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Project Title: "**Forced Resonance Imaging for 3-D Mapping of Buried Gas Pipes**"

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Preface

This Addendum describes tests and measurements made during the month of October - February 2021 using an ocean/land simulator in the laboratory. The parametric studies made can be directly applied to the field. The work presented in this document would account for the completion of Item #3 Task-2 with major overlaps with Item # 5 Task-2. It should also be mentioned that this document is used as one of the main appendices in the Final Report for the subject Agreement.

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1. INTRODUCTION

The activity and deliverable associated with Item #3 Task-2 of the subject Agreement following first three months after the contract award (ACA) required collecting data on buried pipelines and report preparation. The field testing was to be performed at the gas company, Pacific Gas and Electric Company (PG&E) facility. However, the field activity was delayed due to COVID-19 and restrictions imposed by the PG&E on personnel travel as mentioned in the original 1st quarterly report submitted to Ms. Annmarie Robertson (TTI) on December 31, 2020. Still, much progress has been made in the Agreement singed as indicated in the previously submitted monthly status and quarterly reports. The Gas Company (PG&E) have recently announced that tentatively they will make every effort to make a facility available to us for testing and collecting buried pipe data.

The impact on field testing caused by the COVID-19 pandemic prompted the Principal Investigator to look for another viable plan to generate the required data for the parametric investigations recommended in the "Field Testing Plan (FTP)." The Field Test Plan document was submitted to Ms. Annmarie Robertson (TTI) on December 2, 2020.

Following extensive background research on previously compiled field data using BakhtarRadar (formerly referred to as USAF EarthRadar) coupled with the principal investigator experience it was decided to use the land/ocean simulator for testing and the initial parametric investigations as defined by Items #3 and #5 Task-2.

The land/ocean simulator is suggested by the Principal Investigator for the field/parametric investigations under the laboratory conditions - details of which are shown in Figures 1 and 2. The test bed consists of a lead-aluminum box (Figure 1 and 2). It was designed by the chief geophysicist from Royal Dutch Shell in Netherland (Dr. Jonathan Singer) to check Bakhtar Technology by simulating high ground impedance, built it in the United States by the Principal Investigator. Shell offered to buy Bakhtar technology after demonstrations using the simulator lead box that they came to the United States and witnessed the demo – their offer was respectfully declined by the Principal Investigator.

The land/ocean simulator consists of a lead-aluminum box with the overall internal dimensions 61-cm X 61-cm X 61-cm (2-ft x 2-ft X 2-ft) **–** better referred to as the Faraday's Cage. It is to be used for simulation of field testing and related initial parametric investigations as discussed in this document and elaborated upon in the Field Test Plan.

It should be noted that:

- Detection of buried pipe cross-section (profile) is the first step in 3-D mapping. Therefore, the attention should be directed initially in assuring the existence of the buried pipelines in the location of interest before moving forward with the 3-D mapping which is also called "volumetric image reconstructions" (VIR).

- Detection through the lead box (land simulator) is done by force-resonating the low-power electromagnetic energy (10 dBm maximum power almost half as much as those in many cellphones) onto the test bed (lead box) and use the back scattered signature for detection and discrimination of embedded target (plastic pipes). The forced-resonating and resulting detected buried pipe cross-section (profile) is referred to as FRI (Forced-resonance-Imaging) invented by the Principal Investigator.

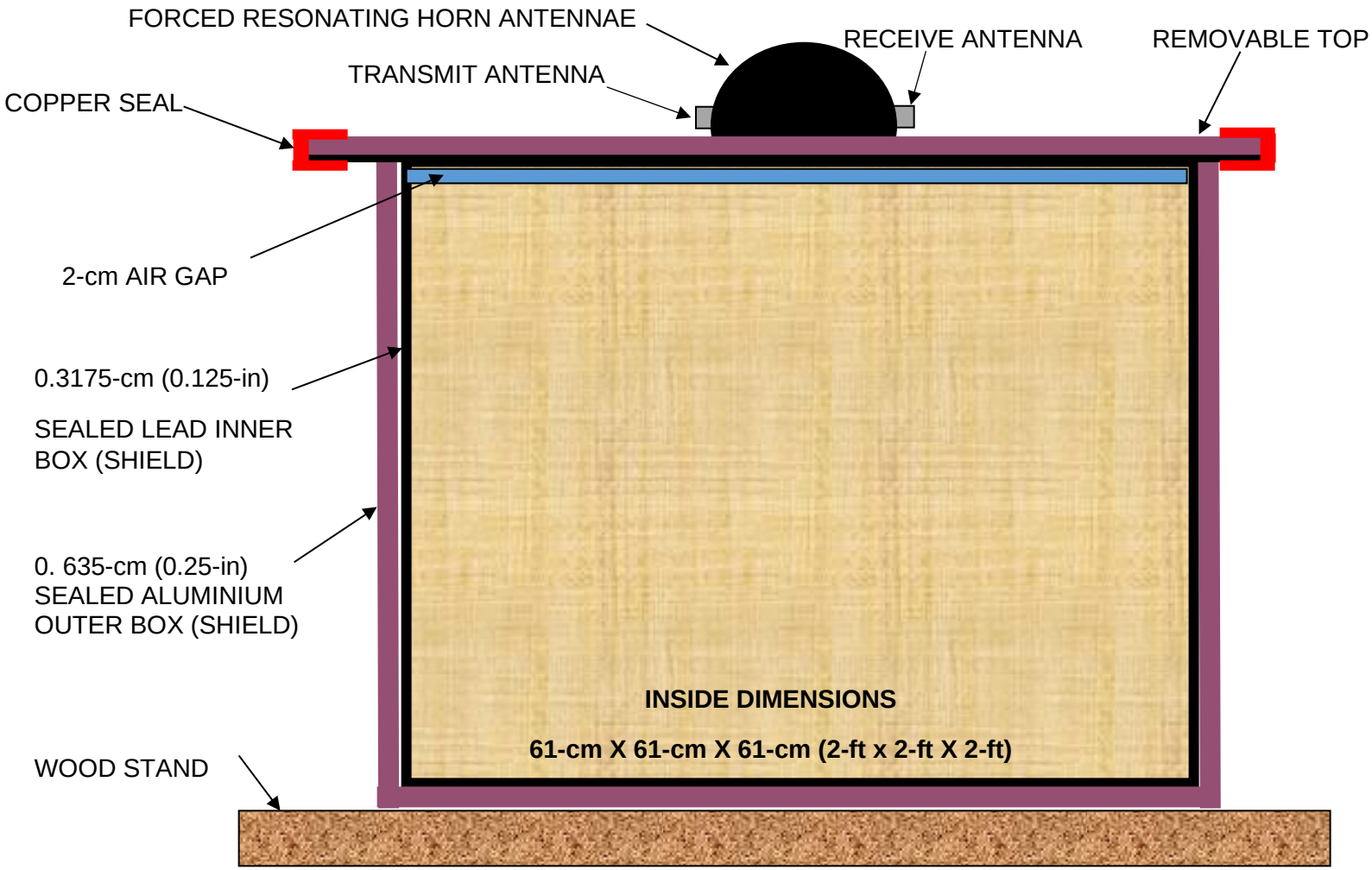


Figure 1 - Section through Center of Double Shielded Sealed Lead-Aluminium Container Land/Ocean Simulator
(**not-to-scale**)

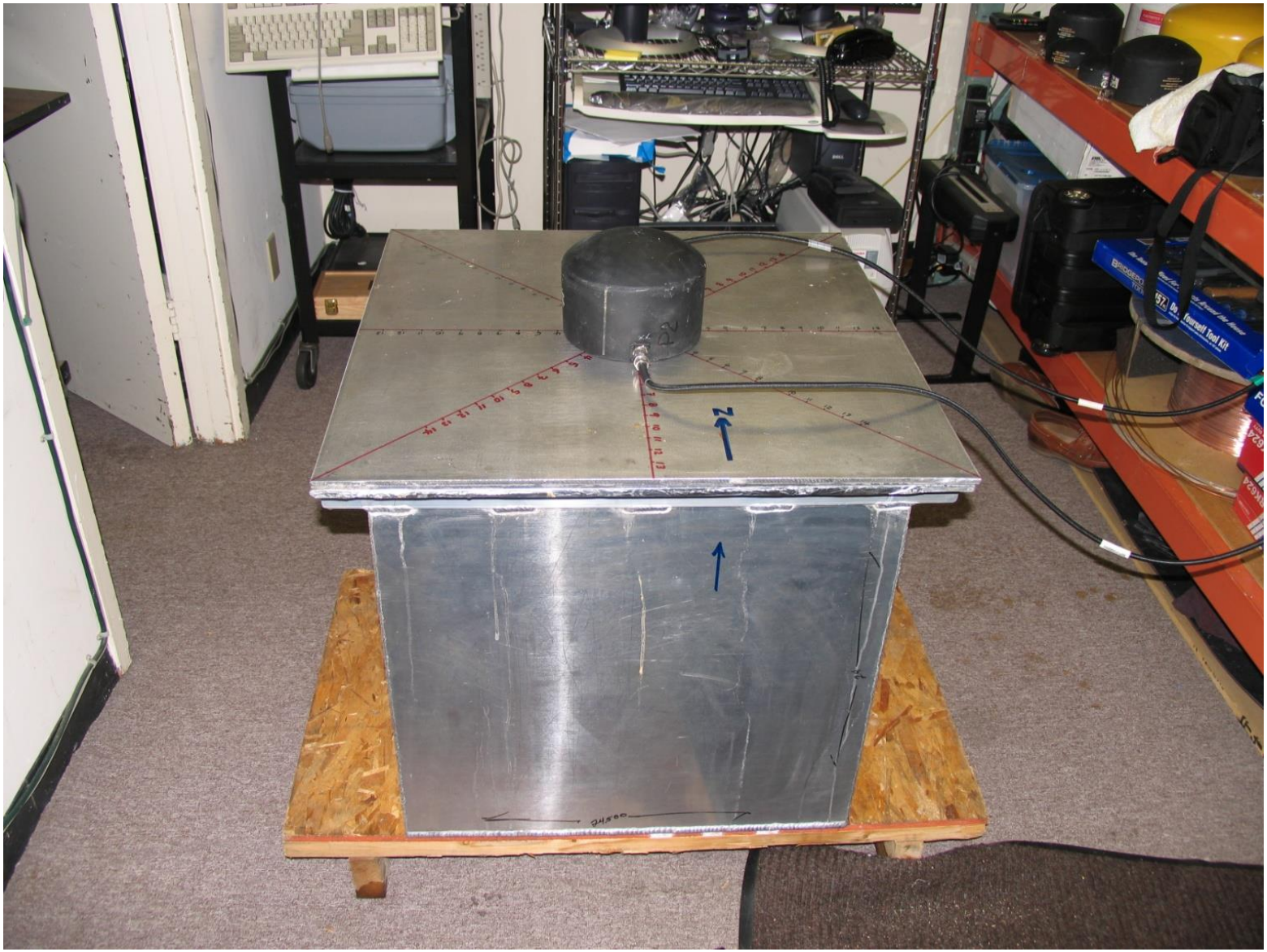


Figure 2 – Test Configuration for Detection under Reflection Mode of EM Transmission

- Transmission of low-power less than 10 dBm electromagnetic energy (EM) is done in stepwise fashion simulating different depths of detection as calculated from the return time in nanoseconds (10^{-09} seconds).

- Simulation tests are done under “reflection” mode in which both transmit and receive antennae are on the same side of the test bed as illustrated in Figures 1 and 2.

- Applications of FRI (Forced-Resonance-Imaging) enables simulation of the ground impedance at different operating frequency bands to establish the required range for the best frequencies ($\Delta f = f_{FINAL} - f_{INITIAL}$) to detect and discriminate between plastic pipes – notice most utility companies are interested in plastic pipes. Similar approach can be taken for detection of metallic pipes, too.

- Because the EM energy is forced resonated onto the high impedance test bed (the lead box simulating ground impedance) for detection the optimized established frequency bands (from the lead box) can be translated into the earth for actual buried pipeline detection. This means that following completion of the on-going laboratory research (parametric investigations) and establishing the correct frequency band only requirement is to spot check that in the field for verifications. The spot checks should be done in at least 4 different sites (different geology/ground characteristics) spending at least one day at each site. It should also mention if the spot checks can be made at ten different sites then we have statistically valid information universally acceptable. It is recommended that spot checks and verifications be done towards the end of Task-2 Item #5 in the field.

- Using land/ocean simulator we can also perform initial parametric investigations to set the ranges for the other important parameters outlined in the FIELD TEST PLAN submitted to Ms. Annmarie Robertson on December 2, 2020.

- Taking current situations into consideration with the Gas Companies laboratory simulation using the lead box (Faraday’s Cage) is probably the most workable and practical approach to substitute for field testing since we should be able to have control over test and perform initial parametric investigations.

- The main purpose of running simulation tests is to determine the optimized frequency band of operations at threshold of detection for different embedded specimens tested. The 3-D mapping is to be done once access to the field is made during spot checking and verifications of the existence of buried pipelines. Access to at least six satellite is needed before 3-D mapping can be done.

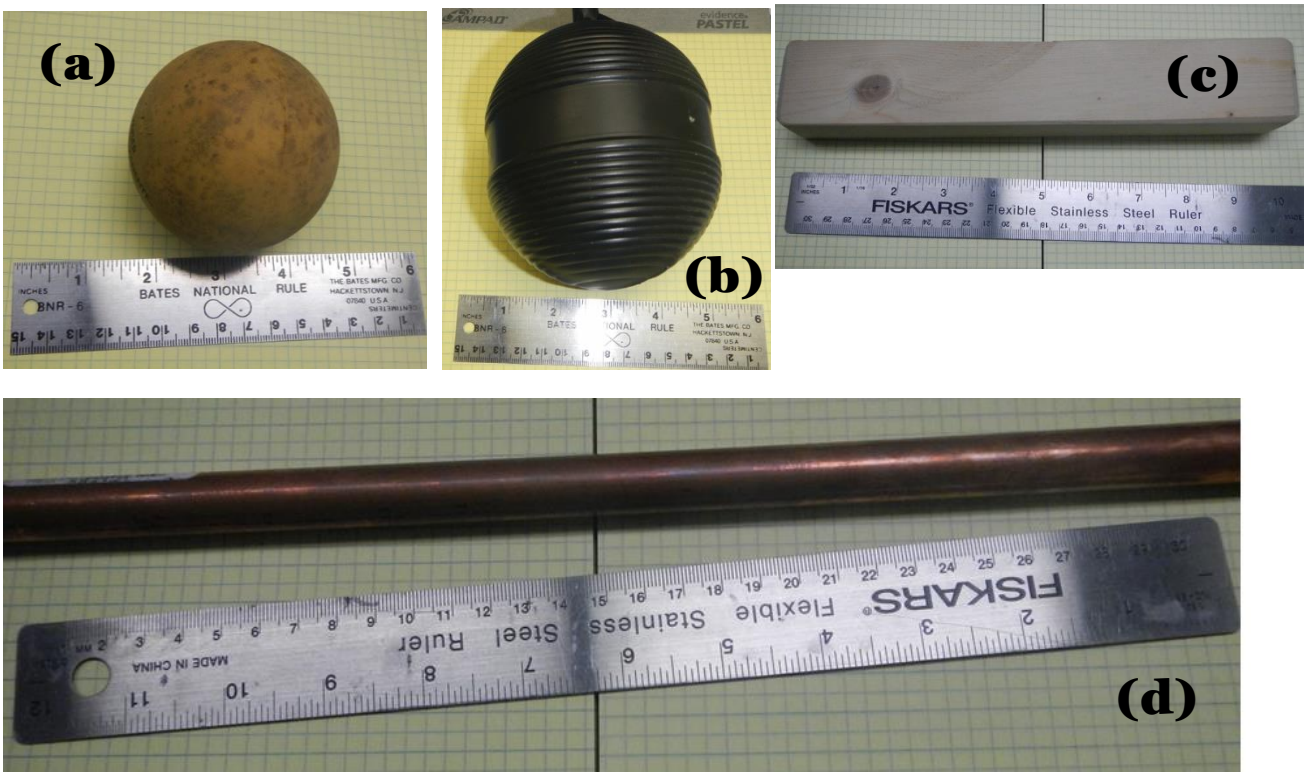
Please note this addendum to the 1st quarter status report completes the task associated with item # 3 and partially covers the task to be completed under Item # 5 Task-2.

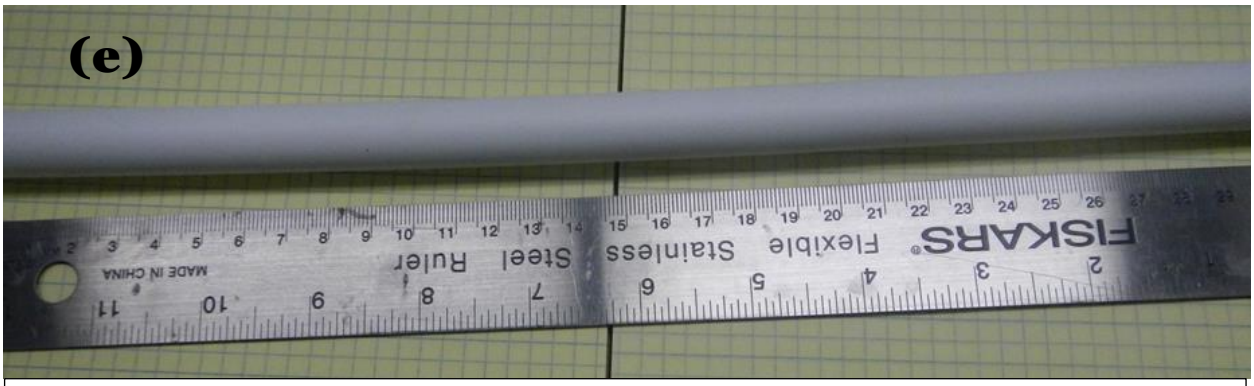
Section 2 of the document deals with simulation tests and measurements done using the high impedance land simulator. Procedures for analysis/signal processing and results are presented in Sections 3 and 4. Recommendations to complete Task 2 Item # 5 are highlighted in Section 5.

2. SIMULATION TESTING AND MEASUREMENTS

2.1 TEST SPECIMENS

Figure 3 shows the test specimens selected for initial tests and measurements, their densities and dimensional details are listed in Table 1.





(a) RUBBER BALL (b) THIN WALL PLASTIC OBJECT
(c) PIEC OF MAHOGANY WOOD
(d) COPPER TUBING (e) PLASTIC TUBING

Figure 3 – Photograph Showing Specimens Tested in Land Simulator

Table 1 – Details of Test Specimens

TEST SPECIMENS	DIMENSIONS (CM)	VOLUME (CM^3)	WEIGHT (gm)	DENSITY (gm/cc)
RUBBER BALL	DIAMETER 6.5	------	26	1.52
THIN WALL PLASTIC OBJECT	IRREGULAR	----------	56	1.27
PIECE OF MAHOGANY WOOD	Thickness 2.4 Width: 4.5 Length: 25.4	274.32	152	0.55
COPPER TUBING	O. D.: 1.2 I. D.: 1.0 Length: 32	----------	175	8.96
PLASTIC TUBING	O. D.: 1.5 I. D.: 1.2 Length: 32	---------	49	1.45

Test order and respective data file name:

Specimen Tested		Recorded File Name
Rubber Ball	Figure 3 (a)	02092102.job
Plastic Hollow Object	Figure 3 (b)	02092103.job
Piece of Mahogany Wood	Figure 3 (c)	02092104.job
Copper Tubing	Figure 3 (d)	02092105.job
Plastic Tubing	Figure 3 (e)	02092106.job

2.2 FORCED RESONATING ANTENNAE

A small adaptive and forced resonating (FR) horn antennae was deployed for the initial parametric investigations reported in this document (Figure 4).

The antennae with both “transmit” and “receive” components integrated into a brick like enclosure was connected to a vector network analyzer (VNA) via transmission line (TL). The VNA was connected to a laptop computer using GPIB via serial cable.

The entire test assembly is shown in Figure 5.

Figure 4 – FR Adaptive Horn Antennae

Figure 5– Test Assembly Showing Ocean/Land Simulator

2.3 TEST SETUP CONFIGURATION

The test configuration is shown in Figure 5. The adaptive FR horn antennae was selected from BakhtarRadar (USAF EarthRadar) inventory at Bakhtar Research and Engineering. The selected antennae have a range from 100 MHz to almost 2500 MHz. The theoretical center frequencies for these antennae (transmitter and receiver integrated into one brick form shown in Figures 4 and 6) were computed to be at 750 MHz (f_{CENTER} = 750 MHz). Note the followings:

f_{CENTER} …… 750 MHz

$f_{INITIAL}$ …… 500 MHz

f_{FINAL} ……1000 MHz

Operating Bandwidth $\Delta f = f_{FINAL} - f_{INITIAL} = 1000 - 500 = 500$ MHz

Electromagnetic Wave Speed (EMWS) …….. 3.5 cm/nanoseconds $\left(\frac{3.5}{10^9}\text{ seconds}\right)$

Frequency Steps ……. 201

Sample Bandwidth (IF frequency) ……... 300 Hz

Power …… 10 dBm

<u>SCALE FUNCTIONS</u>
Scale Function ……. 20 dB
Scale Time …….. 100 nanoseconds

<u>VON HAAN WINDOW</u>
Initial Frequency Index …… 0
Final Frequency Index ……... 200

<u>SIGNAL AVERAGING</u>
Signal Averaging ……. None

Average Coefficient …… 0

INVERSE FAST FOURIER TRANSFORM SIZE (IFFT) ……. 1024

Cable Length …….. 10 meters

The above test parameters, input to SETUP Window, were selected following extensive series of parametric investigations using different frequency bands of operations before the above values were decided upon. Figure 7 illustrates the SETUP Window with the above input values.

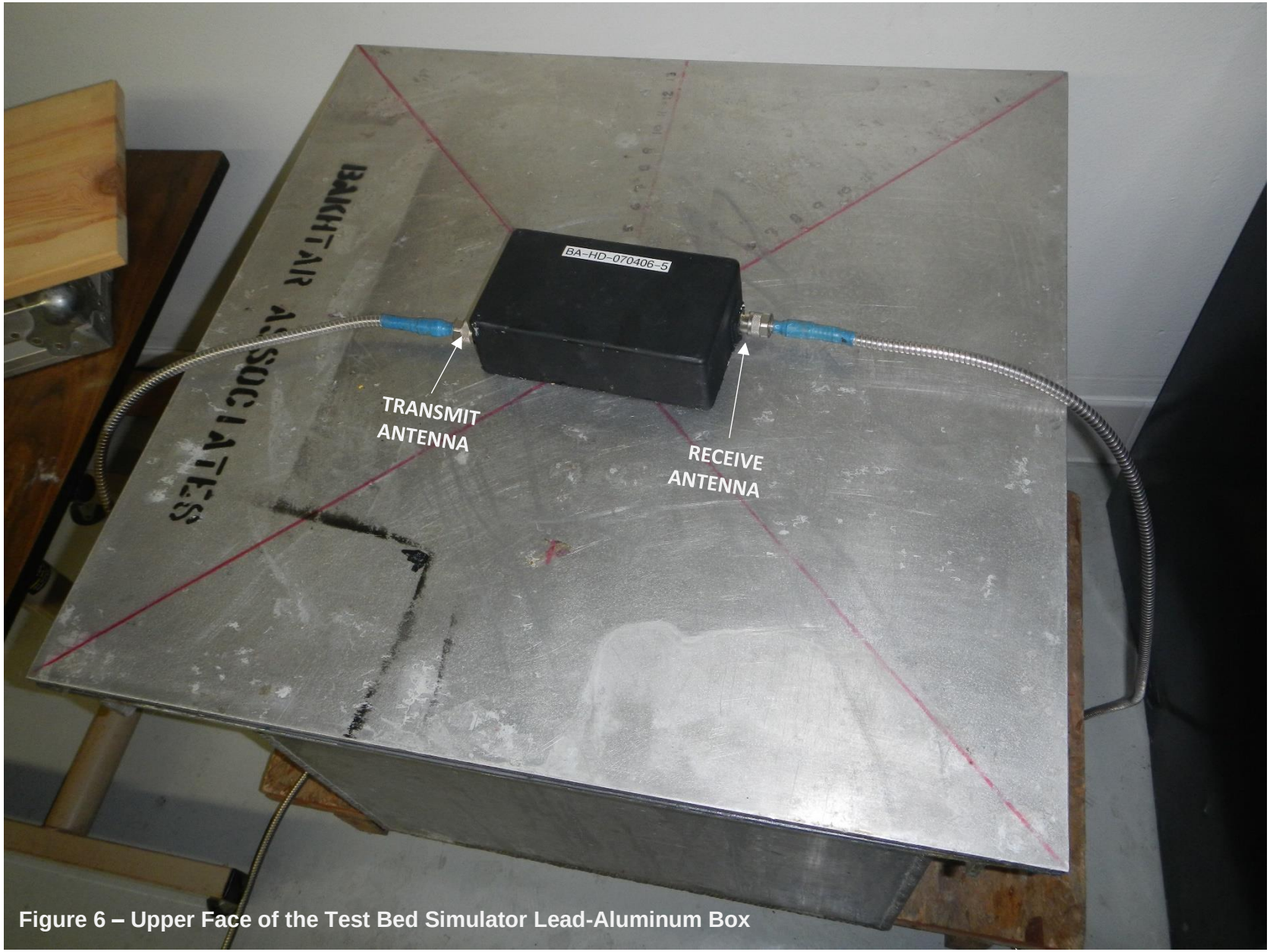


Figure 6 – Upper Face of the Test Bed Simulator Lead-Aluminum Box

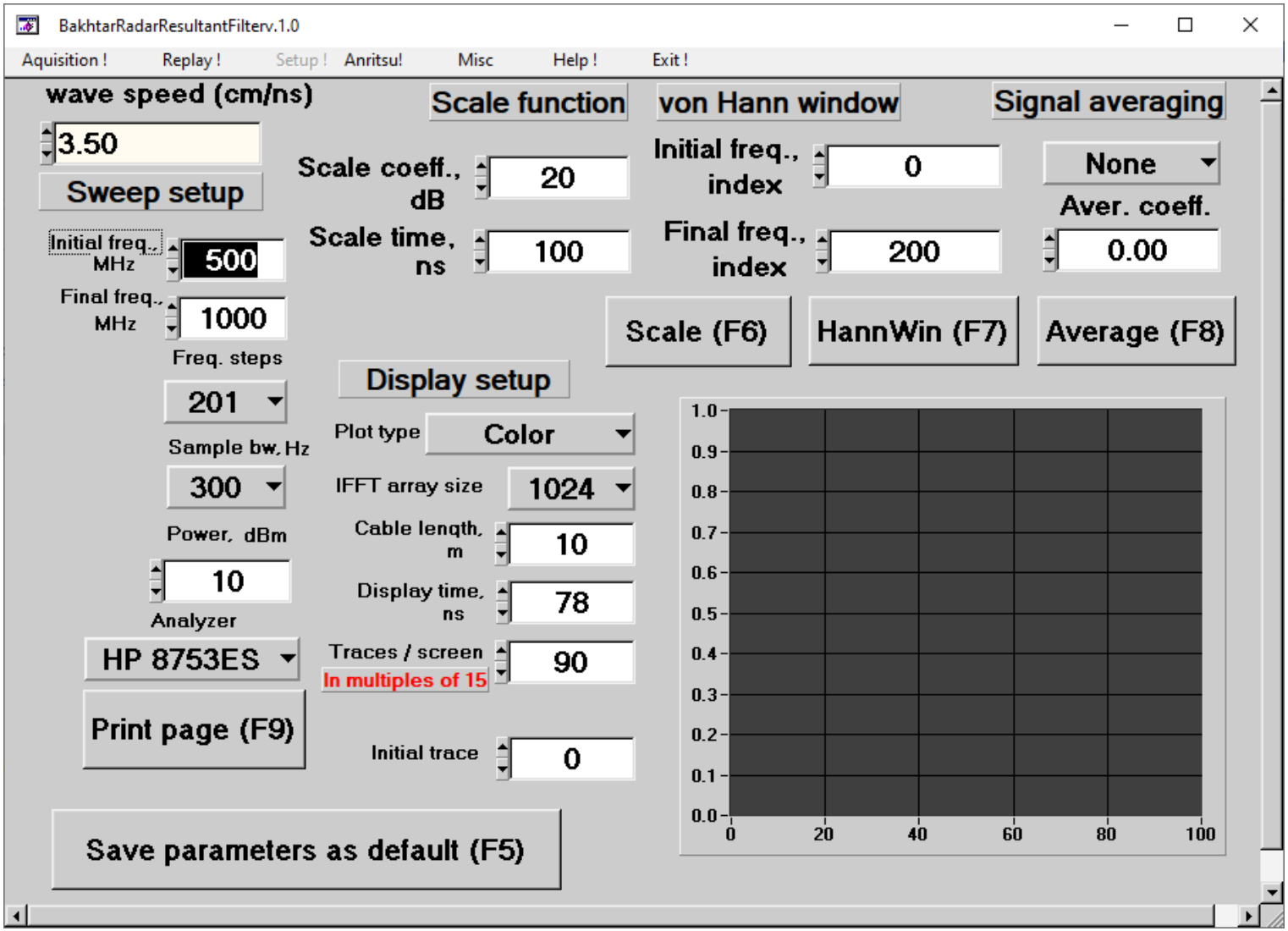


Figure 7 – SETUP Window with Selected Parameters for Land Simulator Tests

2.4 TEST PROCEDURE

Results of previously completed parametric investigations lead to choosing the input values shown in the SETUP Window in Figure 7.

The five test specimens selected, described in Figure 3 and table 1, were systematically placed inside the land simulator box and tested using the procedure described in the Figure 8 flowchart.

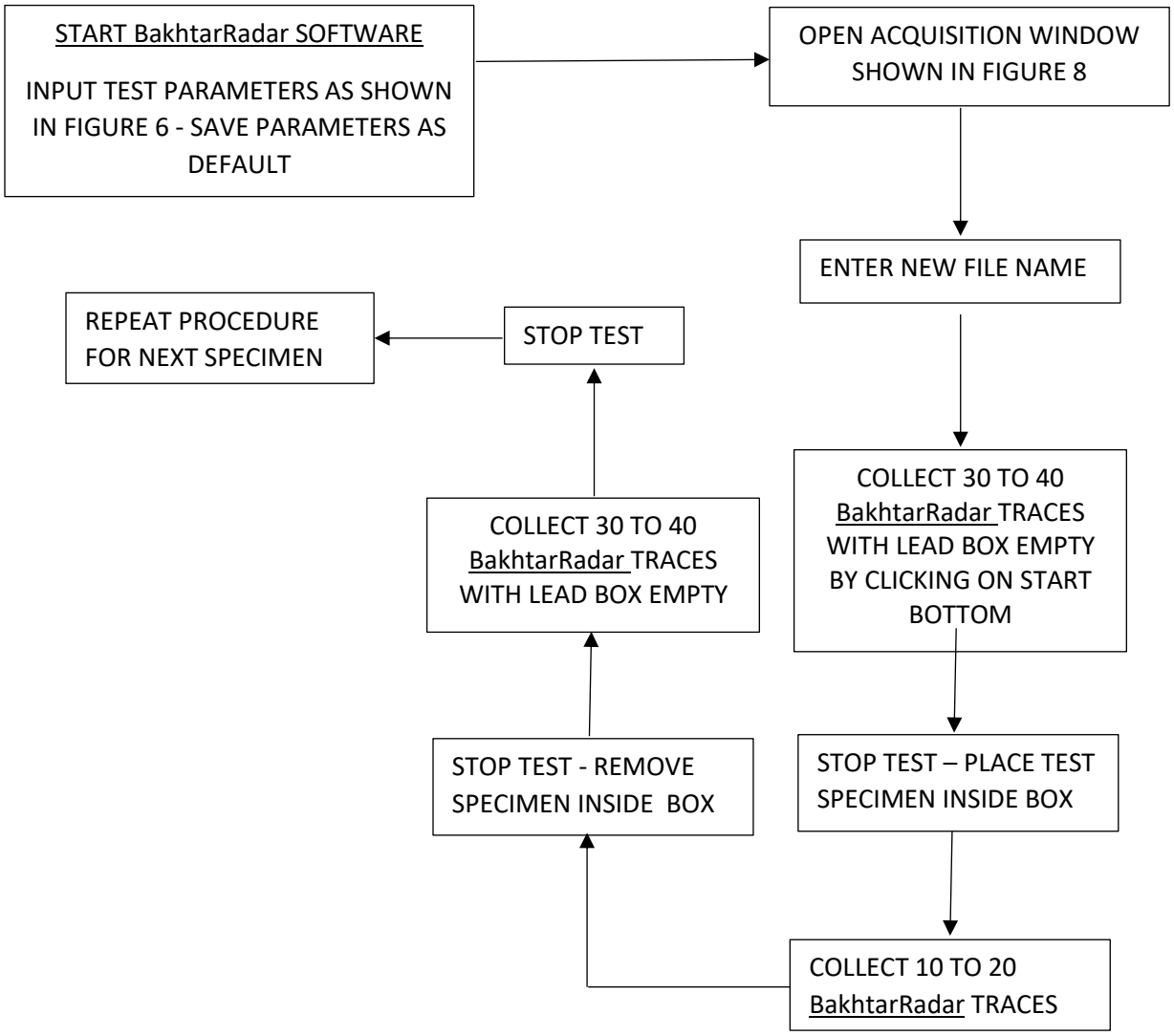


Figure 8 - Test Procedure

It is important to note that the input parameters in the SETUP Window and ACQUISITION Window (Figure 9) are kept the same throughout testing and FILE NAME is changed to account for the new specimens.

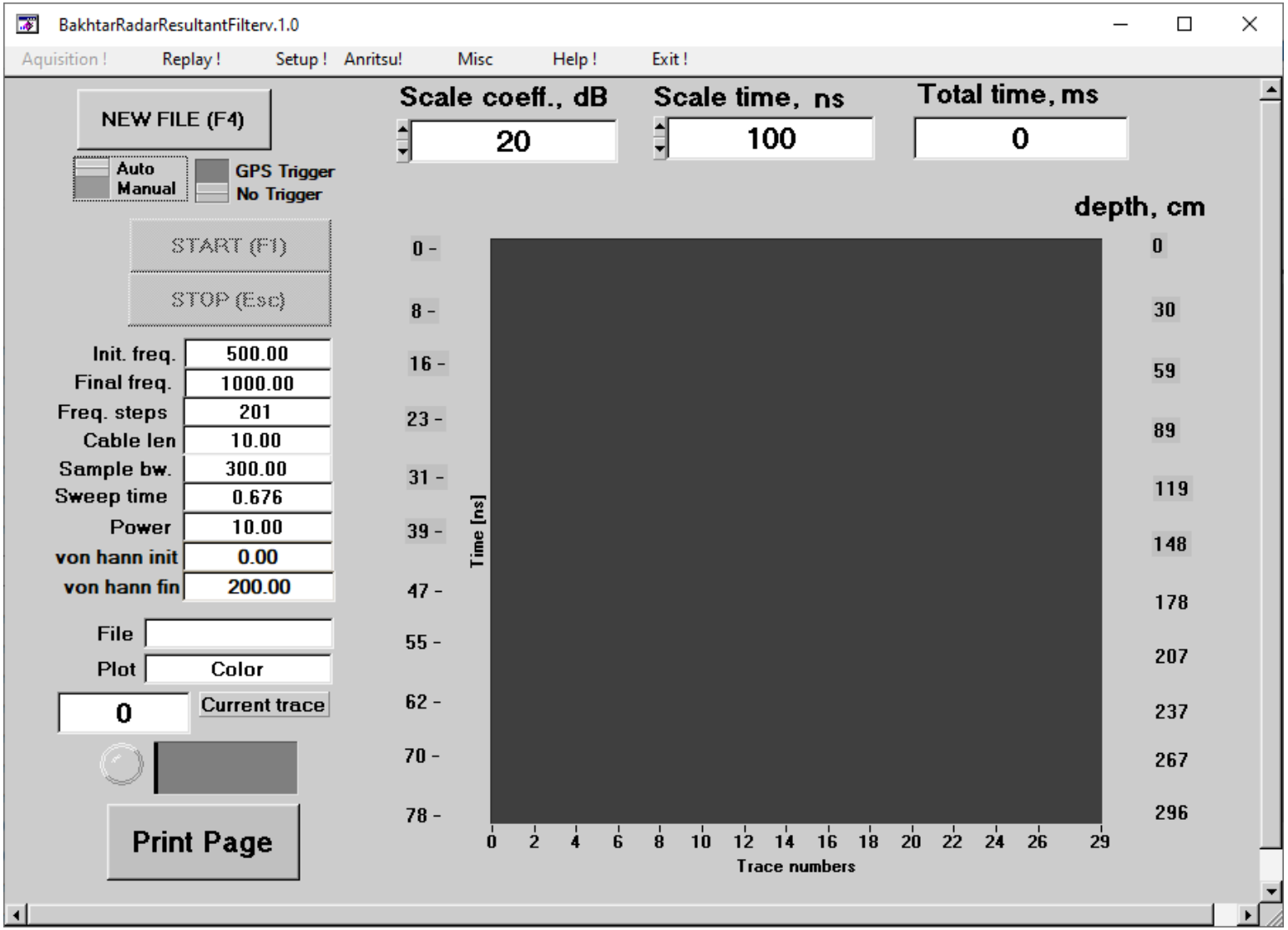


Figure 9 – ACQUISITION Window with Selected Parameters for Land Simulator Tests

3. ANALYSIS AND SIGNAL PROCESING

The flowchart in Figure 8 illustrates the general procedure for data acquisition using the Lead Box simulator. The REPLAY bottom shown in the SETUP Window (Figure 7) is used to recall the data for each specimen tested to perform analysis and post-processing of signal.

The general procedure for analysis and signal processing is illustrated in Figure 10 flowchart.

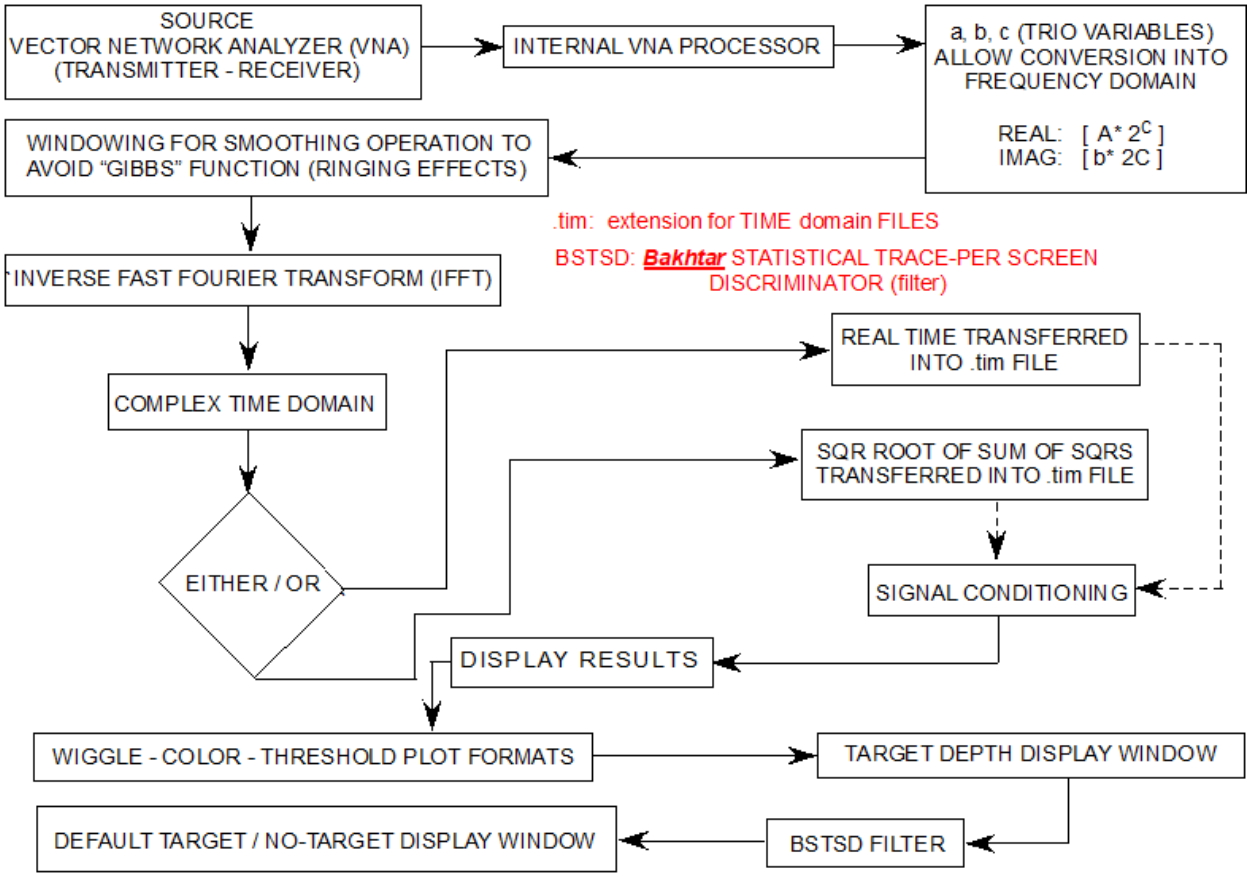


Figure 10 – General Algorithm for Analysis and Signal Processing

It is important to note that for Lead Box tests the adaptive FR antennae and embedded test specimens are stationary and not moving during data acquisition. Therefore, the profiles (BakhtarRadar cross-sections) tend to repeat themselves and form an elongated band rather than a singular shaped elliptical cross-section. Under the stationary conditions the more BakhtarRadar traces collected the longer would become the elongated band at different signal intensity.

Also, the detection results are presented in three different formats.

- Color
- Threshold
- Greyscale

4. RESULTS

Table 2 provides details of the traces collected for each specimen tested with their corresponding file names.

Table 2 – Details of Number of Trace Collected with Lead Box Empty and Loaded

TEST NUMBER	TEST SPECIMEN	TRACES EMPTY	TRACES WITH SPECIMENS	TRACES EMPTY	FILE NAME
1	RUBBER BALL	0 to 30	31 to 49	50 to 74	02082101.job
2	THIN WALL PLASTIC OBJECT	0 to 34	35 to 51	52 to 74	02092101.job
3	PIECE OF MAHOGANY WOOD	0 to 37	38 to 58	59 to 74	02092103.job
4	COPPER TUBING	0 to 38	39 to 59	60 to 74	02092104.job
5	PLASTIC TUBING	0 to 33	34 to 53	54 to 74	02092105.job

General signal information and magnitude for each data point is saved in ASCII text files, which can easily be read into the subsurface coordinate calculation program. The magnitude values from a signal acquisition will be placed in a vector. Parameters for subsurface coordinate and signal magnitude calculation are input using the **Data File Parameters** button. A pop-up window, which allows entry of contrast expansion value, scaling type, ground wave speed and magnitude data range is shown in Figure 3-7. Selecting the **Create time domain file** button calculates the signal magnitudes for each subsurface data point and creates the data parameter input file. This information is of importance for 3-D mapping and will be elaborated in more details in Item #5 task-2 incorporated in the 2nd Quarterly Report to be submitted at the end of March 2021. Still, elaborations are provided on several parameters which are used for detection and discrimination of specimens tested in this document.

Frequency Scaling. This controls the amplitude of the plotted frequency relative to the magnitude of the signal. A scaling of 100 is the default value, meaning that the signal plot is scaled down by a factor of 100.

Threshold value. This parameter controls the value for the boundary between black and white for the threshold plot. Since the signal strength values are expressed in the program as a decimal value between 0.00 and 1.00, the threshold is chosen in this range.

Contrast expansion. When displaying signal plots, the visibility of weak target signals may be improved. This is accomplished by stretching the plotting contrast so that the values for the pixels representing the weak target signals cover a major part of the entire available range. The mapping is linear and one-to-one. Contrast expansion is chosen as a value between 0.00 and 1.00. The smaller the value, the greater the range expansion. A value of 1.00 represents no

expansion.

Scaling function. The directly coupled signal between the transmitter and receiver antennas is much larger than the reflected signals from subsurface objects of interest. In order that the display of the strong direct signal not mask the ability to discern the weaker reflected signals, a scaling function is applied to the time domain direct signal.

The **Scale type** parameter designates the form of the scaling function as either exponential or linear. If **exponential** is chosen, the scaling function is dependent on the scaling factor in decibels. So, for example, 20 dB corresponds to a scaling of 0.1, and 0 dB is a factor of 1.0. The function also contains a parameter to determine the length of time, in nanoseconds, that the scaling factor is applied to the time domain signal. Scaling factor and length are specified in the pop-up menu through descriptors **short weak**, **short strong**, **long weak**, and **long strong**. These descriptors refer to the relative length and intensity of signal scaling. Numerical values associated with these descriptors can be modified in the **Hotkey setup** window. If the **linear** function is chosen, the scaling is only dependent on the length parameter.

von Hann window. The von Hann window is applied to the frequency sampled data to mitigate the abrupt truncation edge effects resulting from discrete sampling of a continuous signal. The span of the window is specified by the start and stop frequencies. The span is specified in the pop-up menu through descriptors **strong lowpass**, **lowpass**, **strong highpass, highpass** and **bandpass**. These descriptors refer to the frequencies allowed to pass through the window specified by start and stop frequencies. Numerical values associated with these descriptors can be modified in the **Hotkey setup** window.

Signal averaging. These operations are applied to the time signal to mitigate the effect that anomalous data from one trace may have on the overall signal characteristic. These operations consist of applying some sort of averaging function to “even out” the extremes in the signal data. The pop-up menu descriptors for this parameter are **subtract**, **weak smooth**, **strong smooth** and **subtract and smooth**. The numerical value associated with these descriptors is a coefficient indicating the relative intensity of “averaging”. The coefficient can be modified in the **Hotkey setup** window. Reference should be made to the Field Test Plan for more information on the test parameters, detection procedure, and 3-D mapping details.

Figures 11 to 25 illustrate detection test results from the Lead Box test bed for the specimens shown in Figure 3 in three formats (Color, Threshold, and Greyscale).

A Summary of Results is presented in Table 3. Discussion of results and recommendations to complete Task-2 are included in Section 5 of this document.

TEST SPECIMENS	DIMENSIONS (cm)	VOLUME (cm^3)	WEIGHT (gm)	DENSITY (gm/cc)
RUBBER BALL	DIAMETER 6.5	------	26	1.52

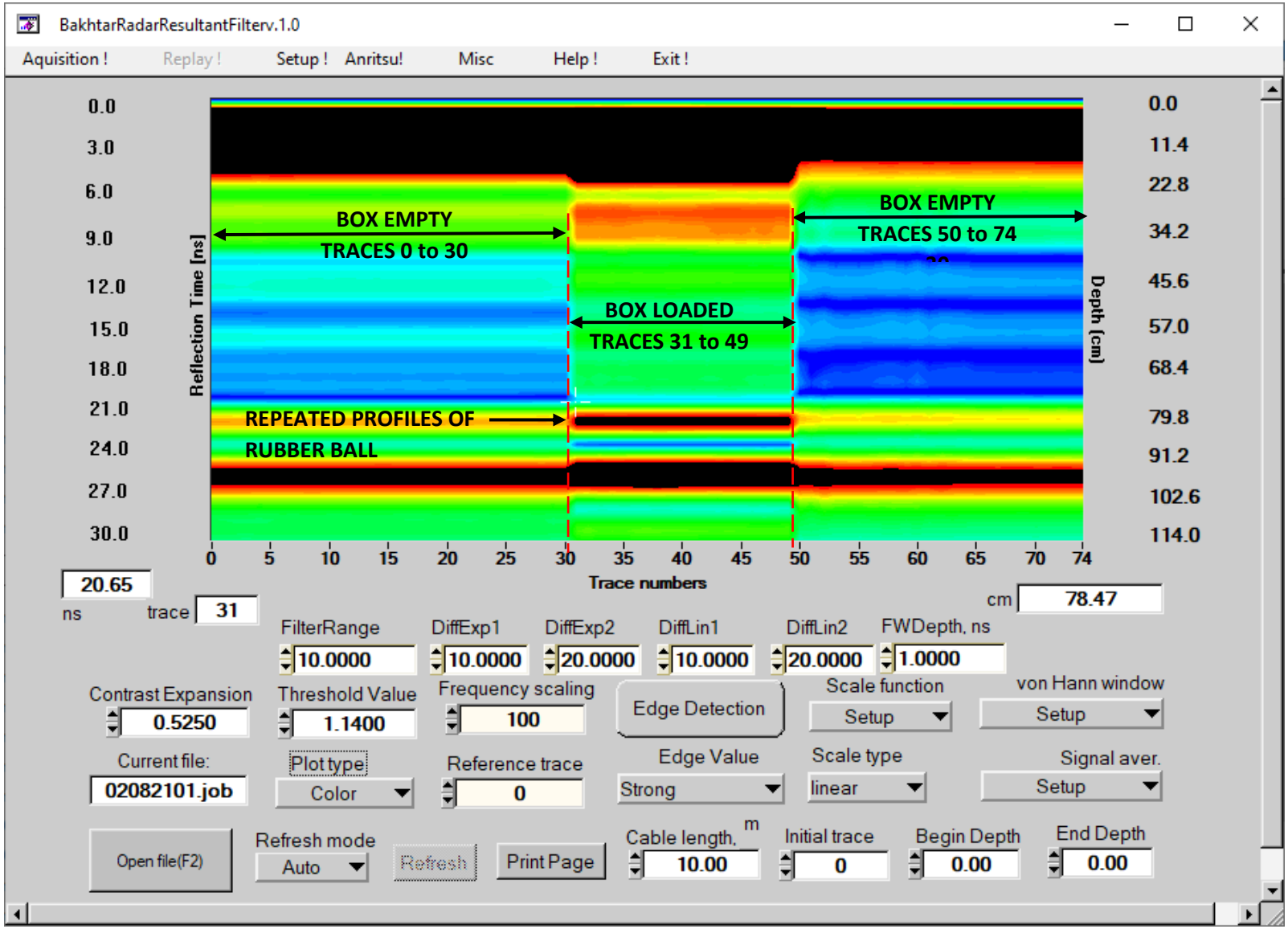


Figure 11 - BakhtarRadar Repeated Profiles of Rubber Ball Specimen inside Lead Box in Color Format

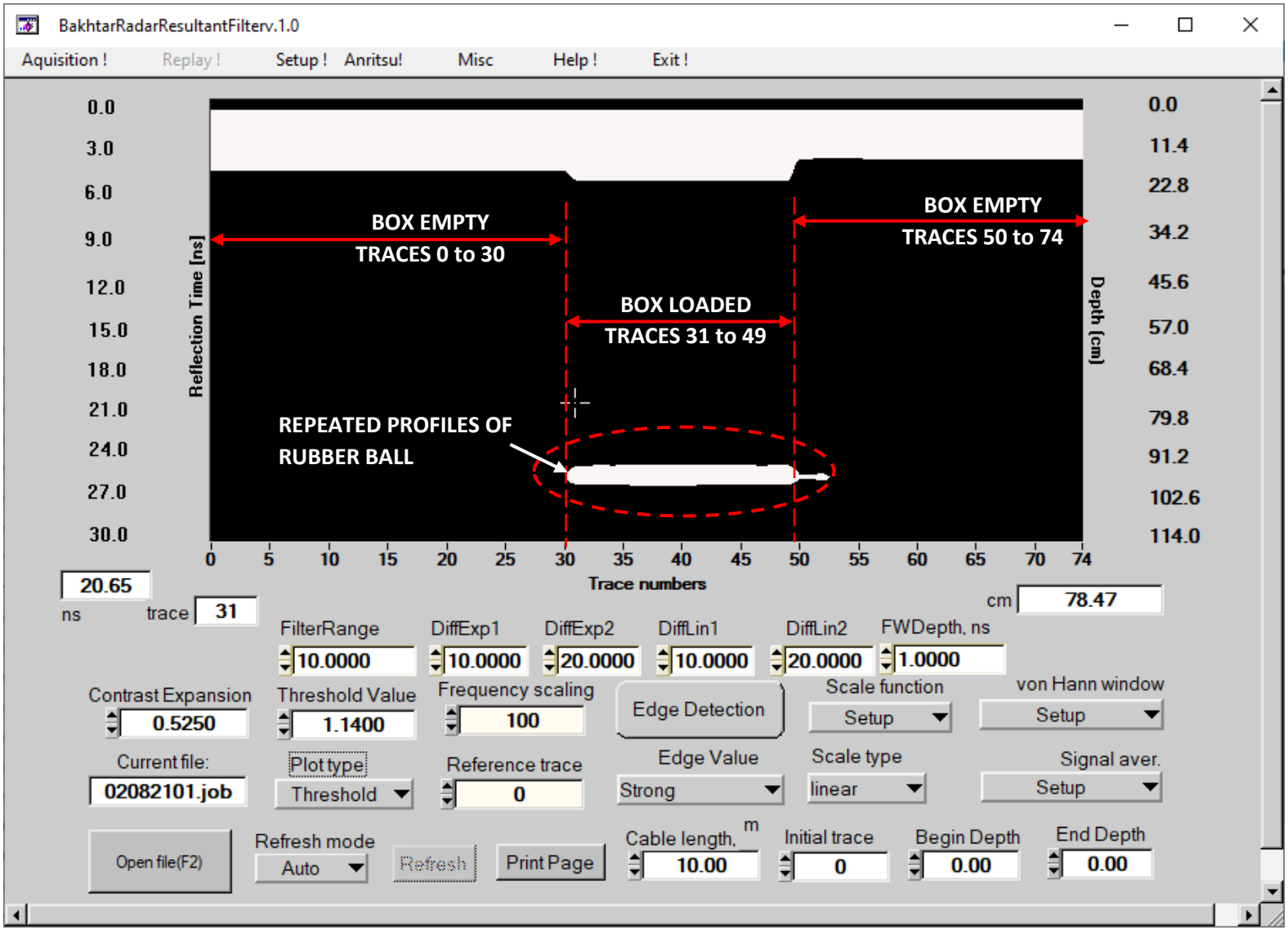


Figure 12 - BakhtarRadar Repeated Profiles of Rubber Ball Specimen inside Lead Box in Threshold Format

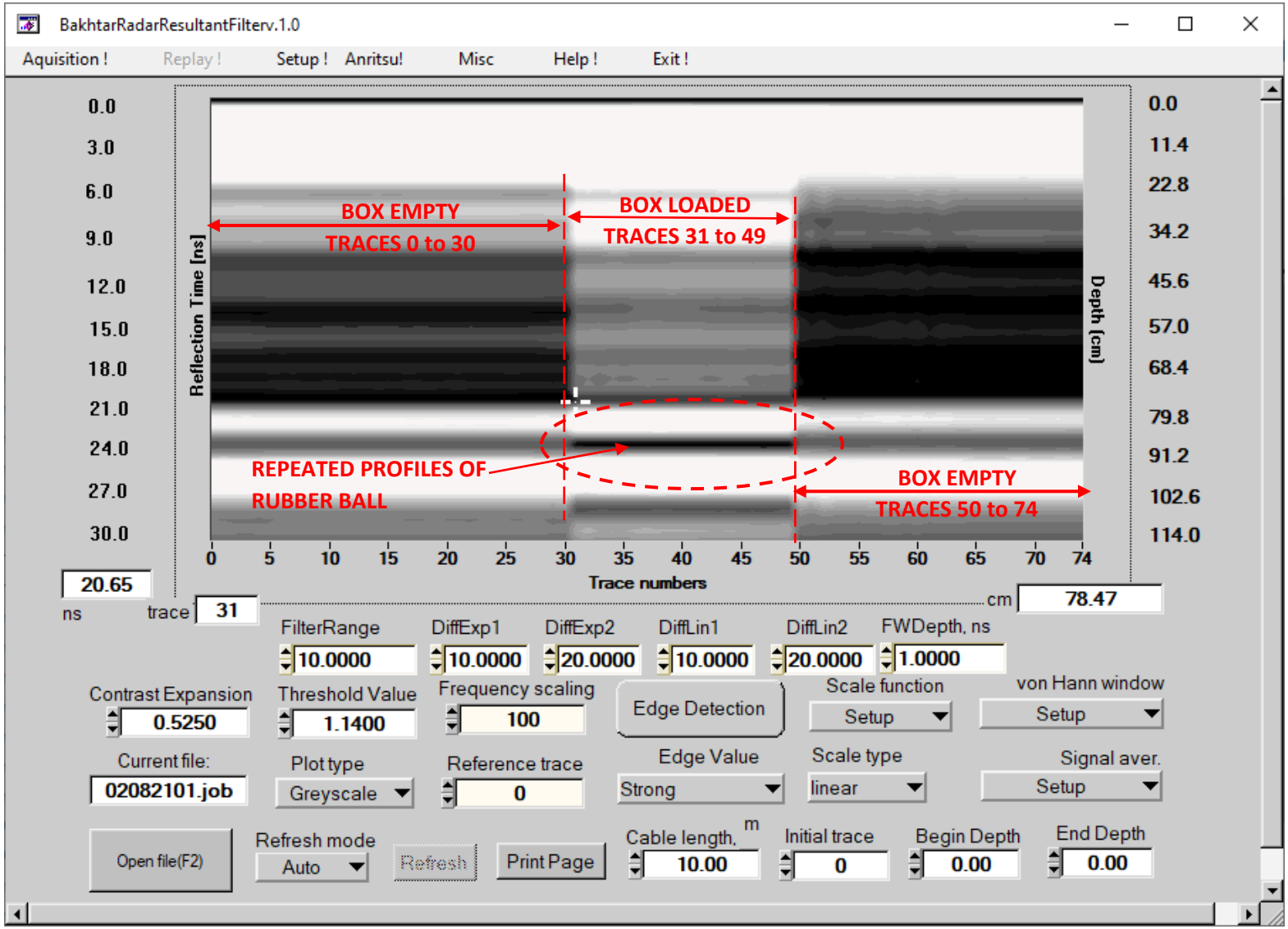


Figure 13 - BakhtarRadar Repeated Profiles of Rubber Ball Specimen inside Lead Box in Greyscale Format

TEST SPECIMENS	DIMENSIONS (cm)	VOLUME (cm^3)	WEIGHT (gm)	DENSITY (gm/cc)
THIN WALL PLASTIC OBJECT	IRREGULAR	----------	56	1.27

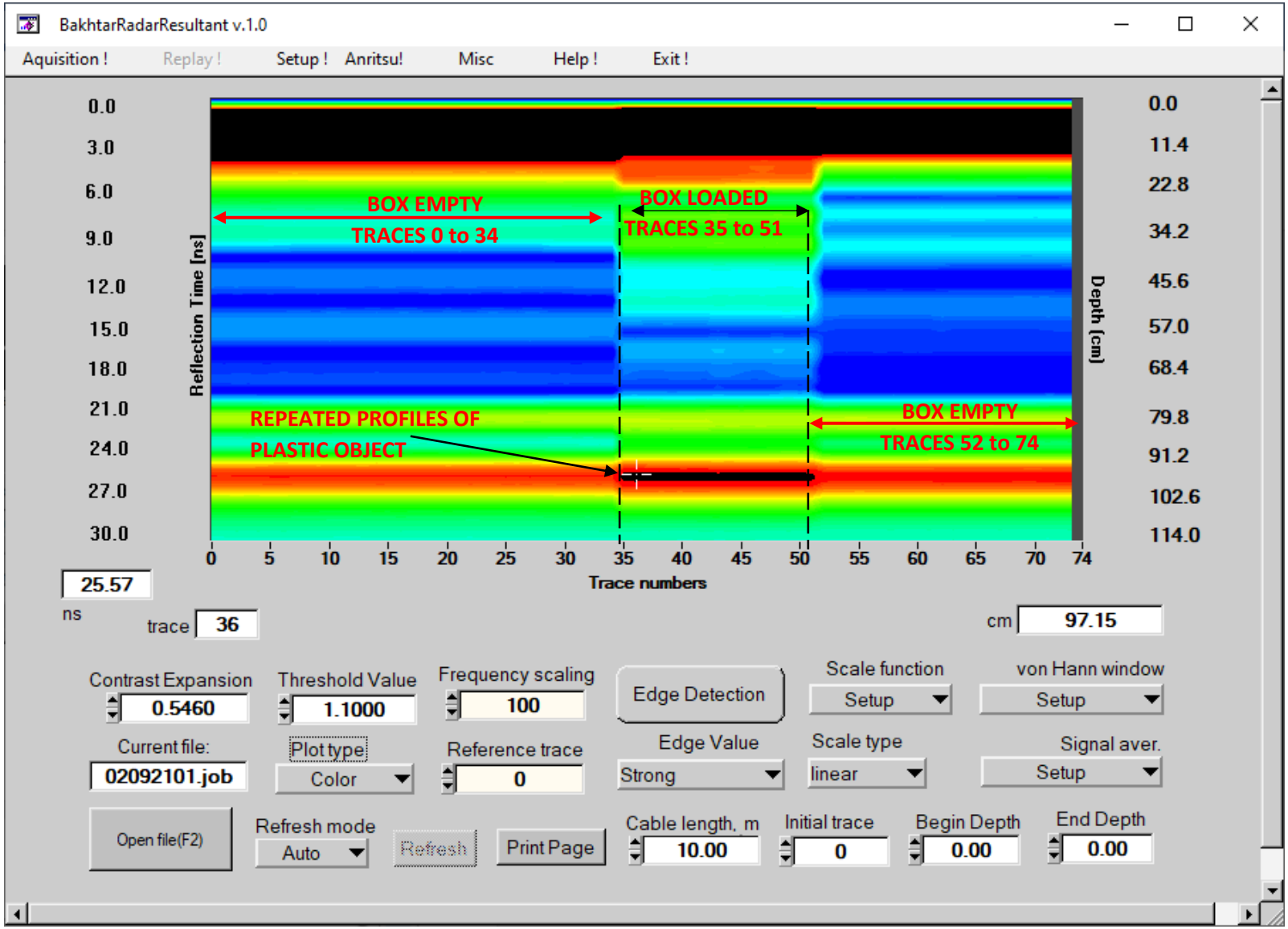


Figure 14 - BakhtarRadar Repeated Profiles of Plastic Object Specimen inside Lead Box in Color Format

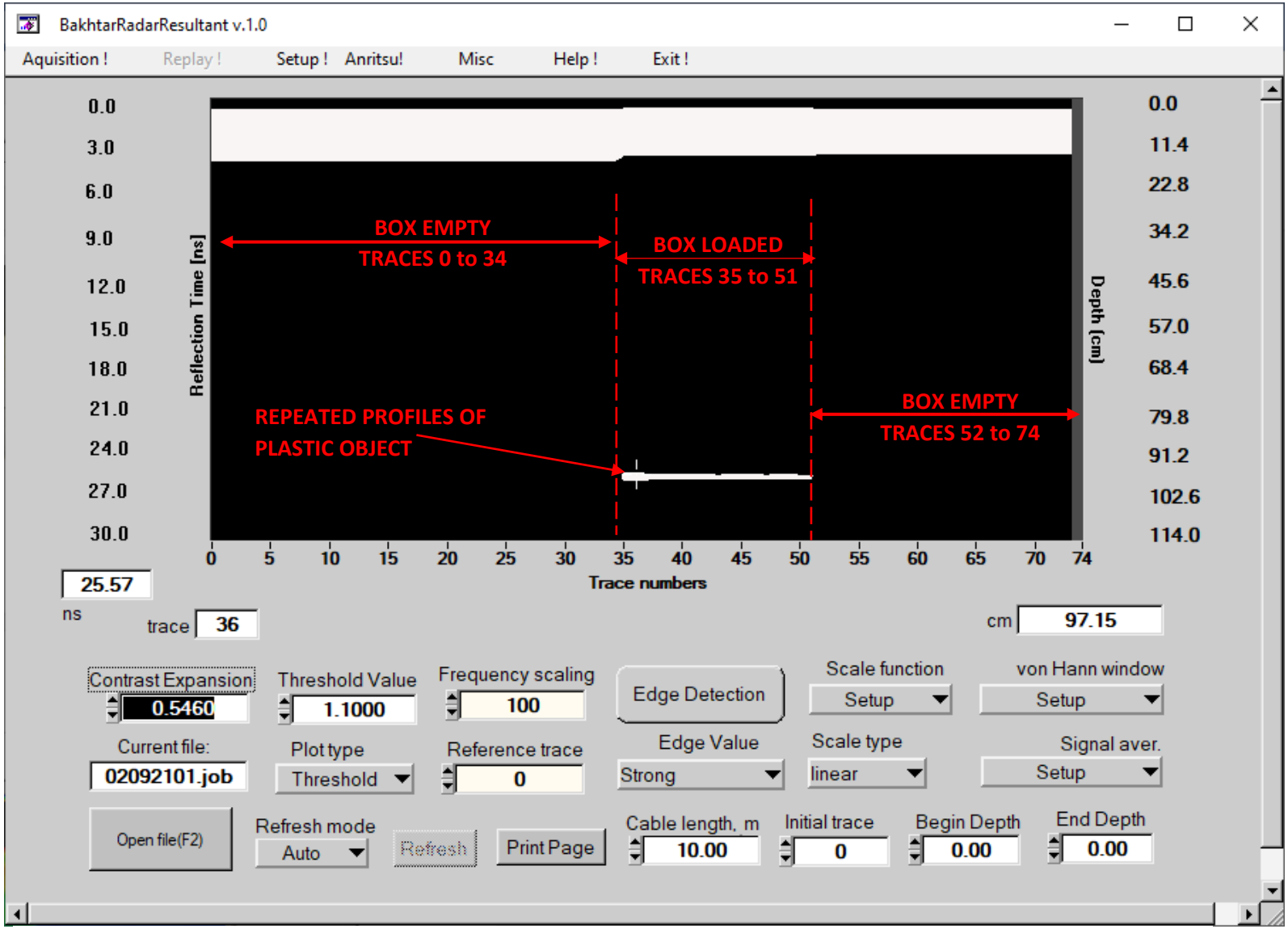


Figure 15 - BakhtarRadar Repeated Profiles of Plastic Object Specimen inside Lead Box in Threshold Format

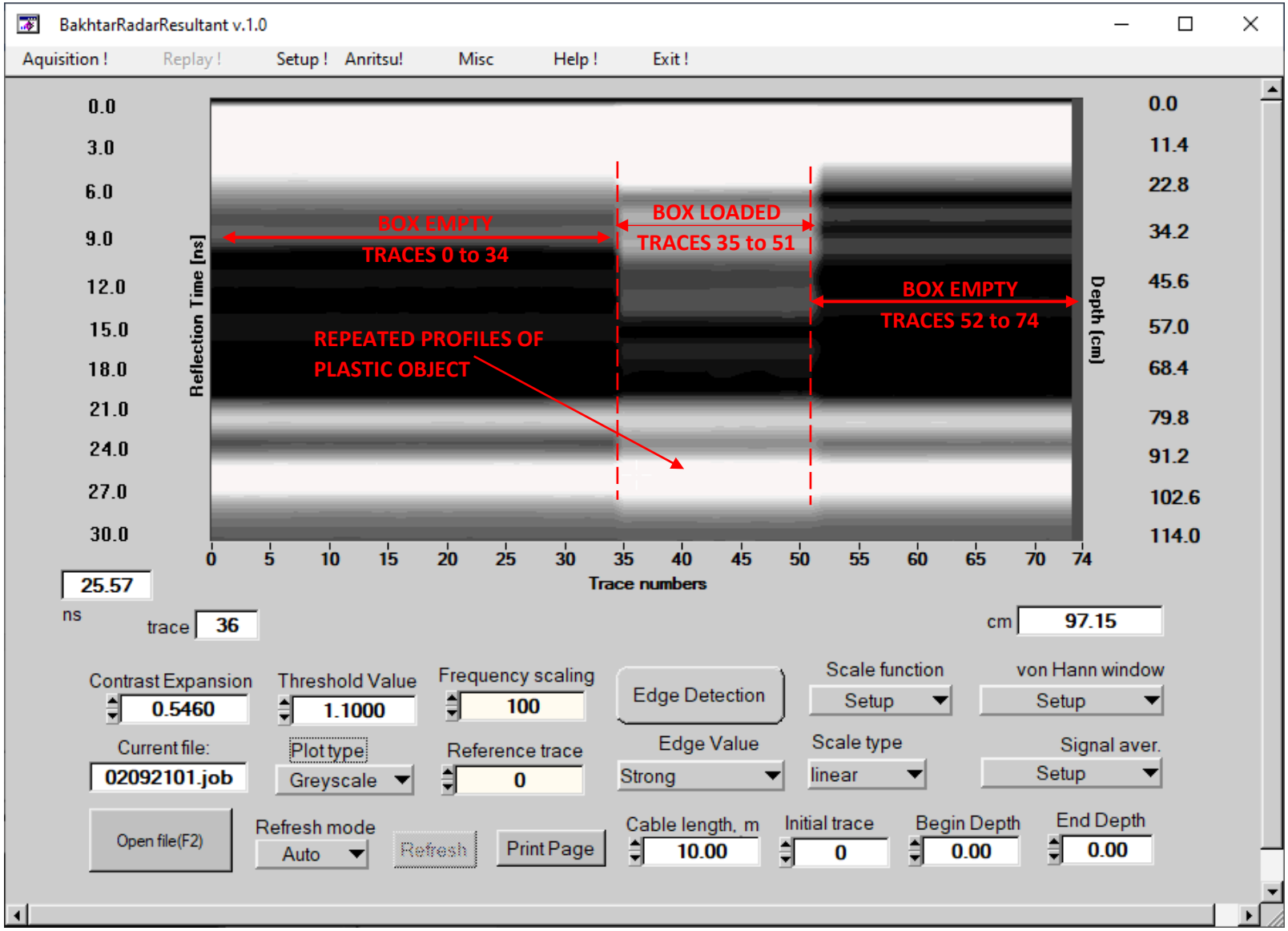


Figure 16 - BakhtarRadar Repeated Profiles of Plastic Object Specimen inside Lead Box in Greyscale Format

TEST SPECIMENS	DIMENSIONS (CM)	VOLUME (CM^3)	WEIGHT (gm)	DENSITY (gm/cc)
PIECE OF MAHOGANY WOOD	Thickness 2.4 Width: 4.5 Length: 25.4	274.32	152	0.55

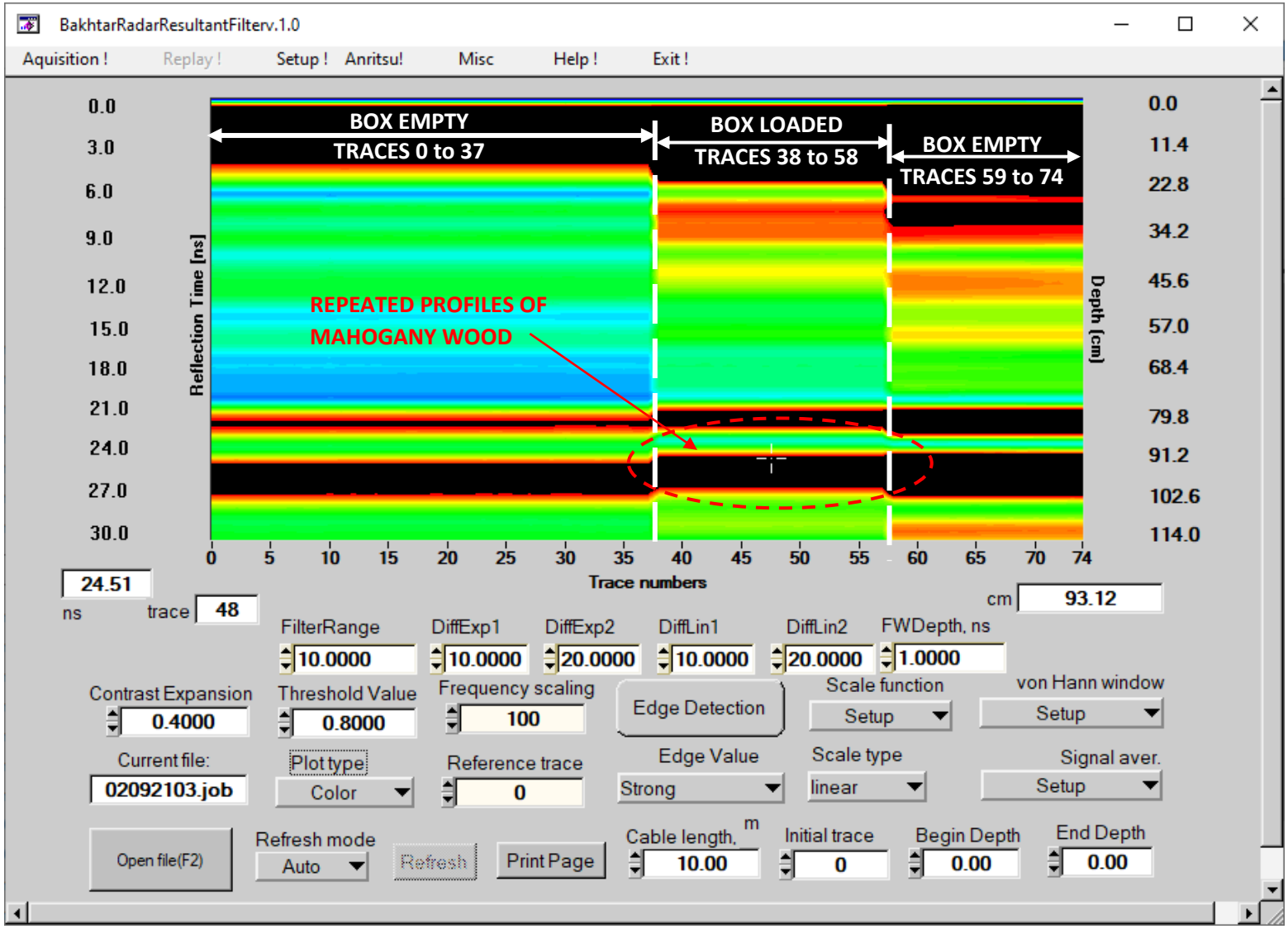


Figure 17 - BakhtarRadar Repeated Profiles of Mahogany Wood Specimen inside Lead Box in Color Format

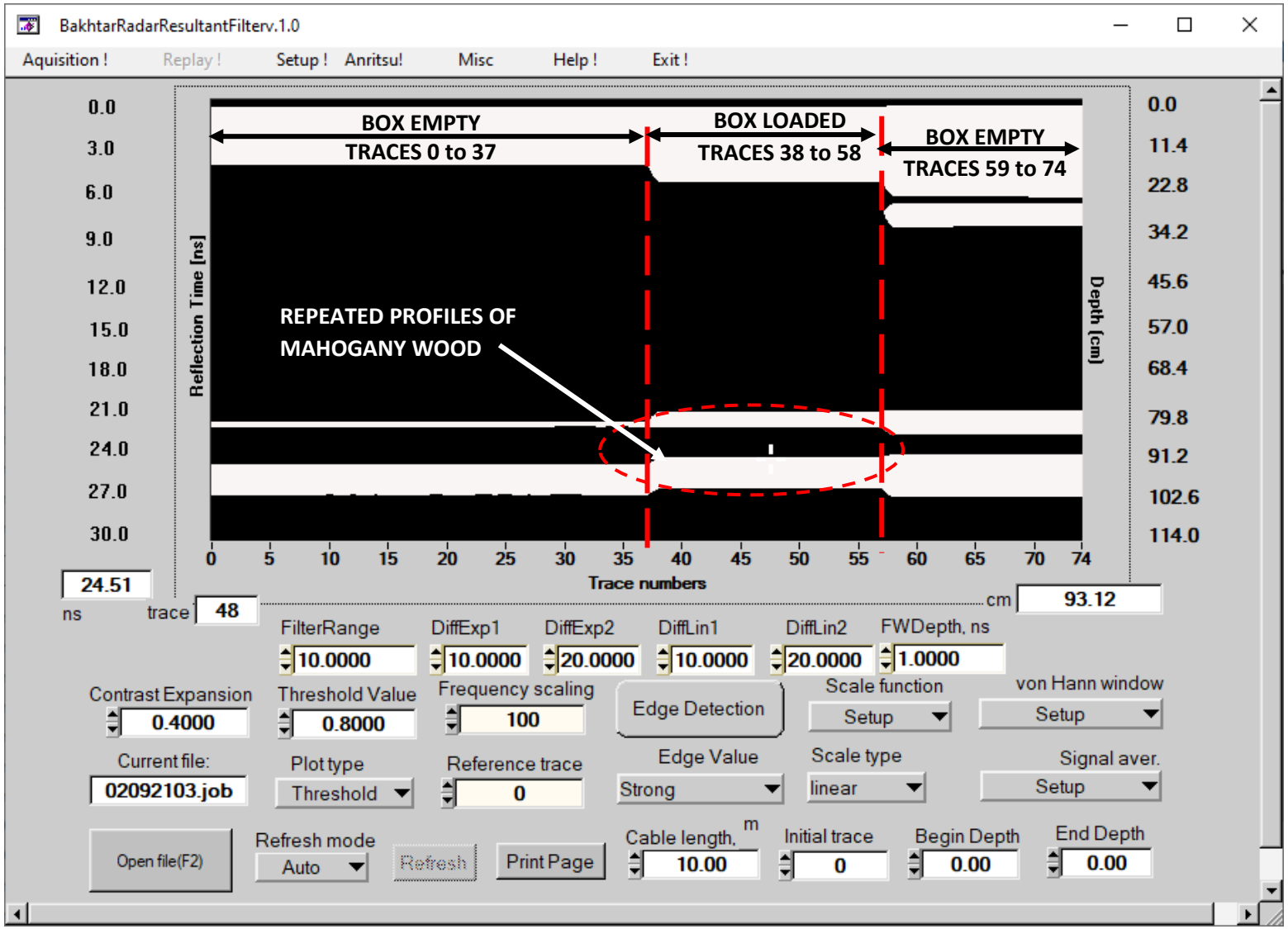


Figure 18 - BakhtarRadar Repeated Profiles of Mahogany Wood Specimen inside Lead Box in Threshold Format

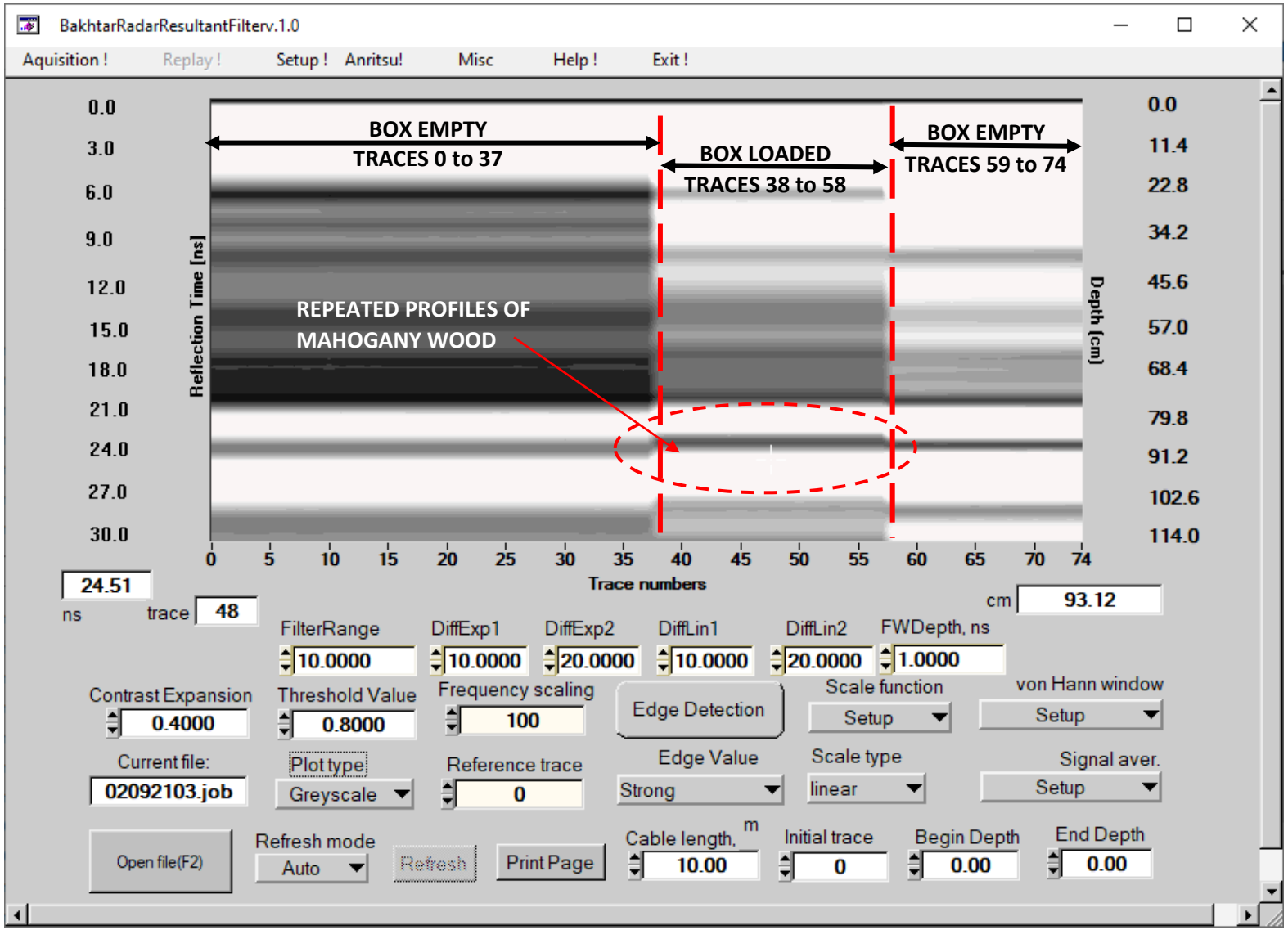


Figure 19 - BakhtarRadar Repeated Profiles of Mahogany Wood Specimen inside Lead Box in Greyscale Format

TEST SPECIMENS	DIMENSIONS (CM)	VOLUME (CM^3)	WEIGHT (gm)	DENSITY (gm/cc)
COPPER TUBING	O. D.: 1.2 I. D.: 1.0 Length: 32	----------	175	8.96

(d)

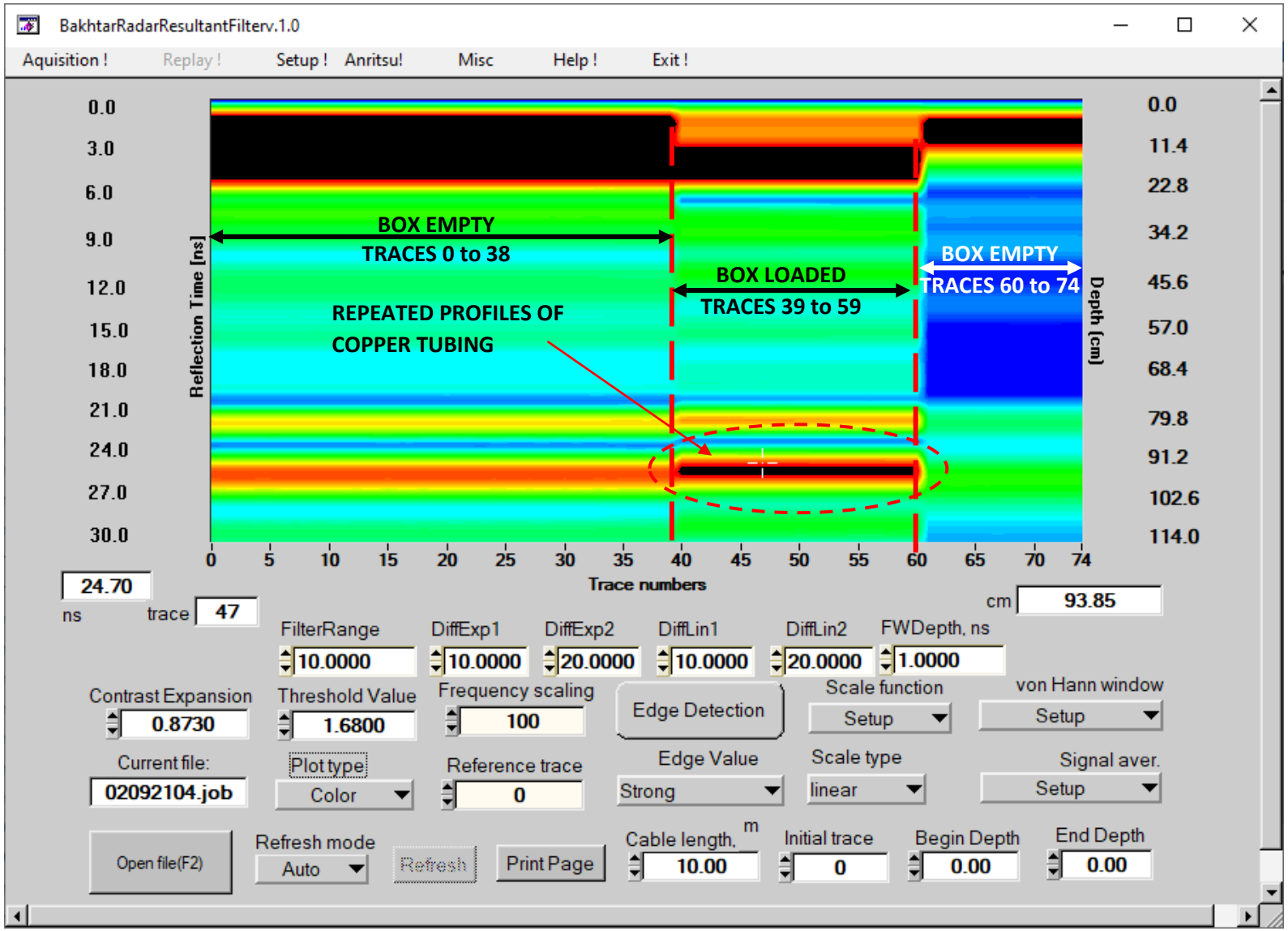


Figure 20 - BakhtarRadar Repeated Profiles of Copper Tube Specimen inside Lead Box in Color Format

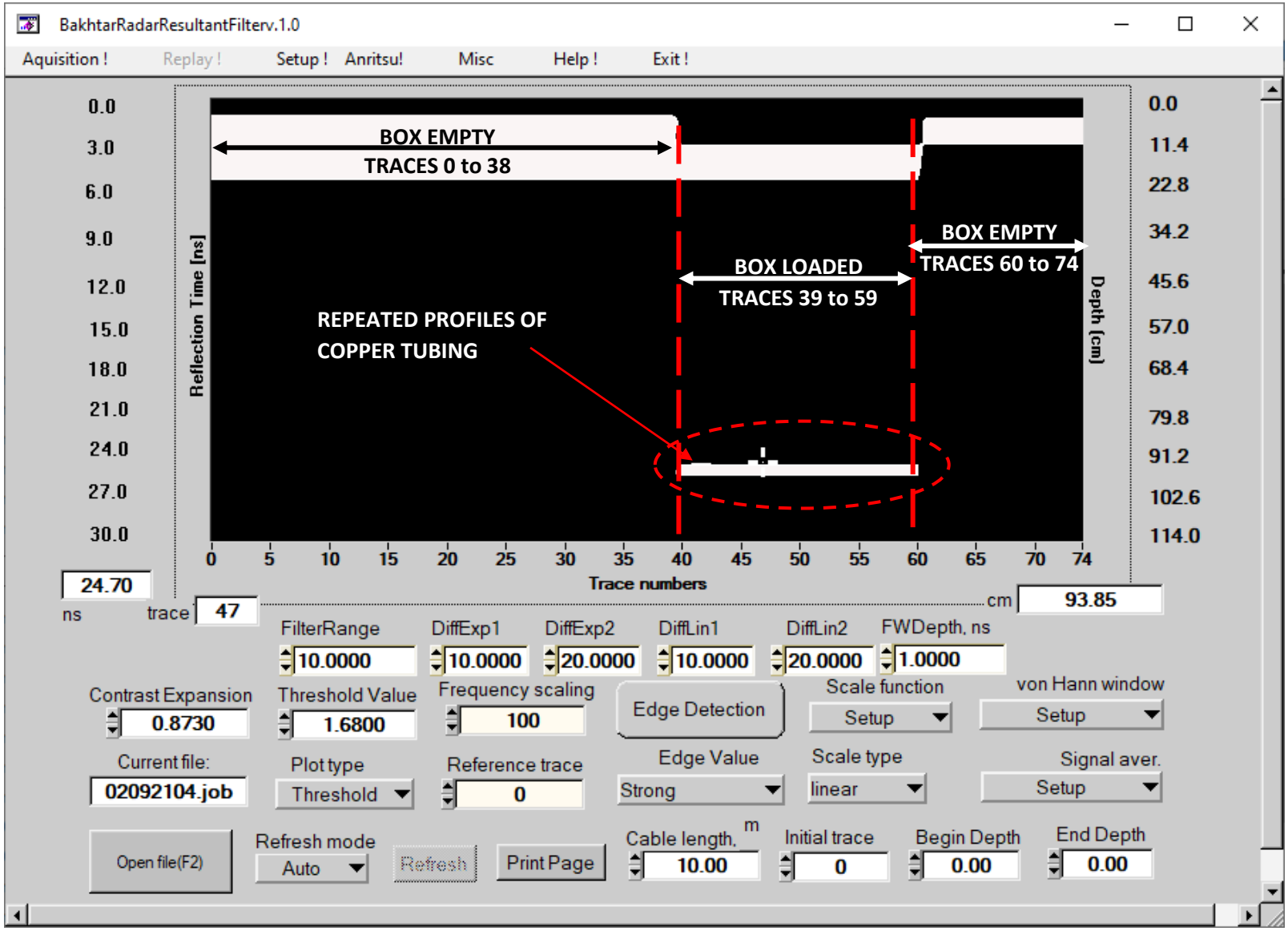


Figure 21 - BakhtarRadar Repeated Profiles of Copper Tube Specimen inside Lead Box in Threshold Format

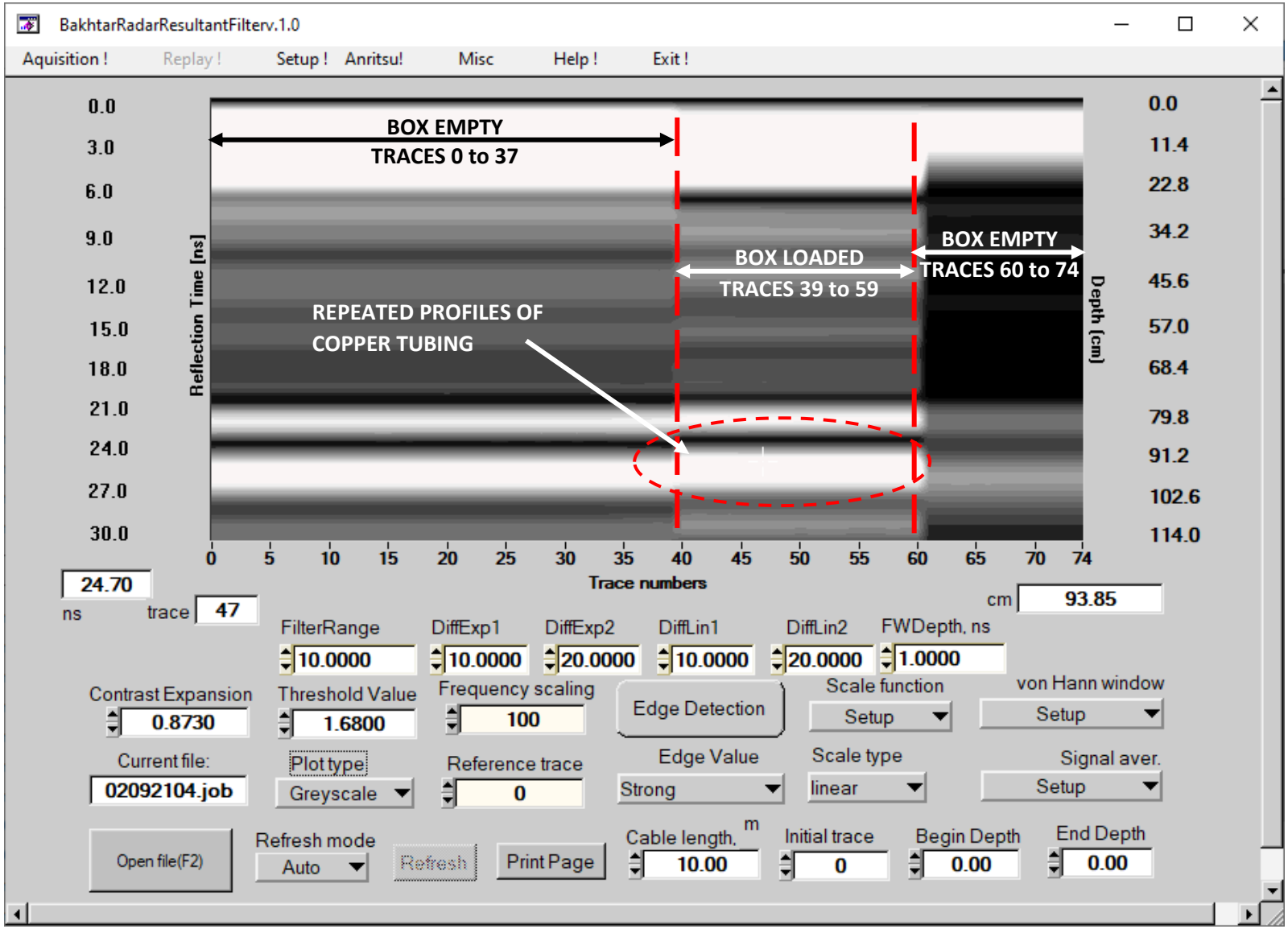
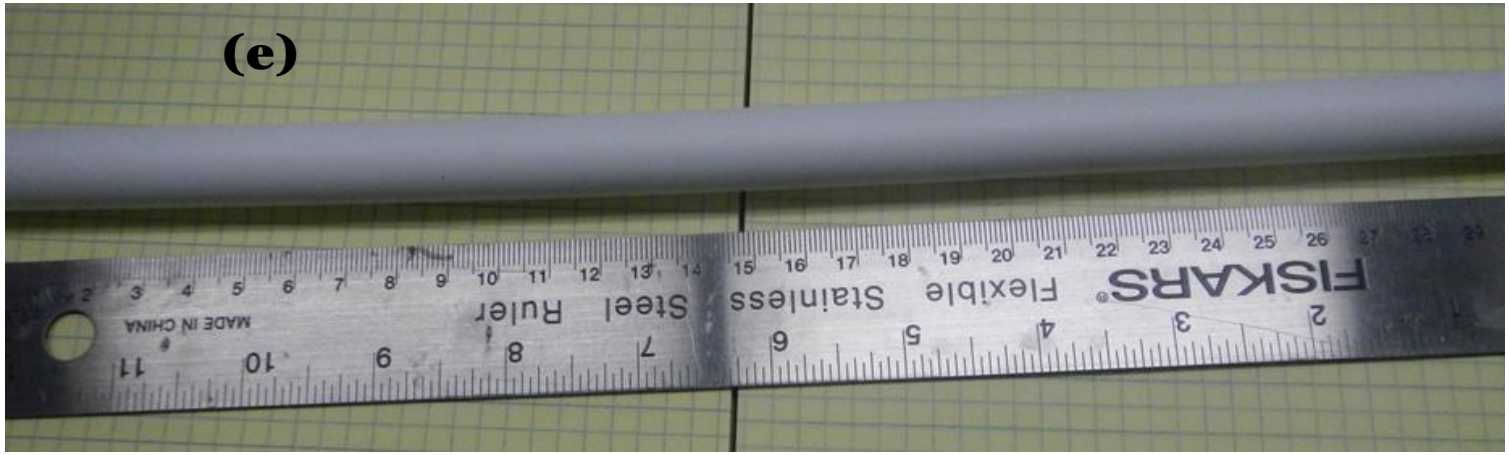


Figure 22 - BakhtarRadar Repeated Profiles of Copper Tube Specimen inside Lead Box in Greyscale Format

TEST SPECIMENS	DIMENSIONS (CM)	VOLUME (CM^3)	WEIGHT (gm)	DENSITY (gm/cc)
PLASTIC TUBING	O. D.: 1.5 I. D.: 1.2 Length: 32	---------	49	1.45



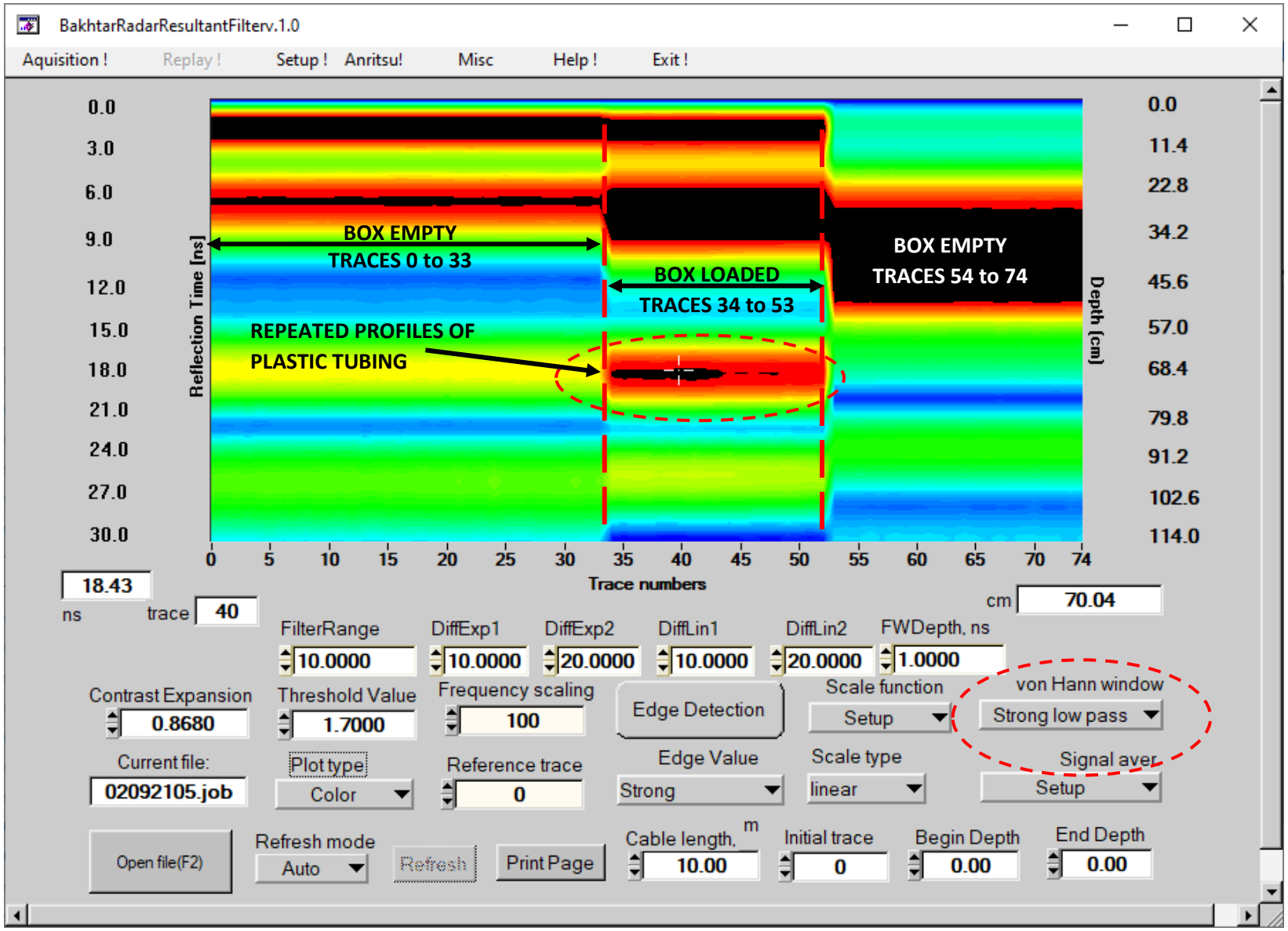


Figure 23 - BakhtarRadar Repeated Profiles of Plastic Tubing Specimen inside Lead Box in Color Format

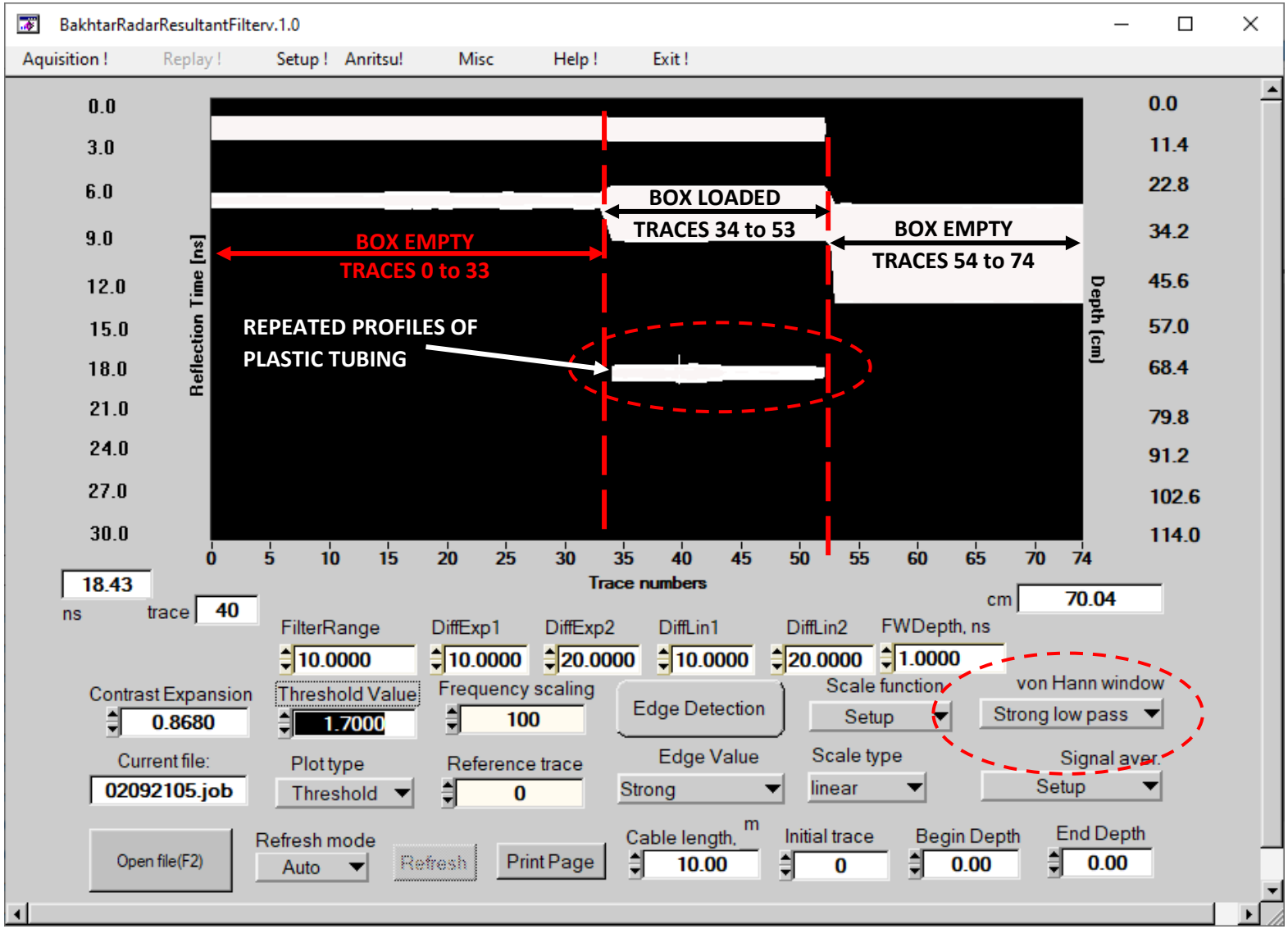


Figure 24 - BakhtarRadar Repeated Profiles of Plastic Tubing Specimen inside Lead Box in Threshold Format

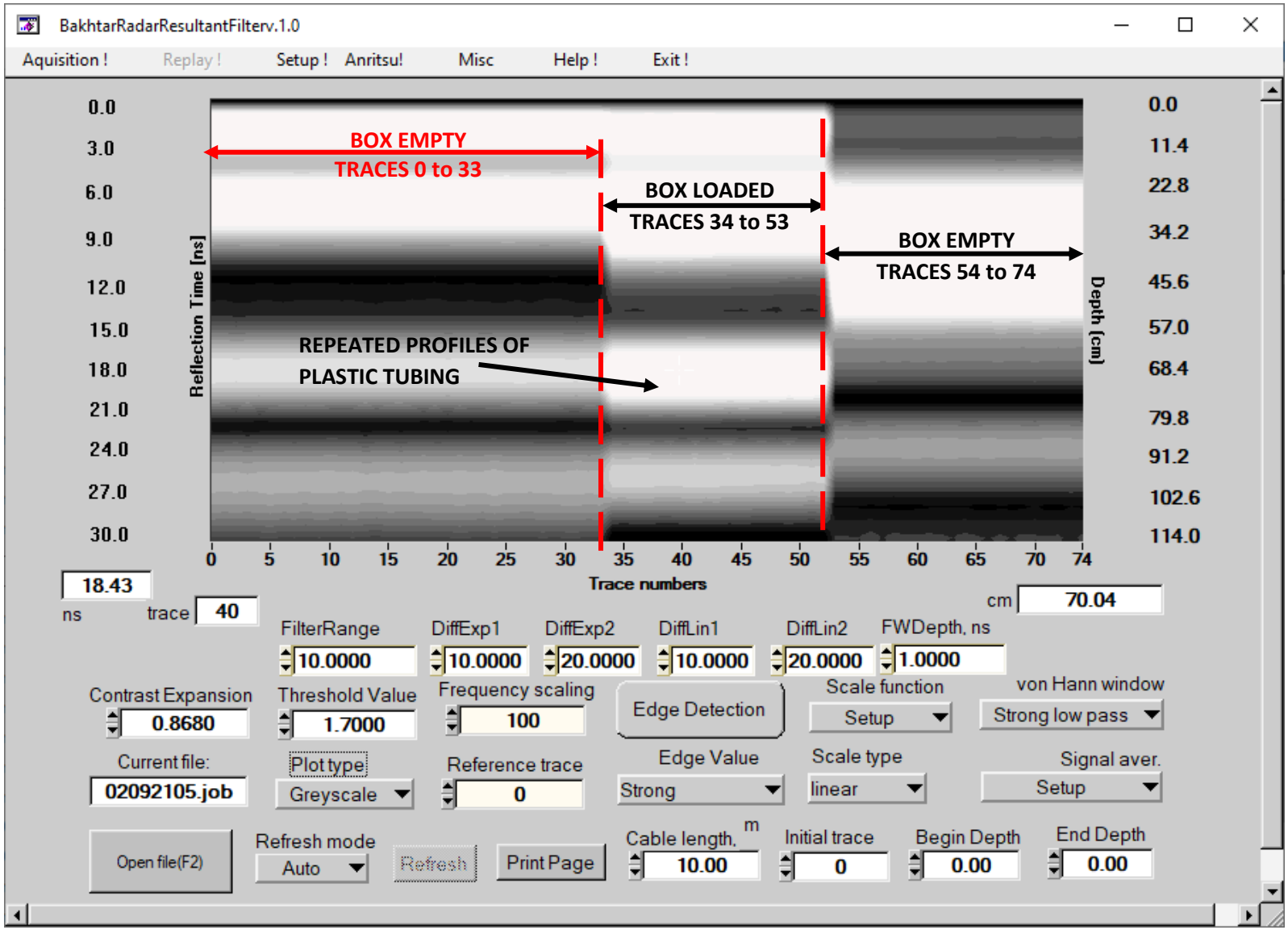


Figure 25 - BakhtarRadar Repeated Profiles of Plastic Tubing Specimen inside Lead Box in Greyscale Format

Table 3 - Summary of Detection Results Using the Ocean/Lead Simulator

TEST NUMBER	FILE NAME	SPECIMEN TESTED	DENSITY (gm/cc)	CONTRAST* EXPANSION	THRESHOLD VALUE
1	02082101.job	RUBBER BALL	1.52	0.5250	1.1400
2	02092101.job	THIN WALL PLASTIC OBJECT	1.27	0.5460	1.1000
3	02092103.job	PIECE OF MAHOGANY WOOD	0.55	0.4000	0.8000
4	02092104.job	COPPER TUBING	8.96	0.8730	1.6800
5	02092105.job	PLASTIC TUBING	1.45	0.8680	1.7000

* The higher the CONTRASST EXPANSION value the easier the detection process

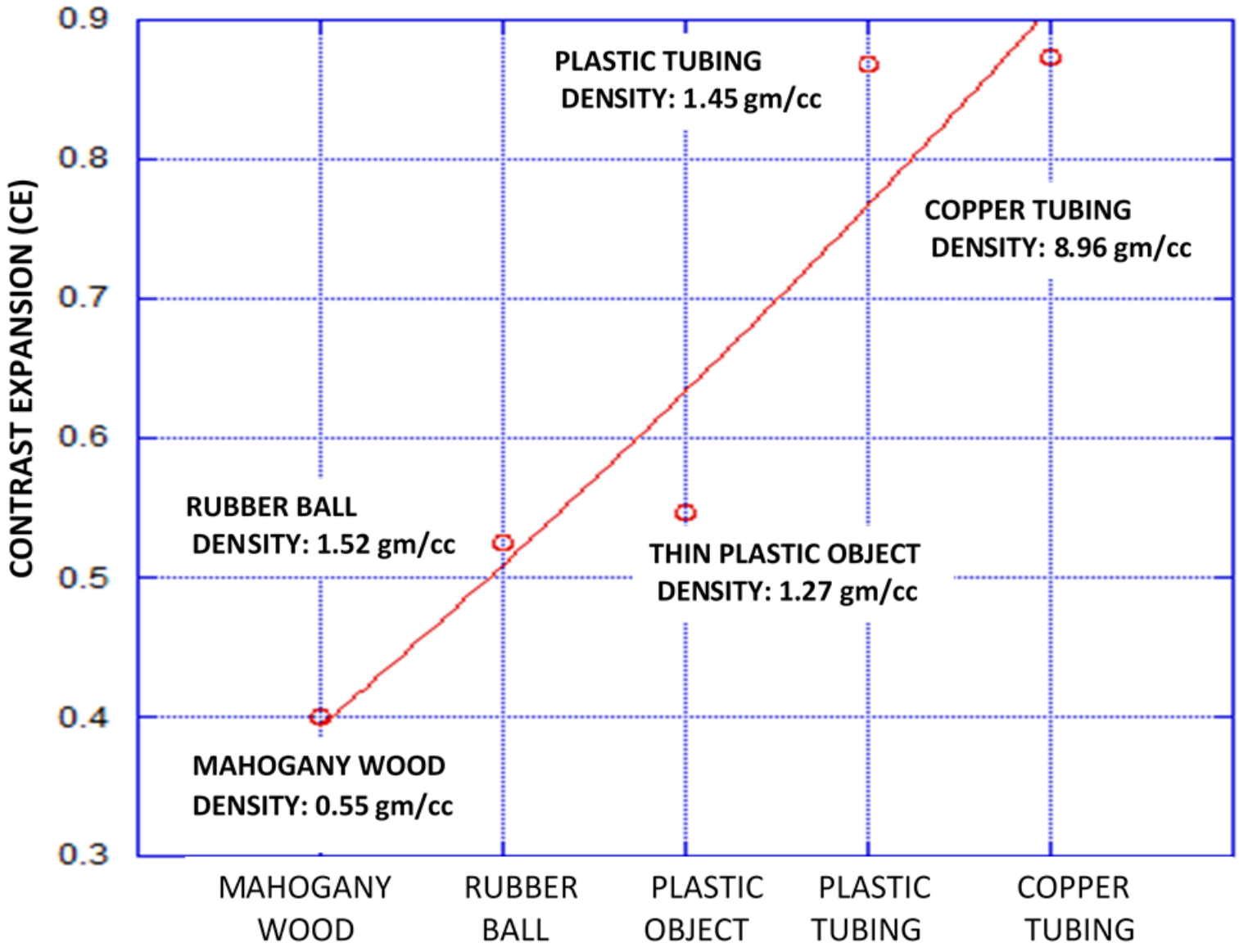


Figure 26 – Contrast Expansion Variations with Specimens Tested

5. CONCLUSIONS AND RECOMMENDATIONS TO COMPLETE TASK-2

5.1 GENERAL

Results of detection exercises reported using the simulator in this document compared well with those conducted in land from previously documented tests confirming the applicability of the deployed land/ocean simulator. The simulator was designed by a renowned geophysicist from the Royal Dutch Shell oil company in Netherland (Dr. Jonathan Singer) and was built by the Principal Investigator in the United States. Earlier demonstrations made before the international audience (experts) further validated the applicability of the forced-resonance imaging (FRI) technique and simulation of electromagnetic impedance of the land and ocean using the simulator for the purpose of embedded target detection.

It is also important to note that the results of detection presented in Figures 11 to 25 are based on repeated accumulation of the BakhtarRadar traces from the embedded target. Therefore, they appear as elongated bands rather than a single cross-section or profile of the specimens tested.

Much more description of tests and measurements were provided in the original Field Test Plan.

5.2 CONCLUSIONS

With reference to the preceding pages and comparison of data acquired from the Lead/Aluminum simulator with those from actual field tests the following conclusions are in order.

- The electromagnetic wave speed (EMS) selected (3.5 cm per nanoseconds equivalent to 1.38 inches per nanoseconds) represents moist sandy-clayey soil formations. This geologic setting is dominant in most part of the California within the depth of 0 to 3 meters (0 to 10 ft.).

- Detection and discrimination were done by adjusting the CONTRAST EXPANSION ((CE) of the collected data in the REPLAY Window which is controlled by the characteristics of the intrinsic material makeup of the specimens tested.

- Overall evaluation of the data plotted in Figure 26 further verify that the detection is based on material makeup rather than their density.

- Detectability, as defined by the CONTRAST EXPANSION - Figure 26, of uniformly elongated tubing is appeared to be facilitated by their curvature and make them more pronounced once fielded in low-power electromagnetic field.

- Filter application, von Haan Window, assisted in uniquely defining the plastic pipe by increasing the CONTRAST EXPANSION and masking noise or clutter additives from return or backscattered signal.

- A scan be deduced from the polynomial plot of test data versus selected specimens of copper and plastic tubing are by for more dominant and their material make-up facilitate much easier detection under buried conditions than other material.

5.3 RECOMMENDATIONS

The scope of investigation reported in this document should be extended to:

- Repeat the above feasibility tests using the simulator with plastic and metallic pipes specimens having cross-sectional details (inside and outside diameters) the same as those used in buried pipelines by the utility companies.

- Validate frequency band of operations ($\Delta f = f_{FINAL} - f_{INITIAL} = 1000 - 500 = 500$ MHz) by conducting actual tests in the field with buried pipelines.

- Use the make-shift configuration of Bakhtar Pipe Detector (BPD) to collect data in the field and reconstruct volumetric images (3-D mapping) by deploying the old software and RTK GPS system.

- Complete Item # 5 TASK-2 and move to the next task (TASK-3) by April 1, 2021.