrum Analyzer Output Signals to Digital Frequency Domain

2.2.3 Interfacing Computers with Spectrum Analyzers

2.3 Modern Spectrum Analyzer Displays

2.3.1 Configurations and Displayed Data in Modern Spectrum Analyzer Displays

2.3.2 Technological Developments in Signal Analyzer Displays

Chapter 3

Methodology

3.1 Methodology Outline

This chapter details the design process and approach employed in achieving the aim of the project which is to digitize and modernize the HP141T display by replacing the CRT monitor with a LCD touchscreen display that offers different functions and modes of operation. Design decision are also documented here, showing the considerations that were made based on the operation and outputs of the HP141T spectrum analyzer and ensuring that the newly integrated display is compatible with the device's hardware. For example, the design required selection of the digital hardware for processing the analog voltage signals from the SA. The selection of the digital processor made from single-board computers such as the Raspberry Pi 4 Model B, microcontrollers like the STM32F4 boards, FPGA such as the Artix-7 from Xilinix, or a heterogeneous digital processor which consists of a combination of these options.

Other considerations were made regarding the electronic circuits for converting the auxiliary output voltages from the HP141T to the appropriate voltage level for the operation of ADC. This chapter describes how together, the ADC and digital processor form a crucial part of the system. Additionally, the chapter details the software development kit (SDK) and associated coding language that was used. The selection of the development framework depended on the choice of processor and digital processing algorithms that were required to fulfil the project requirements. For example, assuming that a FPGA is the chosen digital processor, the SDK would include tools such as the AMD Vivado and electronic design automation (EDA) software and the choice of coding language between Verilog, VHDL, and SystemVerilog would depend on how comfortable the developer is in representing digital processing algorithms, such the DFT, using the chosen language.

Overall, this chapter documents an overview of the design methodology and different phases in the design process. The design process followed a variation of V-Model in which a series of iterative phases was implemented with a process checking mechanism. The chapter begins by highlighting the design stages and modularization of the system. Thereafter, the chapter includes an assessment of the project requirements detailed in introductory section. Finally, the chapter describes the use of findings from the review of requirements in informing the design decisions and specifications.

3.2 Phases in the Design Process

The design process was decomposed into four iterative stages as illustrated in Figure ?? below. The first stage documented the digitization requirements and listed examples of modern SAs in order to define the requirements for modernization. As shown in the methodology overview diagram, the first stage also included thorough investigation into methods that have been implemented in literature for upgrading the functions and performance of SAs. A theoretical framework for relevant information about signal processing was also formulated based on the literature to ensure that the display modes and functions were consistent with the mathematically derived expected outputs in the system.

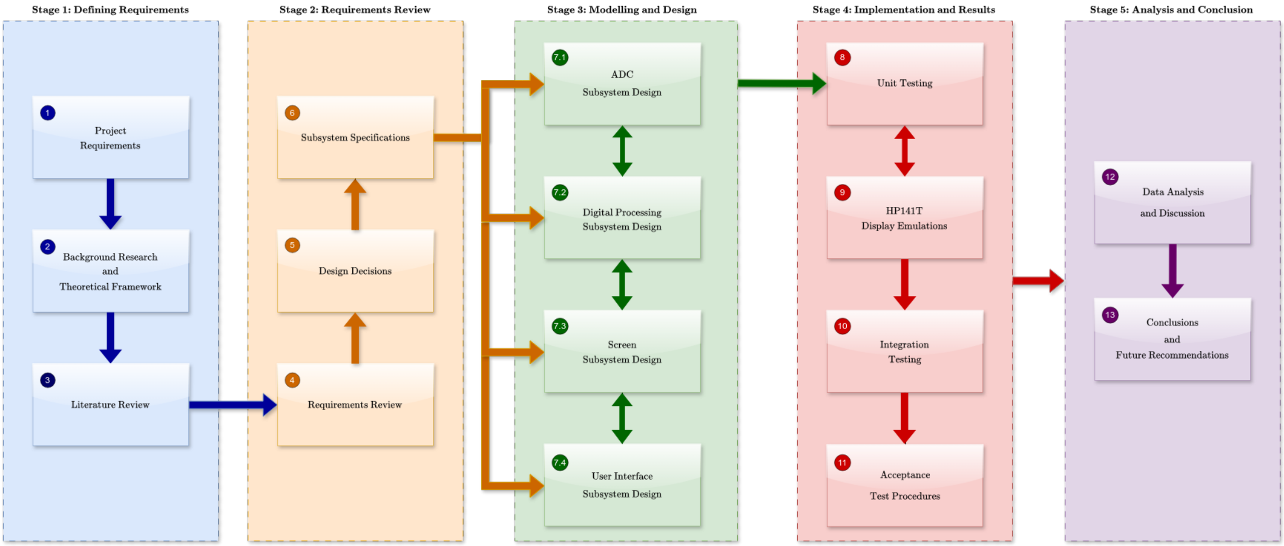

Figure 3.1: Methodology overview showing different stages in the iterative design process that was applied as a variation of the V-Model.

The second stage in the design process involved a review of the user requirements specifications detailed in chapter 1. The aim of this step in the methodology was to clarify the desired functions of the upgraded spectrum analyzer and to inform the design decisions with respect to the digital hardware and software development for digital signal processing. Additionally, the requirements review was employed in modularizing the design into four subsystems including, the Analog-to-Digital Conversion, Digital Processing, Screen and User Interface subsystems.

Stage 3 of the design process dealt with the design specifications of each of these subsystems by further decomposing each module into smaller hardware and software components. Each function is tested against a requirement in Stage 4 where each design specification was verified and the operation of the integrated system was tested to ensure that the interfaces between the subsystems was configured correctly.

In general, implementation of the design process adhered to the following design steps detailed in the project brief and are associated with the user requirement specifications:

1. Surveying the HP141T display and other outputs.

2. Surveying single-board computers and touchscreen options.

3. Phase One: establish a basic XYZ replica or HP141T emulator.
4. Phase Two: implement averaging and peak hold options.
5. Phase Three: annotate display axes.
6. Phase Four: determine the appropriate instrument settings.
7. Phase Five: design new annotations for display taking instrument or operator manual inputs into account.
8. Phase Six: include more tutorial and operational instructions using.

In finalizing the design process of the upgraded SA, results from acceptance tests were assimilated and a conclusion was drawn. Then, based on the outcomes of the project, future recommendations were made for future iterations of the upgrade SA system. Overall, the stages of the methodology included:

- Stage 1: Defining Requirements
- Stage 2: Requirements Review and System Overview
- Stage 3: Modelling and Design
- Stage 4: Implementation and Results
- Stage 5: Analysis and Conclusion

The first four stages of the design process were performed iteratively as a variation of the V-Model in which risk analysis was performed at each step, similar to the Spiral Model for design processes. Each iteration aimed at producing a new version of the upgraded HP141T display and a single conclusion was made when a satisfactory prototype was established.

3.3 Requirements Review

This section aims to clarify the scope and formalization of the user requirements specifications of the project.

3.3.1 Comparing the HP141T System to Modern Spectrum Analyzer Displays

The first user requirement deals with the modernization of the HP141T system. The aim of this section is to review this requirement and to give clarification on the context of the use of 'modernization' in this project. To achieve this objective, the section begins with a description of the HP141T system and the functions that differ from 'modern' spectrum analyzers, such as the range of hand-held SAs by FieldFox, and the N9000B CXA SA manufactured by Keysight®. The section concludes with a summary table comparing the features of the HP141T system and modern spectrum analyzers.

The HP141T system is equipped with three plug-ins, namely the 8555A RF section which operates in the microwave region of the electromagnetic spectrum, the 8552B IF section and the Model 141T display which includes the CRT monitor. The three plug-ins operate in unison to electronically scan signals in the time-domain and provide a visual representation of the input signal's amplitude in the frequency domain on the CRT monitor [3]. Amplitude can be represented on a logarithmic (dB m) or linear scale (mV).

The 8555A and 8552B plug-ins apply principles of heterodyning spectroscopy, allows high frequency input signals with frequencies in the K-band of the microwave portion of the electromagnetic spectrum (i.e. 18 MHz) [4]. Spectrum analyzers which rely on the FFT by sampling the continuous input signal and performing the Fourier transform on N total samples typically deal with signals that have lower frequencies. This is because SAs that employ the heterodyne principle like the HP141T determine the spectrum directly by analysis in the frequency domain and not from the time-dependent characteristics of the input signal. This is achieved by using a heterodyne receiver comprised of a mixer and tunable local oscillator (LO) which convert the input signal to an intermediate frequency as illustrate in figure **??** [5].

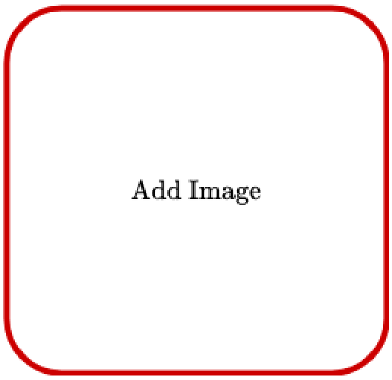

Figure 3.2: Heterodyne Spectrum Analyzer Block Diagram.

In most cases, modern SAs are real-time spectrum analyzers which are a special case of vector spectrum analyzers (VSA) that use the heterodyne principle but digitize the input signal at the intermediate frequency, as shown in Figure **??**, using a bandpass filter which can behave like a pre-select filter to limit distortions that arise from the mixer and shows the result in real-time. The advantage of digitizing the output of the IF section is that it enables large a input range of up to 50 MHz which can be analyzed in the time and frequency domain using digital signal processing techniques [6]. Much like FFT analyzers, vector analyzers are limited by the minimum and maximum sampling rate at which the ADC can operate. Additionally, exceedingly high sampling rates can lead to aliasing which causes frequencies outside of the bandwidth to fold into the frequency band [6].

Examples of modern real-time analyzers include:

- Tektronix RSA2208A which can scan input signals with frequencies of up to 8 GHz.
- Rohde & Schwarz FSP13 which operates within a 9 GHz to 30 GHz RBW.
- Agilent E4445A which offer frequency analysis up to 13.2 GHz.
- FieldFox RTSA which covers 5 kHz up to 50 GHz.

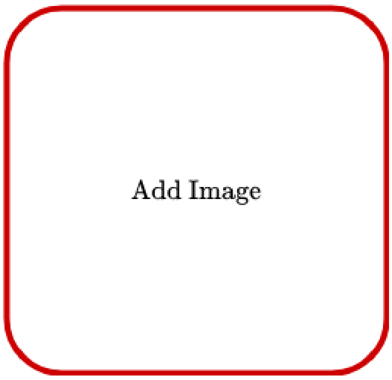

Figure 3.3: Vector analyzer block diagram showing digitization of the IF frequency.

3.3.2 Representation of Signals in Frequency Domain

3.3.3 Spectrum Analyzer Modes of Operation

3.3.4 Display Resolution in the Logarithmic Scale

3.3.5 Components of the Software Development Kit

3.3.6 Display Power Source

3.3.7 Equipment for Debugging and Testing

3.4 System Design

3.4.1 System Modularization

3.4.2 System Block Diagrams

Chapter 4

Results

Chapter 5

Discussion

Chapter 6

Conclusions

> The same rule holds for us now, of course: we choose our next world through what we learn in this one. Learn nothing, and the next world is the same as this one.
>
> —*Richard Bach, Jonathan Livingston Seagull*

The purpose of this project was to...

This report began with...

The literature review was followed in Chapter...

The bulk of the work for this project followed next, in Chapter...

In Chapter...

Finally, Chapter... attempted to...

In summary, the project achieved the goals that were set out, by designing and demonstrating...

Chapter 7

Recommendations

It is for us the living, rather, to be dedicated here to the unfinished work which they who fought here have thus far so nobly advanced.
—*Abraham Lincoln*

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