

# High Bandwidth Oscilloscope requirements

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High Bandwidth Oscilloscope requirements

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# 1 Introduction

## 1.1 Identification

This document contains information and requirements pertaining to the high bandwidth oscilloscope that will be purchased by TNO. This high bandwidth oscilloscope will be added to the tool set for experimental and scientific work that the Optomechatronics group does in the field of Gigahertz Acoustic Metrology. The oscilloscope will be installed in STW P.01.190 (referred to as AFM lab).

## 1.2 System overview

The semiconductor industry needs to fit ever more devices per unit area to improve their performance; hence a trend towards increasingly complex structures by varying material combinations and 3D geometries with increasing aspect ratios. The new materials used may be optically opaque, posing problems for traditional optical metrology methods. Moreover, this modality shows limited detection depths ( $<0.1 \mu\text{m}$ ) at resolutions (wavelength) of  $\sim 0.2 - 1.5 \mu\text{m}$ . Traditional acoustic microscopy is limited by the need for liquid coupling layers between the transducer and the sample. Liquid coupling layers become very attenuative at the high frequencies necessary for a relevant resolution (O(GHz's to 10's of GHz) and therefore limit the achievable penetration depth.

TNO recently introduced its novel GHz acoustic metrology inspection instrument entitled Half Wavelength Contact Acoustic Microscopy (HaWaCAM<sup>1</sup>). It uses acoustic impedance contrasts, is fully linear and employs contact mode GHz piezotransducers without the need for liquid couplants. It is based on a pulse-echo scheme, using a GHz transducer integrated on a probe directly in contact with a sample (see illustrations of this concept in Figure 1).

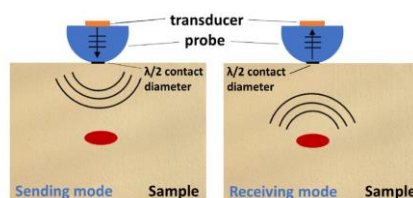


Figure 1. Schematic image showing the half wavelength contact acoustic microscopy (HaWaCAM) inspection concept. Sending (left) and receiving (right) modes during pulse-echo measurements.

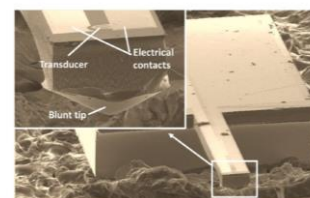


Figure 2. SEM image of the custom probe including (zoom): GHz piezoelectric transducer with electrode electrical contacts on top of blunt probe tip.

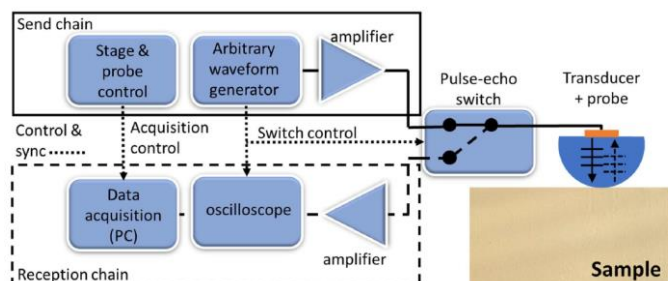


Figure 3. Schematic of the experimental setup.

Figure 1 HaWaCAM pulse-echo acquisition principle (from [1])

<sup>1</sup> Quesson, Benoit & van Neer, Paul & Tamer, Selman & Hatakeyama, Kodai & Es, Maarten & Riel, Martijn & Piras, Daniele. (2022). GHz half wavelength contact acoustic microscopy (HaWaCAM): a feasibility study. 10.1011/12.2613753.

The initial prototypes operate at a centre frequency of 4-5 GHz, and research is ongoing to increase the centre frequency to 20 GHz or more. A characteristic of these high frequency acoustic signals, in contrast to most RF signals, is that they also have a high bandwidth (100% of the centre frequency is typical, so for instance 20 GHz bandwidth for 20 GHz centre frequency). To record these signals, an acquisition systems is needed with a sufficiently high sampling rate. Considering  $f_{\max} = 30$  GHz, this leads to a sampling frequency of ( $>66$  Gs/s with a factor 2.2). Only a few systems can record high bandwidth at GHz frequency, and even fewer can do it fast without using interleaving approaches, as recording only one sample at a time in a time trace or a frequency bin at a time for instance, which slow down the acquisition time significantly.

Additionally, in a typical measurement, many traces have to be recorded and transferred to a computer for analysis. This is due to the fact that the sample must be scanned with an accuracy limited by half the minimal acoustical wavelength to meet Nyquist criterium. This adds additional requirements for the data transfer speed. Additionally, the acoustical measurements rely on the time of flight estimation, which adds requirements on the jitter accuracy.

### 1.2.1 Intended method of use

The main intended use of the high bandwidth oscilloscope is to record the electronic signals resulting from acoustic pulse-echo measurements. These signals typically have a bandwidth of tens of Gigahertz and need to be recorded with a jitter below 0.5ps in order to extract the relevant information from the data. These data should be acquired as fast as possible, in order not to hamper the scanning acquisition on top of the sample.

### 1.2.2 Data acquisition procedure

A typical measurement consists of a transmitted signal, which is commonly a high bandwidth signal such as a chirp, that is generated by a high-bandwidth waveform generator (Keysight M8100 series). With our probes with integrated piezo-acoustic transducer the electrical signal is converted into an acoustic wave. These waves travel through the probe tip and part of the signal refracts into a sample, which can contain features or defects that have to be characterized. Acoustic echoes reflect from these features and have to be recorded. With the piezo transducer these echoes are converted into an electrical signal that is subsequently recorded by the high bandwidth oscilloscope.

To obtain a good signal-to-noise ratio (SNR), for each x-y scan position, a number of traces must be averaged (typically 100-400x). Additionally, a sufficiently large portion of the sample must be covered in order to enable advanced signal processing techniques. In total, many acquisitions are needed (typically 200k measurements).

The total data of these acquisitions has to be transferred from the acquisition system to a storage device (hard drive) as fast as possible. The data transfer speed is the limiting factor in the scanning speed of the system, and can result in measurements that take over a day. An improvement in the transfer speed results directly into an improvement in measurement speed.

## 1.3 Document overview

The purpose of this document is to state and clarify the requirements TNO has for a new [High bandwidth oscilloscope].

The last column of each requirement contains the verification method (VM), this could be; (T)est, (R)evue, (D)emonstration, (A)nalysis, (I)nspect, or (C)ertification. The full detail definitions are described in chapter 2.1.

Remarks noted within a requirement must be seen as guidelines for addressing that requirement. They also provide additional information of relevance and clarify the relationship with other requirements.

This document uses the definitions as explained in chapter 3.

The High Bandwidth Oscilloscope shall be capable of fulfilling all requirements simultaneously, unless indicated otherwise in the requirement.

All preferences that are stated as compliant in the supplier's tender document, automatically become requirements (demands) upon awarding the tender. This requirement document will be updated to represent this.

Stated performance values for such wishes in the supplier's tender document shall, if agreed on by TNO, become the stated required values, whether they are better or worse than the wished value.

## 1.4 Relationship to other documents

Not applicable, this is a standalone document.

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## 2 Definitions, abbreviations and acronyms

### 2.1 Definitions

May	Expresses permissive guidance.
Shall	Expresses a characteristic which is to be present in the item which is the subject of the specification, i.e. "shall" expresses a binding requirement.
Should	Expresses a target or goal to be pursued, but not necessarily achieved.
Will	Expresses a declaration of intent on the part of a party, usually the sponsoring or acquiring organisation. "Will" does not express a binding requirement. "Will" may also be used in cases where the simple future tense is required, for example, "The operating system will be supplied by the government.". Will may also express simple futurity. Any statement which employs the term "will", if used in chapter 4, should be present as a note so as to be clearly distinguishable from requirements.
Goal	The desired value for a requirement.
Threshold	The acceptable value for a requirement.
Remark	Information that is meant to clarify or supplement a requirement.
Rationale	Reasons or logical basis for a requirement.

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Accuracy	The degree to which the result of a measurement, calculation, or specification conforms to the correct value or a standard.
Reproducibility	The degree of agreement between measurements or observations conducted on replicate specimens in different locations by different people, as part of the precision of a test method.
Sample	Object to be measured.
State	A required, permitted or prohibited condition of the system.
Mode	A group of functions related to an aspect of use.
Test (T)	The operation of the system, or part of the system, using instrumentation or other special test equipment to collect data for later evaluation.
Demonstration (D)	The operation of the system, or a part of the system that relies on observable function not requiring the use of the instrumentation, special test equipment, or subsequent analysis.
Analysis (A)	The processing of accumulated data obtained from other qualification methods. Examples are reduction, interpolation, or extrapolation of test results.
Inspection (I)	The visual examination of system components, documentation, etc.
Certification (C)	A declaration by designated stakeholder, usually the supplier or developer.
Review (R)	Detailed review of the received specification of the supplier or developer on the (sub-)system.

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## 3 Requirements

### 3.1 Identification of external interfaces

The High bandwidth oscilloscope could have the following external interfaces. TNO expects that this can be achieved without any problems. Table 2: High Bandwidth Oscilloscope interfaces.

interface type	identification	location
<i>Mechanical</i>		
High Bandwidth Oscilloscope to Floor	High Bandwidth Oscilloscope to Floor	Laboratory
<i>Supplies</i>		
Power	Power	Laboratory
<i>Signals</i>		
Time trace(s)	time traces	Laboratory
Trigger	trigger	Laboratory
Clock synchronization	clock synchronization	Laboratory
Recorded data	USB / LAN?	
<i>Environment</i>		
Laboratory	Lab	-

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## 3.2 Configurations

The High Bandwidth Oscilloscope might have two configurations, one with a single channel acquisition at a higher frequency and bandwidth ( $>50$  GHz) or a second one with two acquisition channels at a lower frequency and bandwidth ( $<50$  GHz). The supplier is responsible for both configurations, if applicable.

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## 4 System function and performance requirements

### 4.1 High Bandwidth Oscilloscope generic requirements

#### 4.1.1 R-0000-005 : Meet all requirements

Description		VM
The High Bandwidth Oscilloscope supplier shall deliver a system that is capable of meeting all the stated requirements, and accepted wishes, in this document at the same time, unless indicated otherwise in a specific requirement.		R
Rationale	Required to meet main function of the High Bandwidth Oscilloscope system.	

#### 4.1.2 R-0000-010 : Human, machine and sample safety

Description		VM
The High Bandwidth Oscilloscope shall ensure, human, machine and sample safety.  Remark: close-out of this requirement is done by review of the provided FMEA and demonstration that the implemented mitigation actions function, therefor VM is demonstration.		D
Rationale	TNO requires a safe system.	

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#### 4.1.3 R-0000-015 : Operational lifetime

Description		VM
The High Bandwidth Oscilloscope system shall have an operation lifetime of at least 10 years.  Remark: Close out shall be done through review of design, proof of heritage, used materials and equipment.		R
Rationale	Minimum expected lifetime of such a system.	

#### 4.1.4 -R0000-020 : Collaboration and Maintenance contract

Description		VM
The oscilloscope comes with a calibration and maintenance contract.  Remark: Close out shall be done through review of design, proof of heritage, used materials and equipment.		R
Rationale	Rationale: Minimum expected lifetime of such a system.	

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#### 4.1.5 R0000-025 : Software and all components

Description	VM
Software will be delivered, including all components.  Remark: The supplier shall state in the tender document the included software	R
Rationale	Rationale: Software is an integral and essential part of such a system.

#### 4.1.6 R0000-030 : Software updates

Description	VM
Free software updates and upgrades within the period of the extended warranty.  Remark: The supplier shall state in the tender document update policy of the included software.	R
Rationale	Rationale: Up-to-date software is an integral and essential part of such a system.

#### 4.1.7 R0000-035 : Electrical connection & Power supply

Description	VM
Electrical connection & Power supply according to European standards.  Remark: Close out shall be done through review of design, proof of heritage, used materials and equipment.	R
Rationale	Rationale: The equipment will be used in a lab space that has to comply with European standards

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## 4.2 Aspect 'Triggering and jitter'

### 4.2.1 R1000-005 : Trigger jitter below 250 fs RMS

Description		VM
Trigger jitter below 250 fs RMS		T
Remark: The quotation shall state the trigger jitter		
Rationale	the trigger jitter is an essential parameter for the project, when scans of pulse-echoes traces must be acquired, and time of flight should be compared.	

### 4.2.2 R1000-010 : Trigger jitter below 250 fs RMS

Description		VM
This determines the main performance of the overall system.		T
Remark: The content of the response is assessed based on measurement results delivered with the quotation.		
Rationale	The jitter in this case is defined as the random time difference between two consecutively recorded signal traces of a periodic signal (such as a linear chirp) for consecutive trigger events.	

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#### 4.2.3 R1000-015 : The jitter between channels

Description		VM
The jitter between channels is lower than 200fs rms		T
Remark: The quotation shall state the minimum jitter between channels.		
Rationale	the trigger jitter is an essential parameter for the project, when scans of pulse-echoes traces must be acquired and time of flight should be compared.	

#### 4.2.4 R1000-020 : The jitter on the sample clock is below 150fs rms

Description		VM
The jitter on the sample clock is below 150fs rms		T
Remark: The quotation shall state the sample clock jitter.		
Rationale	the clock synchronization with a pulse generator is an essential parameter for the project, when scans of pulse-echoes traces must be acquired and time of flight should be compared.	

#### 4.2.5 R1000-025 : Acquisition is possible with an interval of 5 $\mu$ s or less

Description		VM
Acquisition is possible with an interval of 5μs or less		T
Remark: The quotation shall state the minimum trigger/measurement interval.		
Rationale	The acquisition repetition rate should be compatible with the project use cases.	

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#### 4.2.6 R1000-030 : Trigger repetition interval lower than 5 $\mu$ s

Description		VM
Trigger repetition interval lower than 5 $\mu$ s.  Remark: The content of the response is assessed, based on: <ul style="list-style-type: none"><li>• It has been shown in the quotation what the minimum trigger interval specification is.</li></ul>		T
Rationale	A shorter repetition rate can be used to reduce the scanning time of the system.	

### 4.3 Aspect 'Bandwith'

#### 4.3.1 R2000-005 : Minimum analog bandwidth 2 input channels

Description		VM
The oscilloscope is a real-time oscilloscope with a minimum analog bandwidth of 30GHz on at least 2 input channels.  Remark: The quotation shall state the analog bandwidth achieved with the system when at least two input channels are used.		I
Rationale	For future projects the expected bandwidth is significantly higher than 30GHz. Therefore, the system should be compatible with higher bandwidths, but we foresee that only one channel will suffice.	

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#### 4.3.2 R2000-010 : Minimum analog bandwidth 1 input channel

Description		VM
The real-time oscilloscope is capable of measuring signals with an analog bandwidth of 60GHz on at least 1 input channel.  Remark: The quotation shall state the analog bandwidth achieved with the system when at least one input channel is used.		I
Rationale	For future projects the expected bandwidth is significantly higher than 30GHz. Therefore, the system should be compatible with higher bandwidths, but we foresee that only one channel will suffice.	

#### 4.3.3 R2000-015 : Higher Bandwidth

Description		VM
Higher bandwidth than 60GHz.  Remark: The content of the response is assessed, based on: <ul style="list-style-type: none"><li>• It has been shown in the quotation what the maximum analog bandwidth of the device is.</li></ul>		I
Rationale	A higher bandwidth is beneficial for future research.	

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#### 4.3.4 R2000-020 : Sample rate

Description		VM
The oscilloscope has a sample rate of at least 150 GSa/s.  Remark: The quotation shall state the maximum sample rate of the oscilloscope.		I
Rationale	The sample rate should be compatible with the highest channel bandwidth. 150 GSa/s is a minimum for a single 60 GHz analog bandwidth channel.	

#### 4.3.5 R2000-025 : The effective number of bits

Description		VM
The effective number of bits (ENOB) is at least 4.0 at 60GHz  Remark: The quotation shall state the ENOB of the oscilloscope at 60GHz and 30 GHz.		I
Rationale	The quantization noise is an essential parameter for the project, where we aim at detection of very small amplitudes in pulse-echo traces.	

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#### 4.3.6 R2000-030 : The effective number of bits

Description		VM
The ENOB is higher than 4.0 at 60GHz.		I
Remark: The quotation shall state the ENOB of the oscilloscope at 60GHz and 30 GHz.		
Rationale	The quantization noise is an essential parameter for the project, where we aim at detection of very small amplitudes in pulse-echo traces.	

#### 4.3.7 R2000-035 : The input noise floor

Description		VM
The input noise floor is below 2.5mV rms.  Remark: The quotation shall state the input noise floor of the oscilloscope.		I
Rationale	The noise floor is an essential parameter for the project, where we aim at detection of very small amplitudes in pulse-echo traces.	

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## 4.4 Aspect ‘Software interfacing’

### 4.4.1 R3000-005 : SCPI command interface

Description		VM
The oscilloscope has a SCPI command interface.  Remark: The quotation shall state the compatibility with SCPI commands.		I
Rationale	With SCPI commands the oscilloscope is compatible with most lab setups, facilitating an automated test setup.	

### 4.4.2 R3000-010 : MATLAB and Python

Description		VM
The oscilloscope comes with MATLAB and Python interfacing scripts  Remark: The quotation shall state the available interfacing scripts.		I
Rationale	For automating test setups, it is important to have full control over the equipment with Matlab and Python	

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#### 4.4.3 R3000-015 : Costum script

Description		VM
Custom scripts can be run on the oscilloscope  Remark: The quotation shall show what the capabilities of the oscilloscope are with respect to running local scripts and saving files to an internal hard drive on the oscilloscope.		I
Rationale	For system performance and reduction in complexity it is relevant to be able to run custom scripts (e.g. Python scripts) on the oscilloscope itself that can pre-process the data and save it to the oscilloscope's hard drive for later processing.	

### 4.5 Aspect ' Memory size and transfer speed'

#### 4.5.1 R4000-005 : Amount of memory per channel

Description		VM
The amount of memory per channel is at least 1 Gpts.  Remark: The quotation shall state the amount of memory per channel of the oscilloscope.		I
Rationale	It is important to acquire several short waveforms with a high repetition rate. Therefore, time to save the waveforms shall be minimized.	

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#### 4.5.2 R4000-010 : Record data

Description		VM
The recorded data can be transferred to an (internal) hard drive with a speed of 400 waveforms of 1000 points per second.  Remark: Evaluation shall be done based on (provided) measurements.		I
Rationale	It is important to acquire several short waveforms with a high repetition rate. Therefore, time to save the waveforms shall be minimized.	

#### 4.5.3 R4000-015 : Transfer speed

Description		VM
Transfer speed higher than 400 waveforms of 1000 samples per second.  Remark: Shall be evaluated based on test results provided with the quotation.  Data transfer speed determines the overall speed of the system. A high transfer speed for many short recordings is required. This will be evaluated based on acquisitions of 1000 samples with 8 bit resolution. A transfer speed of 2Ms/s is not necessarily equivalent because single waveform data could have extra overhead.		D
Rationale	Data transfer speed determines the overall speed of the system>	

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## 4.6 Aspect ' warranty'

### 4.6.1 R5000-005 : Warranty

Description		VM
<p>Extended warranty for N (N) years and yearly calibration for the period of the extended warranty.</p> <p>Extended warranty for three or five years after standard 24 months warranty and yearly calibration contract for a period of the extended warranty.</p> <p>Remark: The content of the response is assessed, based on:</p> <ul style="list-style-type: none"><li>• The price for the extended warranty that has been offered in the quotation;</li><li>• The content of the extended warranty.</li></ul>		C
Rationale	Longer period of calibration and extended warranty ensures the oscilloscope will work properly for at least 3/5 years.	

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