Action TU1208
Civil Engineering Applications
of Ground Penetrating Radar

This lecture is part of
TU1208 Education Pack

GPR system performance compliance

Authors: Lara Pajewski (Italy), Xavier Derobert (France), Sébastien Lambot (Belgium), Milan Vrtunski (Serbia), Željko Bugarinović (Serbia), Aleksandar Ristić (Serbia), Miro Govedarica (Serbia), Carl Van Geem (Belgium), Audrey van der Wielen (Belgium), Colette Grégoire (Belgium), Vladislav Borecky (Czech Republic), Salih Serkan Artagan (Turkey), Simona Fontul (Portugal), Vânia Marecos (Portugal)

COST is supported by the
EU Framework Programme Horizon2020

Introduction

- GPR systems shall be periodically calibrated and their performance verified, in accordance with the manufacturer's recommendations and specifications.
- Within the framework of COST Action TU1208, guidelines for the use of GPR in civil engineering were developed. Such guidelines include the description of procedures for testing the performance of GPR equipment.
- The following slides describe **four tests**, which can be periodically carried out to check the performance of GPR systems.
- Common parameters for all tests are:
    1. Warm-up time of the GPR under test: At least 30 minutes, or according to recommendations by the manufacturer
    2. Size of a square metal reflector: At least $L = 2\sqrt{5}\,\lambda_c$, where $\lambda_c = c/f_c$ is the wavelength at the central frequency, being c the light velocity in air.

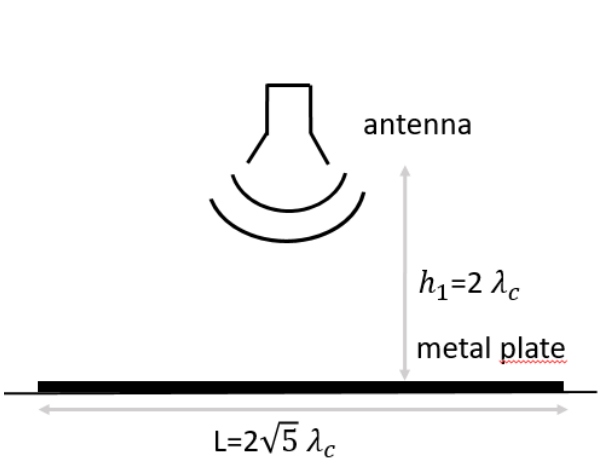
Test 1: Signal-to-Noise ratio (1/4)

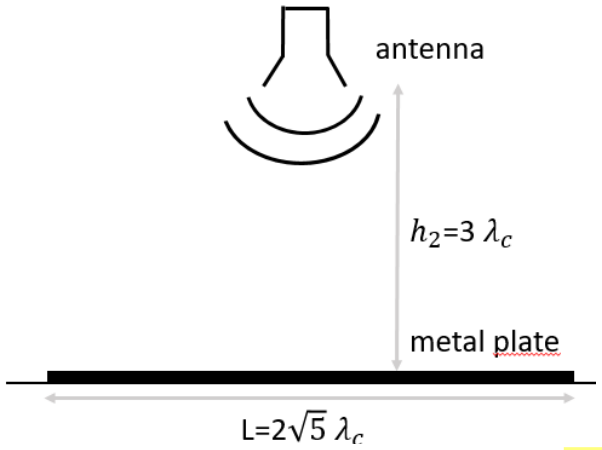
- Two series of measurements, at two different distances between the metal plate and the antenna under test.
- In the first series of measurements:
  - The distance between the metal plate and the antenna is $h_1 = 2\lambda_c$
  - The time window (TW) is at least twice the two-way travel time from the antenna to the metal plate (TW>$8\lambda_c$/c).
  - 100 waveforms are recorded
  - The average amplitude $<A_{mp}>$ is evaluated: this quantity is defined as the average peak-to-peak amplitude of the first echo coming from the metal plate.

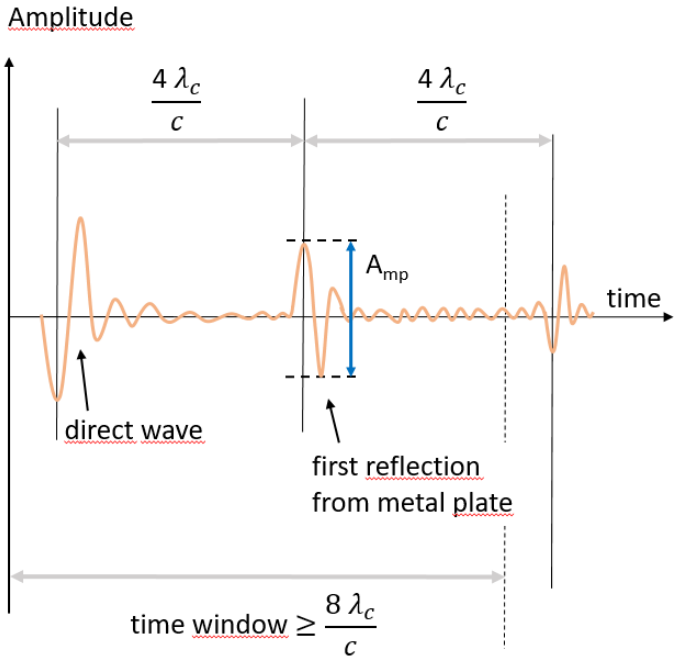
Test 1: Signal-to-Noise ratio (2/4)

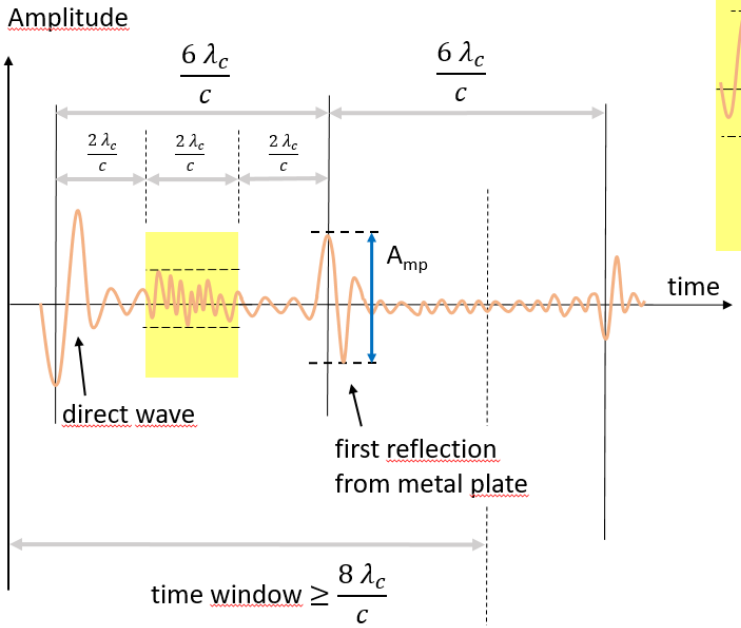
- In the second series of measurements:
  - The distance is $h_2 = 3\lambda_c$.
  - The GPR setting parameters the same as in the first series.
  - 100 waveforms
  - The average amplitude $\langle A_n \rangle$ is evaluated: this quantity is defined as the average peak-to-peak amplitude of the noise, over a relevant time window.
  - The suggested relevant time window starts $2\lambda_c/c$ [s] after the absolute maximum amplitude of the signal.
  - The suggested relevant time window is $2\lambda_c/c$ [s] long.

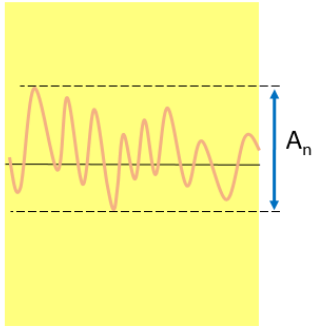
Test 1: Signal-to-Noise ratio (3/4)











Test 1: Signal-to-Noise ratio (4/4)

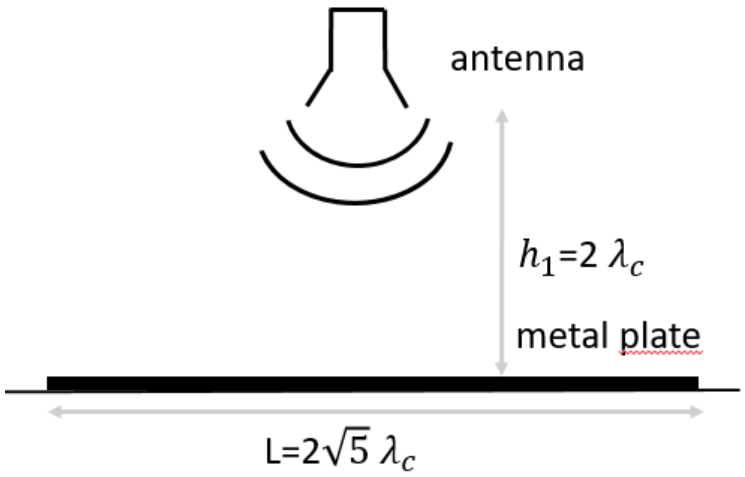
An indicator of the signal-to-noise ratio is finally calculated, by using the following equation:

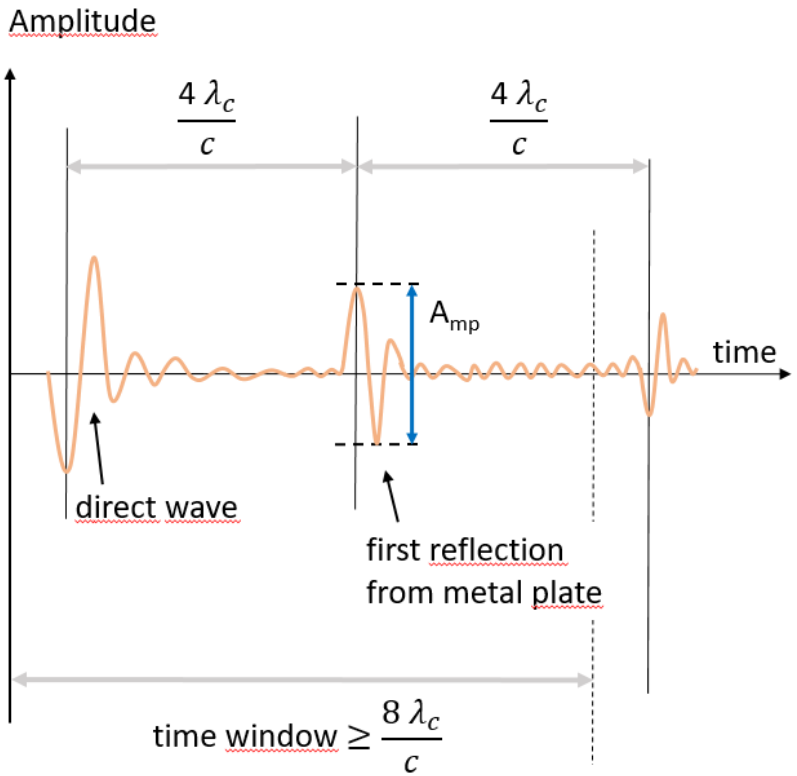
$$Indicator_{SNR} = \frac{< A_{\mathrm{mp}} >}{< A_{\mathrm{n}} >}$$

This quantity (which is not the SNR), should be larger than 20 (+26.0 dB).

Test 2: Signal stability (1/2)

- The same test configuration as in test 1, with h_1.
- The time window (TW) is at least twice the two-way travel time (TW>8λ_c/c).
- 100 traces are recorded, at the maximum data acquisition rate.





Test 2: Signal stability (2/2)

- The signal stability is evaluated by using the following formula:

$$Stability = \frac{A_{\max} - A_{\min}}{A_{\text{avg}}}$$

  - A_{max} is the maximum peak-to-peak amplitude of the metal plate reflection, selected among all 100 recorded traces
  - A_{min} is the minimum peak-to-peak amplitude of the metal plate reflection, selected among all 100 traces
  - A_{avg} is the average trace peak-to-peak amplitude of the metal plate reflection of all 100 traces.

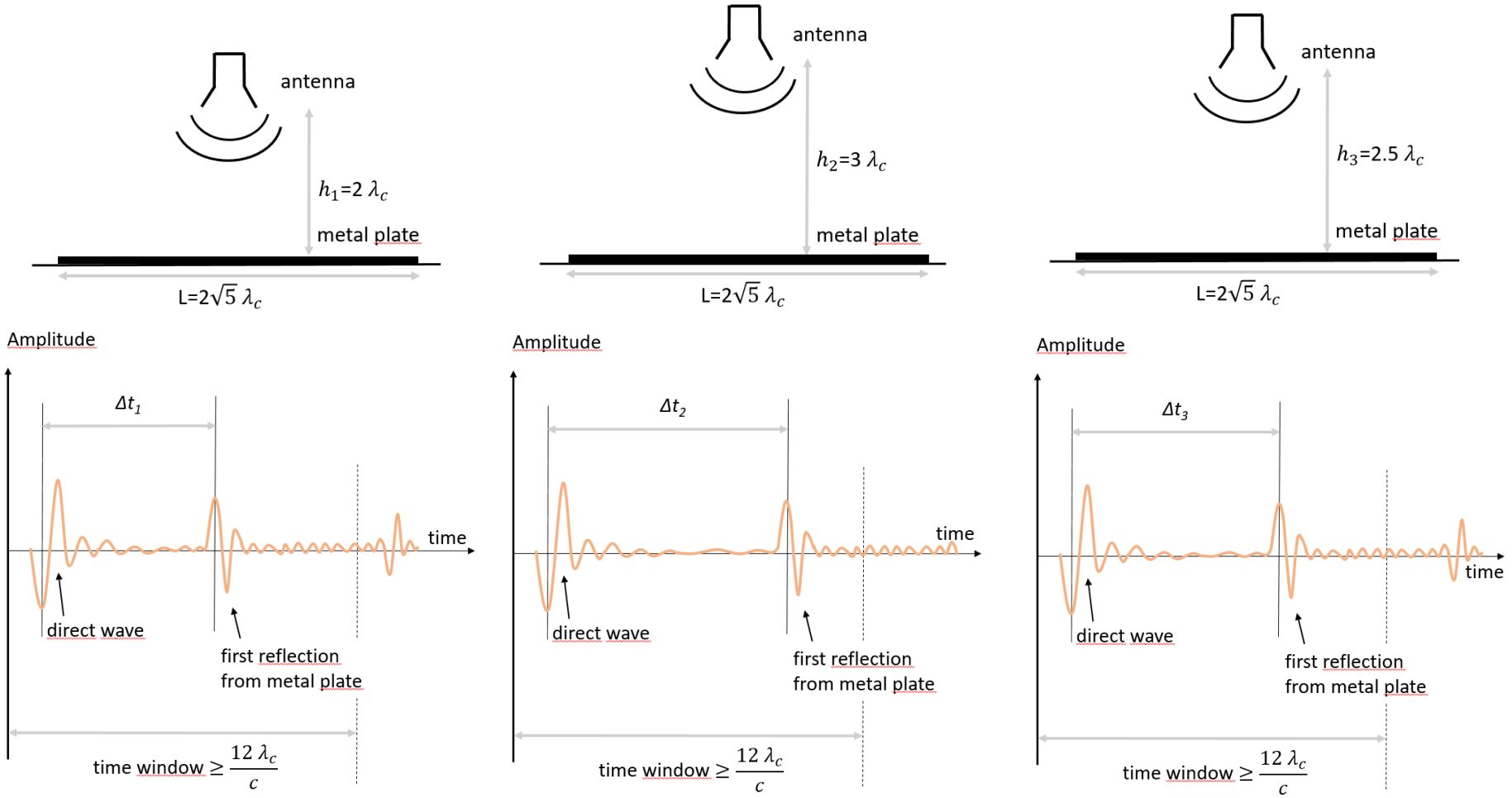
- ***The signal stability has to be less than 1 %.***

Test 3: Linearity in the time axis (1/3)

- The same test configurations as described in test 1, plus a third configuration with $h_3 = 2.5\lambda_c$.
- The time window (TW) should be at least twice the two-way travel time, at the longest distance h_2 (TW>$12\lambda_c$/c).
- A single waveform per configuration is recorded.
- For each configuration i (i = 1, 2, 3), corresponding to h_i, the time delay Δt_i has to be determined.
- The time delay is defined as the difference between the absolute maximum amplitude of the direct wave and the absolute maximum amplitude of the echo coming from the metal plate.

Test 3: Linearity in the time axis (2/3)

- The absolute differences: $T_{21}=|\Delta t_2 - \Delta t_1|$; $T_{31}=|\Delta t_3 - \Delta t_1|$



Test 3: Linearity in the time axis (3/3)

- The corresponding speed factors C_{21} and C_{31} are calculated:

$$C_{21} = \frac{h_2 - h_1}{T_{21}} \qquad C_{31} = \frac{h_3 - h_1}{T_{31}}$$

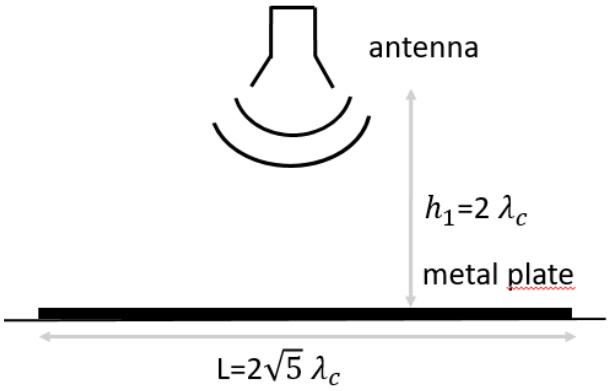
- The relative variation in the measured speed is evaluated, as follows:

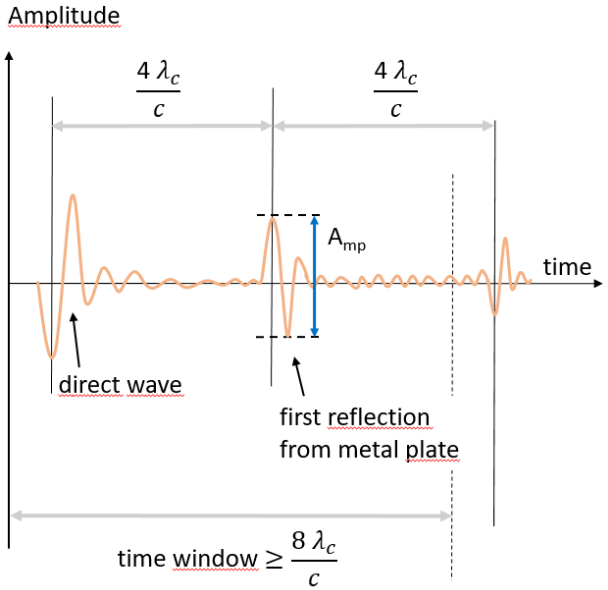
$$Speed\ factor = \frac{2|C_{21} - C_{31}|}{C_{21} + C_{31}}$$

- ***The speed factor should be less than 0.02 (2%).***

Test 4: Long-term stability (1/3)

- The same test configuration as described in Test 1, with h_1.
- The time window (TW) should be at least twice the two-way travel time (TW>$8\lambda_c$/c).
- 10 waveforms have to be captured every 1 min, for 120 min (hence, 1200 traces have to be recorded in total).
- For each waveform w (w = 1, … , 1200) the peak-to-peak amplitude A_w of the echo from the metal plate is determined.





Test 4: Long-term stability (2/3)

- The sliding-average amplitudes M_q (q = 1, …, 1200 – (N – 1)) are calculated, by using the following equation:

$$M_q = \frac{1}{N}\sum_{h=0}^{N-1} A_{q+h}$$

- N = 10 is suggested.
- The long-term stability factor is the maximum between the following two quantities:

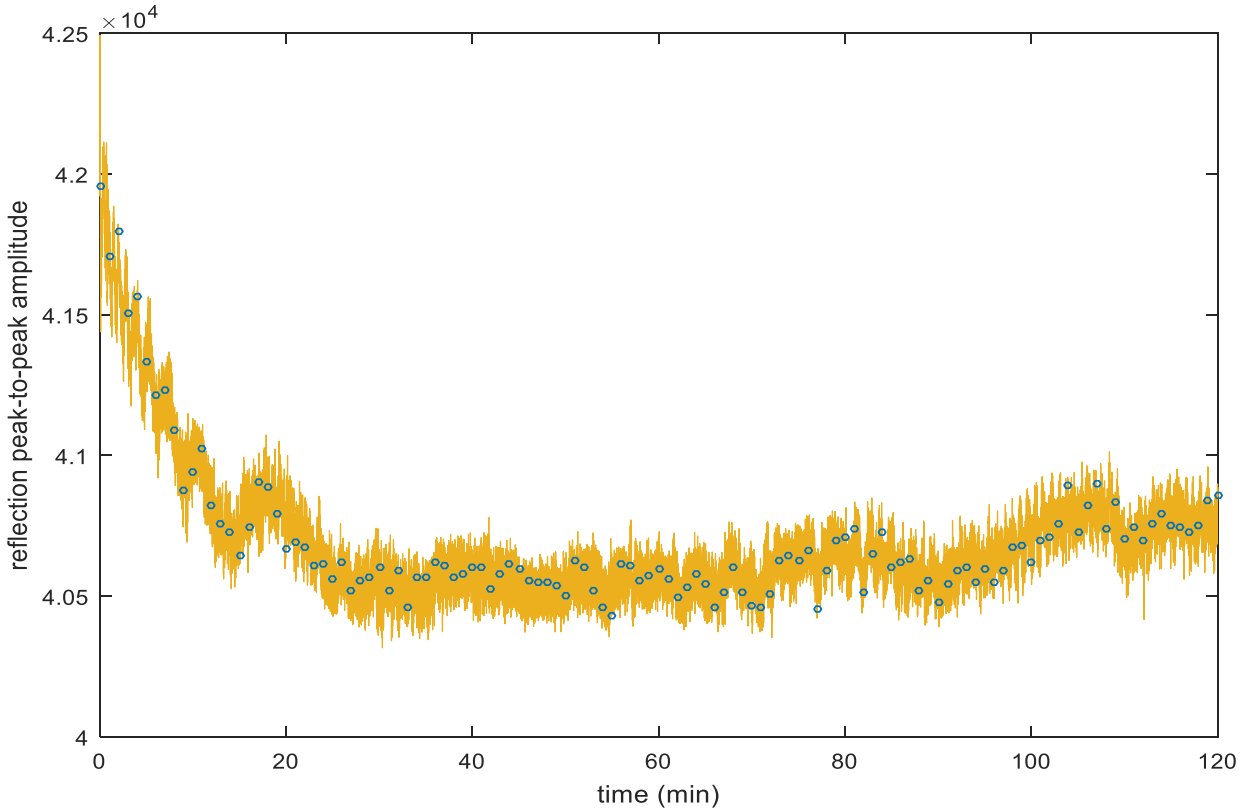
$$Q_1 = \frac{M_{\max} - A_1}{A_1} \qquad Q_2 = \frac{|M_{\min} - A_1|}{A_1}$$

- $M_{\max}$ and $M_{\min}$ are the largest and smallest values, respectively, among the M_q values.

- ***For N = 10, the long-term stability factor should be less than 3 %.***

Test 4: Long-term stability (3/3)

- It is useful to plot M_q against time (or simply, as a function of q). Realizing such a graph helps to gain awareness about the behaviour of the GPR system over time.



Tested antennas

Institution	Antennas	Tests	Remarks
Faculty of Technical Sciences Novi Sad Serbia	Ground coupled GSSI 400MHz GSSI 900MHz	Tests 1, 2, 3, 4	
Belgium Road Research Centre Brussels Belgium	Horn GSSI 1GHz GSSI 2GHz	Tests 1, 2, 3, 4	Tests performed on raw and filtered data
University of Pardubice Pardubice Czech Republic	Horn IDS 2GHz	Tests 2, 3, 4	Tests performed several times, not strictly to COST guidelines
National Laboratory for Civil Engineering Lisbon Portugal	Horn GSSI 1GHz GSSI 1.8GHz	Tests 1, 2	Tests performed on raw and filtered data, at different samples per trace

GPR antennas testing at FTS

- At Faculty of Technical Sciences testing of two antennas was done:
  - Ground coupled shielded antennas, manufactured by GSSI.
  - Central frequencies: 400 MHz and 900 MHz.
- Experimental setup:
  - Control unit GSSI SIR 3000, with Terra SIRch software.
  - Sidelength of the metal reflector:
    - 3.5 m (400 MHz antenna)
    - 1.7 m (900 MHz antenna).
  - Samples per trace: 512
- Data processing: RADAN, MatGPR and MATLAB.
- Testing carried out by Željko Bugarinović and Milan Vrtunski.

GPR antennas testing at FTS
400MHz antenna

GPR antennas testing at FTS
GPR setting parameters

400MHz

Test 1		Test 2		Test 3		Test 4	
Measurement 1				Measurement 1			
Height	1.50m	Height	1.50m	Height	1.50m	Height	1.50m
Two-way travel time	10ns	Two-way travel time	10ns	Time window	30ns	Time window	20
Time window	20ns	Time window	20ns	Traces	1	Traces/sec	1
Traces/sec	10	Traces/sec	60	Measurement 2		Traces	7200
Traces	100	Traces	100	Height	2.25m		
Measurement 2				Time window	30ns		
Height	2.25m			Traces	1		
Two-way travel time	10ns			Measurement 3			
Time window start	5ns			Height	1.875m		
Time window length	5ns			Time window	30ns		
Traces/sec	10			Traces	1		
Traces	100						

900MHz

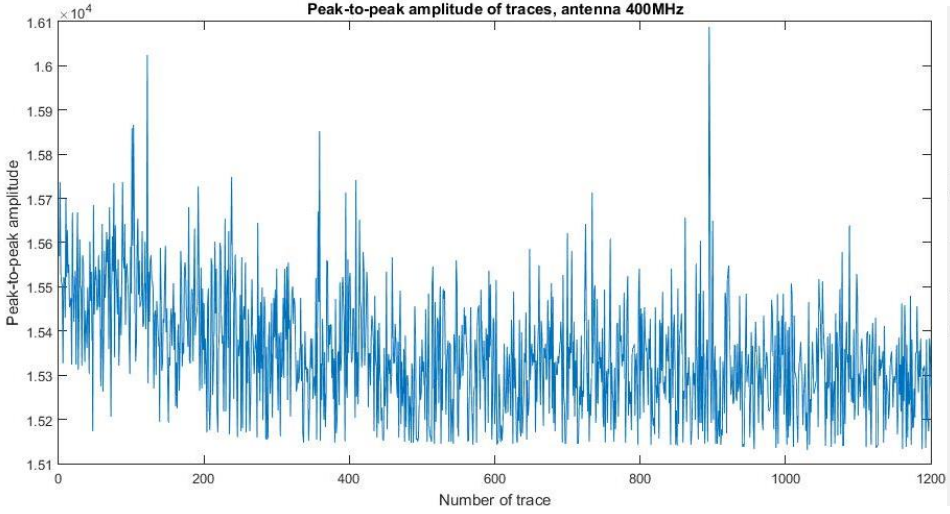
Test 1		Test 2		Test 3		Test 4	
Measurement 1				Measurement 1			
Height	0.66m	Height	0.66m	Height	0.66m	Height	0.66m
Two-way travel time	4.4ns	Two-way travel time	4.4ns	Time window	15ns	Time window	10
Time window	10ns	Time window	10ns	Traces	1	Traces/sec	1
Traces/sec	10	Traces/sec	60	Measurement 2		Traces	7200
Traces	100	Traces	100	Height	0.99m		
Measurement 2				Time window	15ns		
Height	0.99m			Traces	1		
Two-way travel time	6.6ns			Measurement 3			
Time window start	2.2ns			Height	0.825m		
Time window length	2.2ns			Time window	15ns		
Traces/sec	10			Traces	1		
Traces	100						

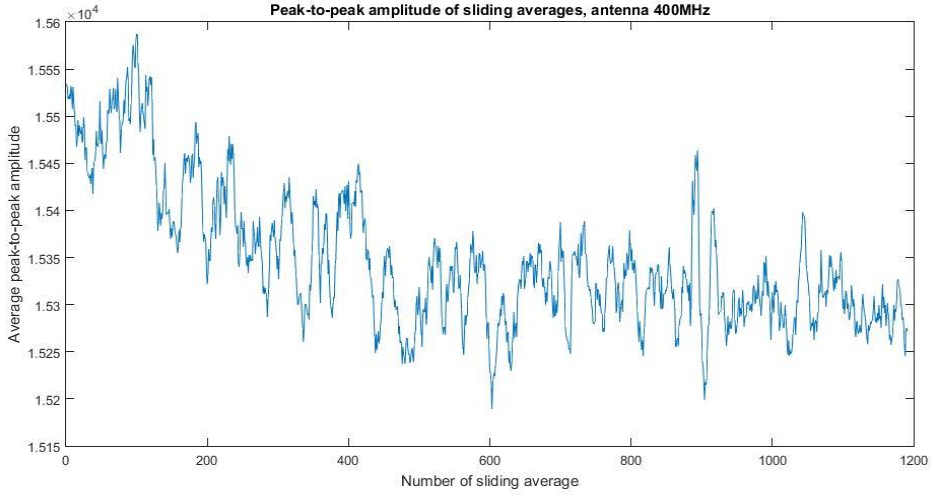
GPR antennas testing at FTS Results

		400MHz	900MHz
Test 1	Signal to Noise Ratio	**10.576**	**12.479**
Test 2	Signal Stability	**7.914 %**	**2.879 %**
Test 3	Linearity in the time axis	**5.18 %**	**2.99 %**
Test 4	Long -term Signal Stability	**2.44 %**	**1.574 %**

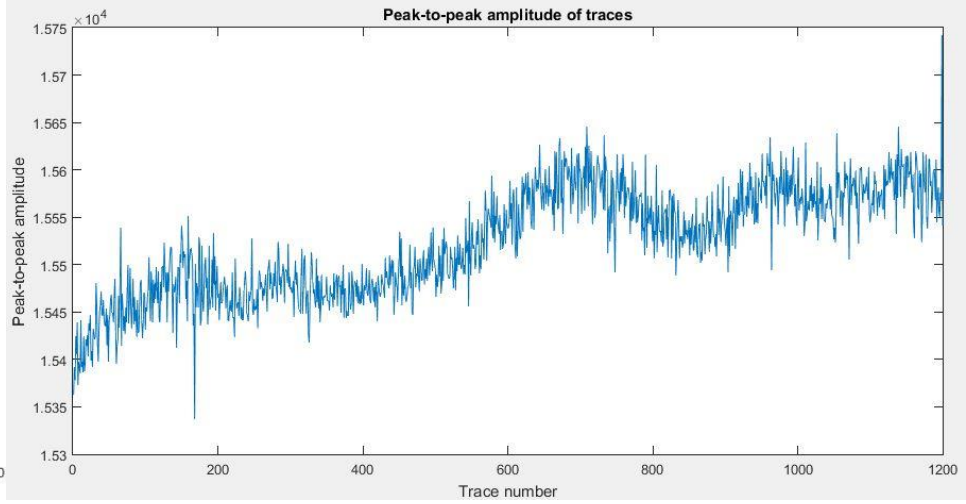
GPR antennas testing at FTS
Test 4 - plots

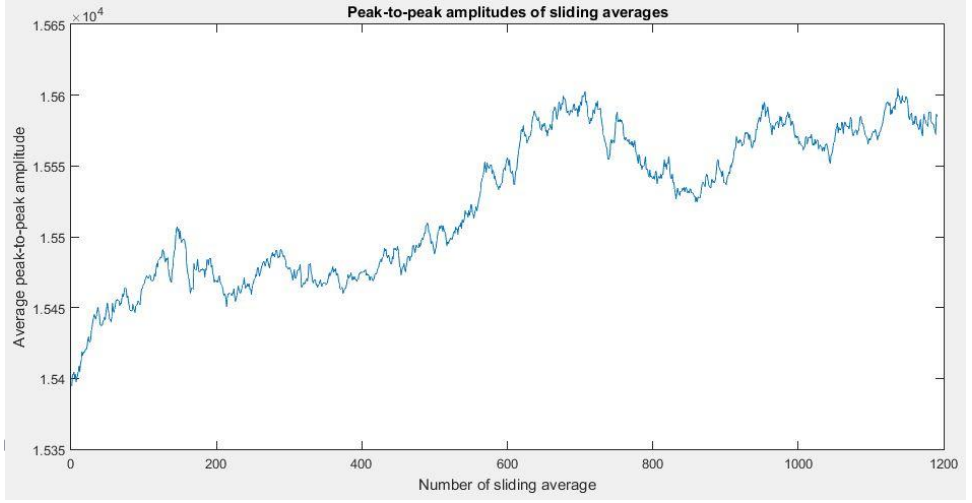
400MHz





900MHz

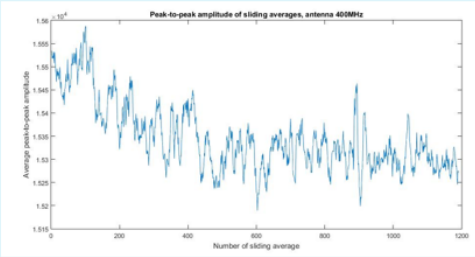




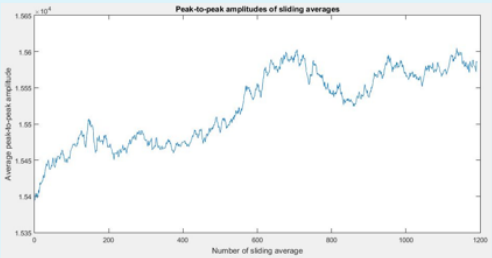
Periodical GPR antennas testing at FTS

		400MHz	900MHz	900 MHz	900 MHz
Test 1	Signal to Noise Ratio	**10.576**	**12.479**	**13.411**	**13.256**
Test 2	Signal Stability	**7.91 %**	**2.88 %**	**0.83 %**	**1.27 %**
Test 3	Linearity in the time axis	**5.18 %**	**2.99 %**	**0.47 %**	**0.61 %**
Test 4	Long -term Signal Stability	**2.44 %**	**1.57 %**	**0.22 %**	**0.46 %**

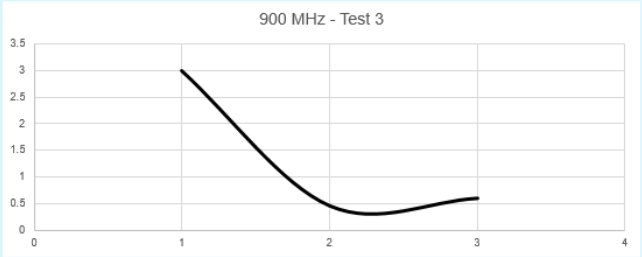
Test 4 – sliding averages 400 MHz antenna

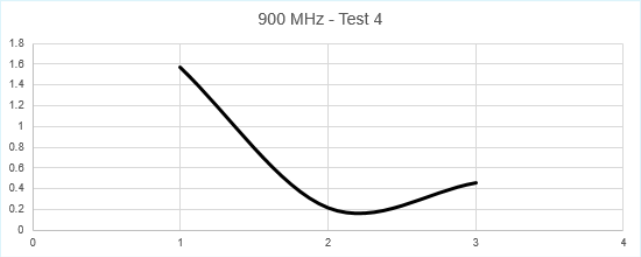


Test 4 – sliding averages 900 MHz antenna



900 MHz antenna - periodical testing





GPR antennas testing at BRRC

- At Belgium Road Research Centre testing of two antennas was done:
  - Horn antennas, manufactured by GSSI.
  - Central frequencies: 1GHz and 2GHz.
- Experimental setup:
  - Control unit GSSI SIR20
  - Sidelength of the metal reflector: 1.5m for both antennas
- Testing carried out by Colette Grégoire, Carl Van Geem and Audrey van der Wielen.

GPR antennas testing at BRRC
Test 1 - results

Characteristics of GPR and antenna	Characteristics of the setup	Results (SNR)
2 GHz Horn Time window = 10 ns 512 samples per trace	h1=29.5 cm h2=45.15 cm metal plate dimensions: 150 *150 cm	**16.2086**
2 GHz Horn Time window = 10 ns 512 samples per trace	h1=29.5 cm h2=45.15 cm metal plate dimensions: 150 *150 cm FIR filter (250-5000 MHz)	**17.4542**
2 GHz Horn Time window = 10 ns 512 samples per trace	h1=29.5 cm h2=45.15 cm metal plate dimensions: 150 *150 cm GSSI Noise filter	**21.9950**
1 GHz Horn Time window = 20 ns 512 samples per trace	h1=59.37 cm h2=89.9 cm metal plate dimensions: 150 *150 cm	**7.2380**
1 GHz Horn Time window = 20 ns 512 samples per trace	h1=59.37 cm h2=89.9 cm metal plate dimensions: 150 *150 cm FIR filter (250-3000 MHz)	**9.7012**

GPR antennas testing at BRRC
Test 2 - results

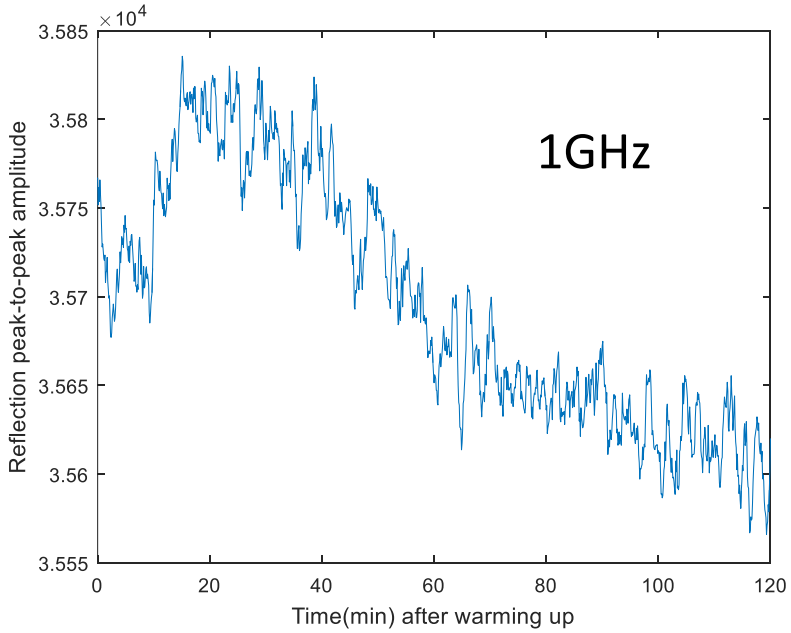
Characteristics of GPR and antenna	Characteristics of the setup	Results (Signal stability, %)
2 GHz Horn Time window = 10 ns 512 samples per trace	h1=29.5 cm metal plate dimensions: 150 *150 cm	**4.51 %**
2 GHz Horn Time window = 10 ns 512 samples per trace	h1=29.5 cm metal plate dimensions: 150 *150 cm FIR filter (250-5000 MHz)	**3.10 %**
2 GHz Horn Time window = 10 ns 512 samples per trace	h1=29.5 cm metal plate dimensions: 150 *150 cm GSSI Noise filter	**2.54 %**
1 GHz Horn Time window = 20 ns 512 samples per trace	h1=59.37 cm metal plate dimensions: 150 *150 cm	**10.61%**
1 GHz Horn Time window = 20 ns 512 samples per trace	h1=59.37 cm metal plate dimensions: 150 *150 cm FIR filter (250-3000 MHz)	**10.96%**

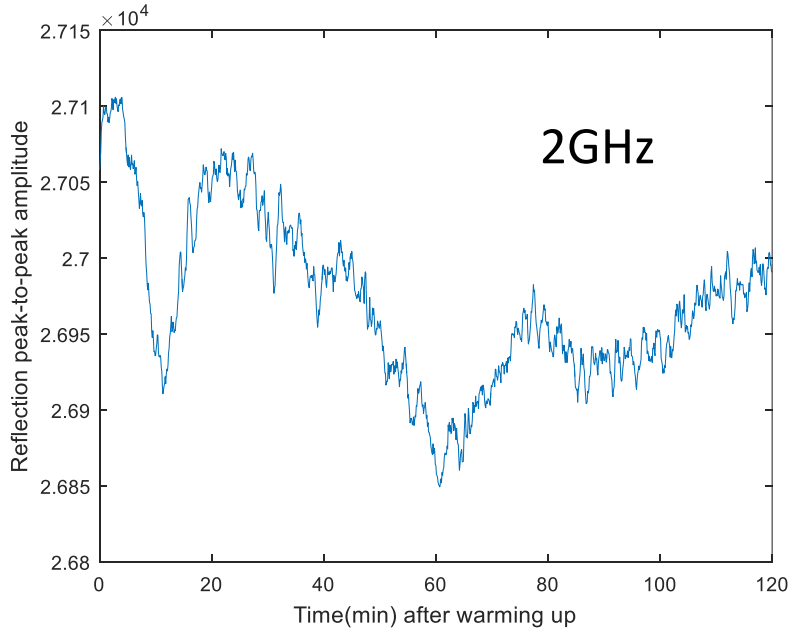
GPR antennas testing at BRRC
Test 3 - results

Characteristics of GPR and antenna	Characteristics of the setup	Results (Variation in time calibration factor, %)
2 GHz Horn Time window = 10 ns 512 samples per trace	h1=29.5 cm h2=45.15 cm h3=37.25 cm metal plate dimensions: 150 *150 cm	(0.91%-17.6%) Mean: 6.29%
2 GHz Horn Time window = 10 ns 512 samples per trace	h1=29.5 cm h2=45.15 cm h3=37.25 cm metal plate dimensions: 150 *150 cm FIR filter (250-5000 MHz)	(0.87-11.29%) Mean: 3.91%
2 GHz Horn Time window = 10 ns 512 samples per trace	h1=29.5 cm h2=45.15 cm h3=37.25 cm metal plate dimensions: 150 *150 cm GSSI Noise filter	(0.94-7.04%) Mean: 4.56%
1 GHz Horn Time window = 20 ns 512 samples per trace	h1=59.37 cm h2=89.9 cm h3=75 cm metal plate dimensions: 150 *150 cm	(0%-15.12%) Mean: 4.26%
1 GHz Horn Time window = 20 ns 512 samples per trace	h1=59.37 cm h2=89.9 cm h3=75 cm metal plate dimensions: 150 *150 cm FIR filter (250-3000 MHz)	(0.34%-10.69%) Mean: 3.17%

GPR antennas testing at BRRC
Test 4 - results

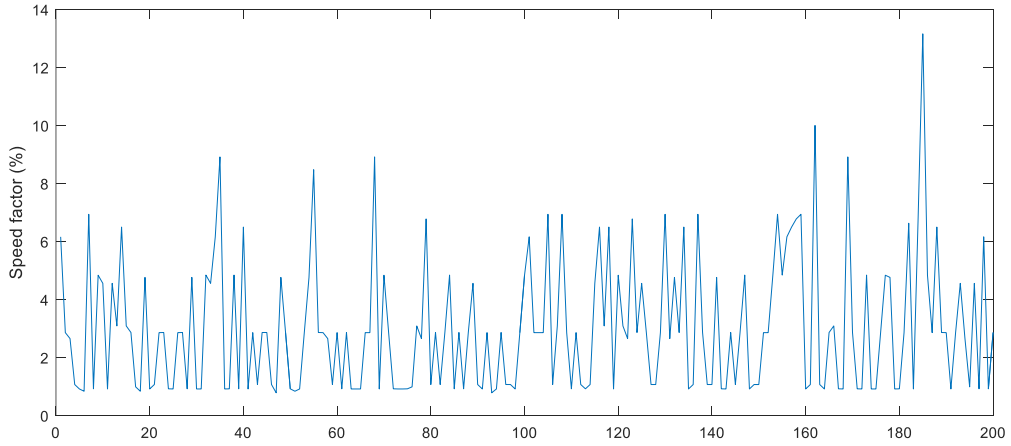
N° d'essai	Antenne	Date+ lieu + T°	L plaque	Hauteur (cm) (th + mesurée)	Samples /trace	Time window	Calibration time factor
STAB014	2 GHz	27/02/17, 19.0°C	150 cm	30	512	10	**0.69 %**
STAB015	2 GHz (idem précédent)	28/02/17, 18.4°C	150 cm	30	512	10	**0.72 %**
STAB016	2 GHz + filtre	01/03/17, 19.1°C	150 cm	30	512	10	**0.65 %**
TEXS001	1 GHz	28/07/17, 23.6°C	150 cm	60	512	20	**0.92%**





GPR antennas testing at BRRC: Remarks

- The maximum amplitude of the direct wave is not the absolute maximum amplitude of the signal. The amplitude on the metallic plate is always stronger than the direct wave amplitude.
- The first collected sample has always a random value, which can be larger than any reflection.
- The results of test 3 seem to be highly variable and dependent on the laboratory precision. For 200 traces of the same measurement it varies from 0.9% to 17.6% (for the same configuration)! An error of 1 mm in the measurement of the antenna position can result in an error superior to 2%.



GPR antennas testing at University of Pardubice, Czech Republic

- At University of Pardubice testing of one antenna was done:
  - Horn antenna, 2 GHz, manufactured by IDS.
- Experimental setup:
  - IDS RIS Hi-Pave, DAD MCH Fast-Wave control unit
  - Sidelength of the metal reflector: 1m
  - 15 ns time window, 512 samples per trace
- Testing carried out by Vladislav Borecky and Salih Serkan Artagan.

GPR antennas testing at University of Pardubice
Test 2 - results

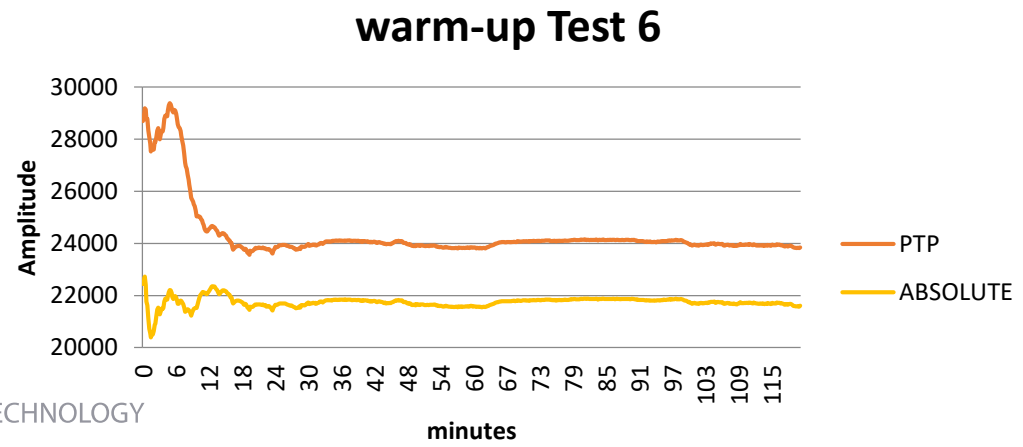
Characteristics of GPR and antenna	Characteristics of the setup	Results (Signal stability, %)
2 GHz Horn Time window = 15 ns 512 samples per trace	h1=30 cm metal plate dimensions: 100*100 cm	**0.9 %**
2 GHz Horn Time window = 15 ns 512 samples per trace	h1=30 cm metal plate dimensions: 100*100 cm	**0.4 %**
2 GHz Horn Time window = 15 ns 512 samples per trace	h1=30 cm metal plate dimensions: 100*100 cm	**1.2 %**
2 GHz Horn Time window = 15 ns 512 samples per trace	h1=30 cm metal plate dimensions: 100*100 cm	**0.8%**

GPR antennas testing at University of Pardubice
Test 3 - results

Characteristics of GPR and antenna	Characteristics of the setup	Results (Variation in time calibration factor, %)
2 GHz Horn Time window = 15 ns 512 samples per trace	h1=34 cm h2=68 cm h3=113 cm (distances according to ASTM) metal plate dimensions: 100 *100 cm	**10.5 % - 12.5 %**

GPR antennas testing at University of Pardubice
Test 4 - results

Characteristics of GPR and antenna	Characteristics of the setup	Results (Long Term Signal stability, %)
2 GHz Horn Time window = 15 ns 512 samples per trace	h1=30 cm metal plate dimensions: 100*100 cm	**0.5 %**
2 GHz Horn Time window = 15 ns 512 samples per trace	h1=30 cm metal plate dimensions: 100*100 cm	**0.0 %**
2 GHz Horn Time window = 15 ns 512 samples per trace	h1=30 cm metal plate dimensions: 100*100 cm	**0.6 %**
2 GHz Horn Time window = 15 ns 512 samples per trace	h1=30 cm metal plate dimensions: 100*100 cm	**0.27%**



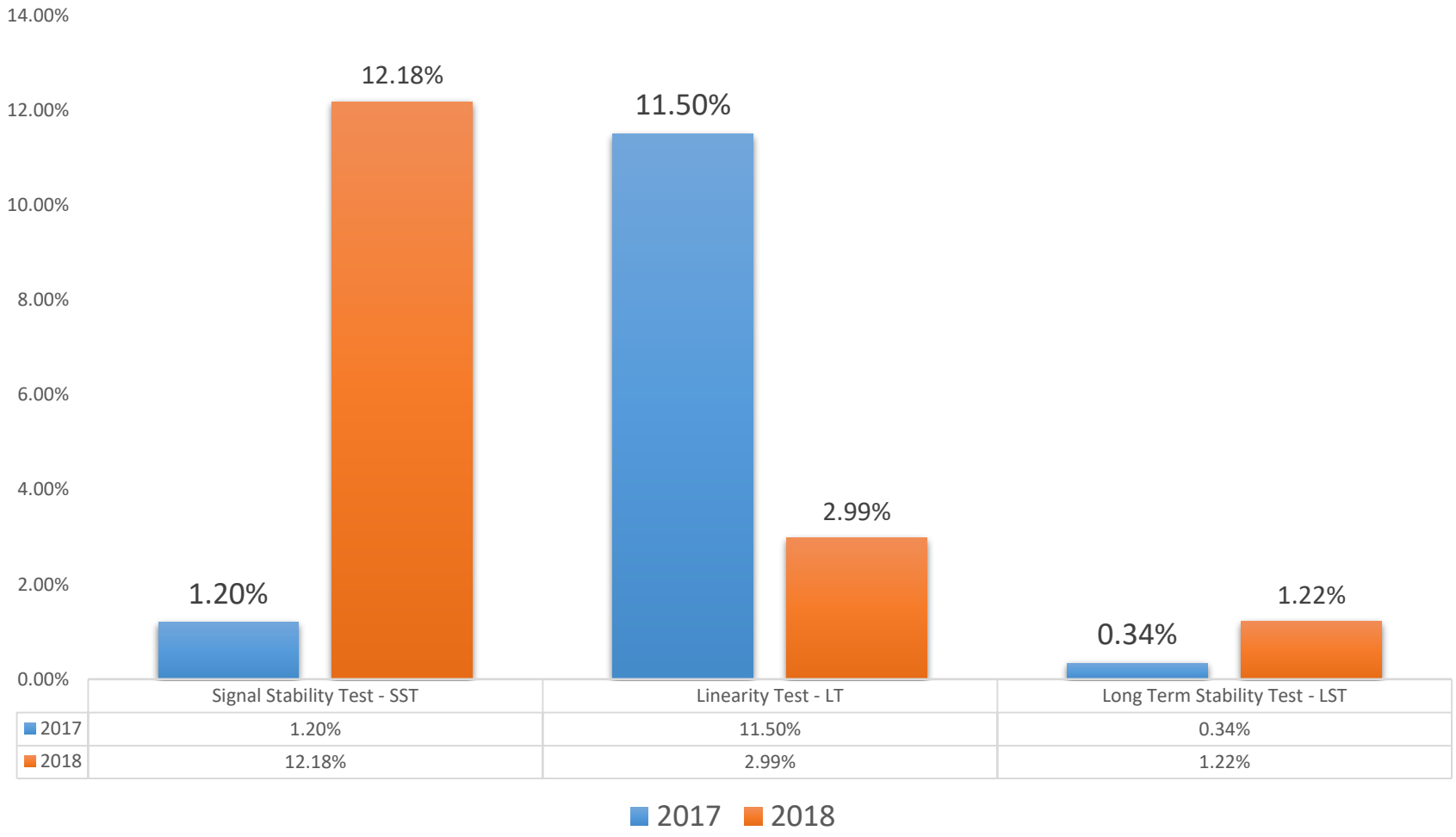
GPR antennas testing at University of Pardubice New tests in 2018

- Testing was done again in March 2018, with two antennas: IDS ground-coupled 400/900 MHz and IDS horn 2 GHz.
- All four tests were performed.

Frequency in MHz	**400**	**900**	**2000**	**2000**
Type of Total Reflector	A.S.	A.S.	A.S.	T.M.P.
Signal to Noise Ratio Test- SNR	9.75	1.19	23.74	29.30
Signal Stability Test - SST	4.08%	15.89%	12.18%	10.24%
Linearity Test - LT	4.88%	3.39%	2.99%	3.01%
Long Term Stability Test - LST	0.14%	0.63%	1.22%	1.27%

- A.S. – aluminium sheet; T.M.P. – Thick Metal Plate

Periodical GPR antennas testing at University of Pardubice



GPR antennas testing at LNEC

- At National Laboratory for Civil Engineering in Lisbon, testing of two antennas was done:
  - Horn antennas, manufactured by GSSI.
  - Central frequencies: 1 GHz and 1.8 GHz.
- Experimental setup:
  - Control unit GSSI SIR20
  - Sidelength of the metal reflector: **2 x 1 m** for both antennas
  - Raw and filtered data
  - Samples/trace: 512,1024 (1.8 GHz); 256, 1024 (1 GHz)
- Testing carried out by Simona Fontul and Vânia Marecos.

GPR antennas testing at LNEC

GPR antennas testing at LNEC
Test 1 - results

Characteristics of GPR and antenna	Characteristics of the setup	Results (SNR)	
1 GHz Horn Time window = 20 ns 512 samples per trace	h1=60.5 cm h2=90 cm metal plate dimensions: 200 *100 cm IIR: 100-1000MHz FIR: 500-3000MHz	raw	**22.2082**
		filtered	**20.3498**
1 GHz Horn Time window = 20 ns 1024 samples per trace	h1=60.5 cm h2=90 cm metal plate dimensions: 200 *100 cm IIR: 100-1000MHz FIR: 500-3000MHz	raw	**17.6366**
		filtered	**20.3631**
1.8 GHz Horn Time window = 10 ns 256 samples per trace	h1=33.2 cm h2=49.5 cm metal plate dimensions: 200 *100 cm IIR: 100-2000MHz FIR: 500-5000MHz	raw	**20.8047**
		filtered	**25.8752**
1.8 GHz Horn Time window = 10 ns 1024 samples per trace	h1=33.2 cm h2=49.5 cm metal plate dimensions: 200 *100 cm IIR: 100-2000MHz FIR: 500-5000MHz	raw	**15.8056**
		filtered	**28.0741**

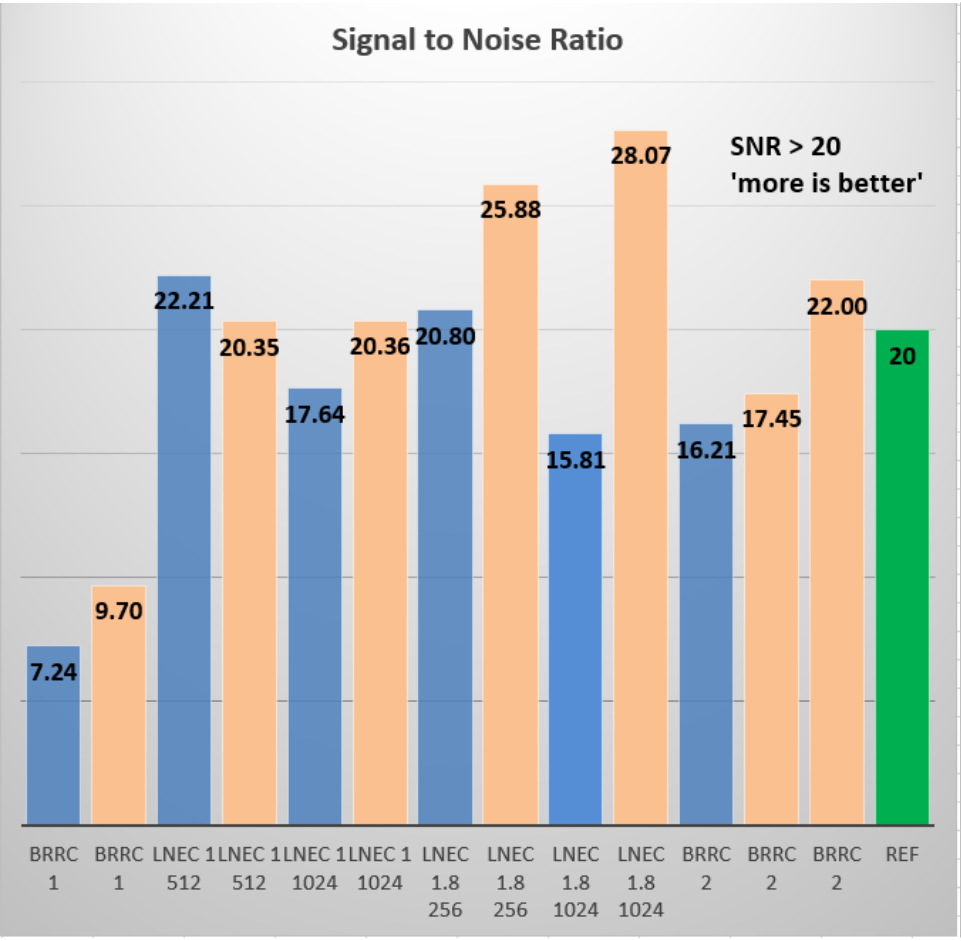
GPR atnennas testing at LNEC
Test 2 - results

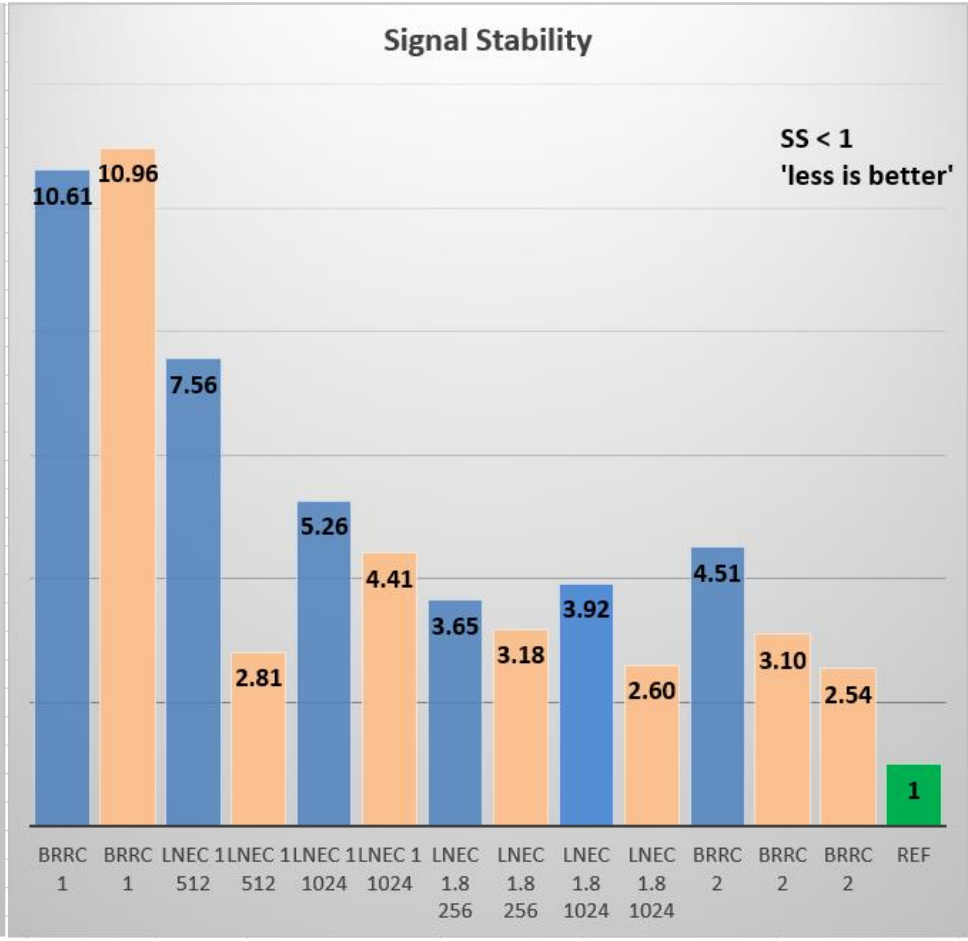
Characteristics of GPR and antenna	Characteristics of the setup	Results (SST)	
1 GHz Horn Time window = 20 ns 512 samples per trace	h1=60.5 cm metal plate dimensions: 200 *100 cm IIR: 100-1000MHz FIR: 500-3000MHz	raw	**7.56%**
		filtered	**4.08%**
1 GHz Horn Time window = 20 ns 1024 samples per trace	h1=60.5 cm metal plate dimensions: 200 *100 cm IIR: 100-1000MHz FIR: 500-3000MHz	raw	**7.42%**
		filtered	**4.41%**
1.8 GHz Horn Time window = 10 ns 256 samples per trace	h1=33.2 cm metal plate dimensions: 200 *100 cm IIR: 100-2000MHz FIR: 500-5000MHz	raw	**3.65%**
		filtered	**3.18%**
1.8 GHz Horn Time window = 10 ns 1024 samples per trace	h1=33.2 cm metal plate dimensions: 200 *100 cm IIR: 100-2000MHz FIR: 500-5000MHz	raw	**3.92%**
		filtered	**2.60%**

Summary

	Antenna	Filter	Signal to Noise Ratio	Signal Stability	Linearity in time axis	Long Term Stability
1	FTS 0.4	Raw	10.576	7.914	5.18	2.44
2	FTS 0.9	Raw	12.479	2.879	2.99	1.574
3	BRRC 1	Raw	7.238	10.61	4.26	0.92
4	BRRC 1	FIR	9.7012	10.96	3.17	
5	LNEC 1	Raw	17.6366	5.26		
6	LNEC 1	FIR IIR	20.3498	2.81		
7	LNEC 1.8	Raw	15.8056	3.89		
8	LNEC 1.8	FIR IIR	28.0741	1.59		
9	BRRC 2	Raw	16.2086	4.51	6.29	0.69
10	BRRC 2	FIR	17.4542	3.1	3.91	0.65
11	BRRC 2	GSSI NF	21.995	2.54	4.56	
12	UP 2	Raw		1.2	11.5	0.6

Usage of filters

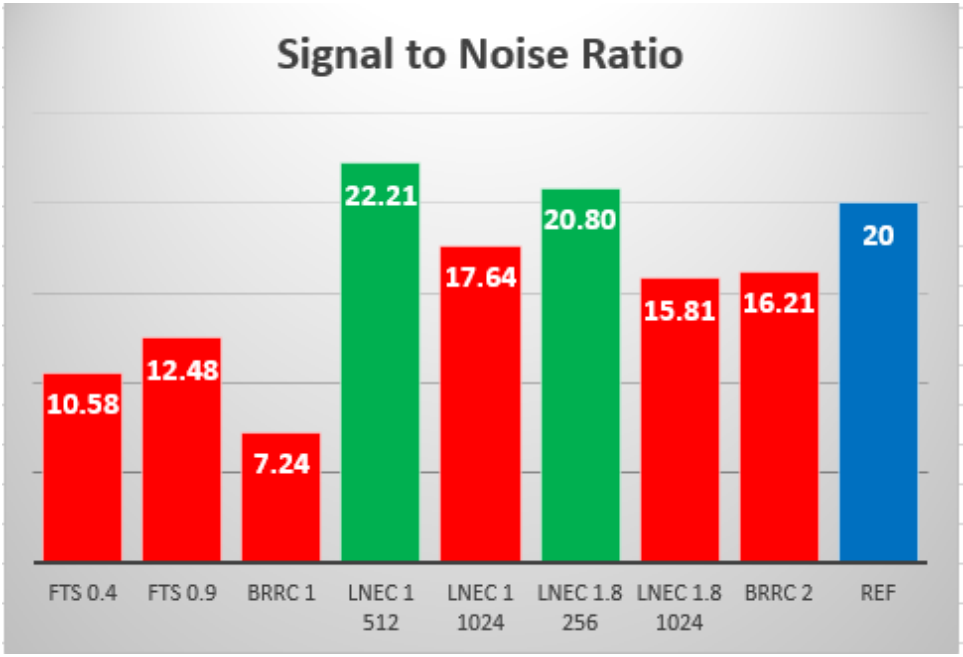


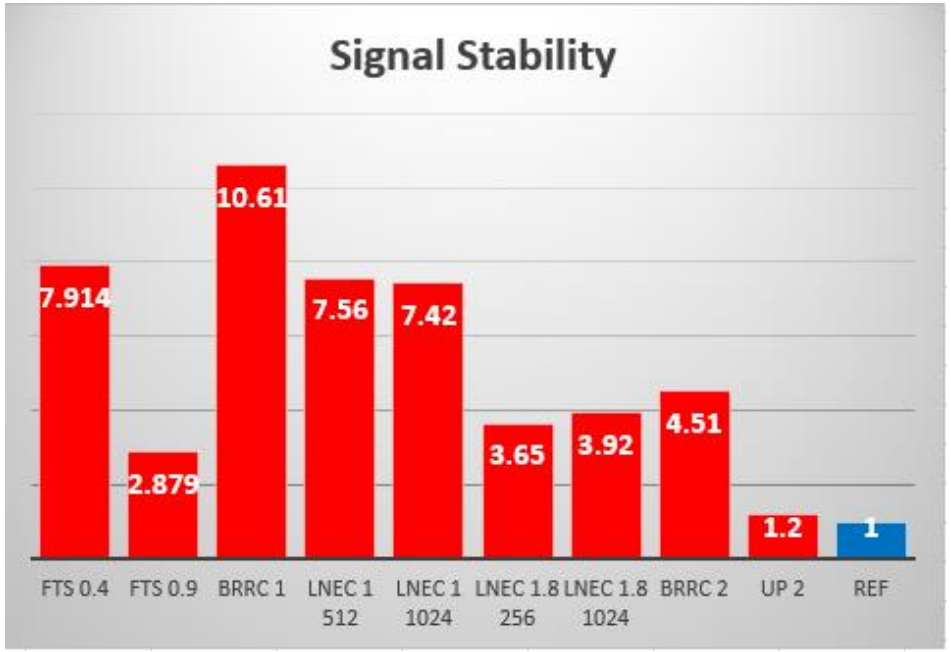


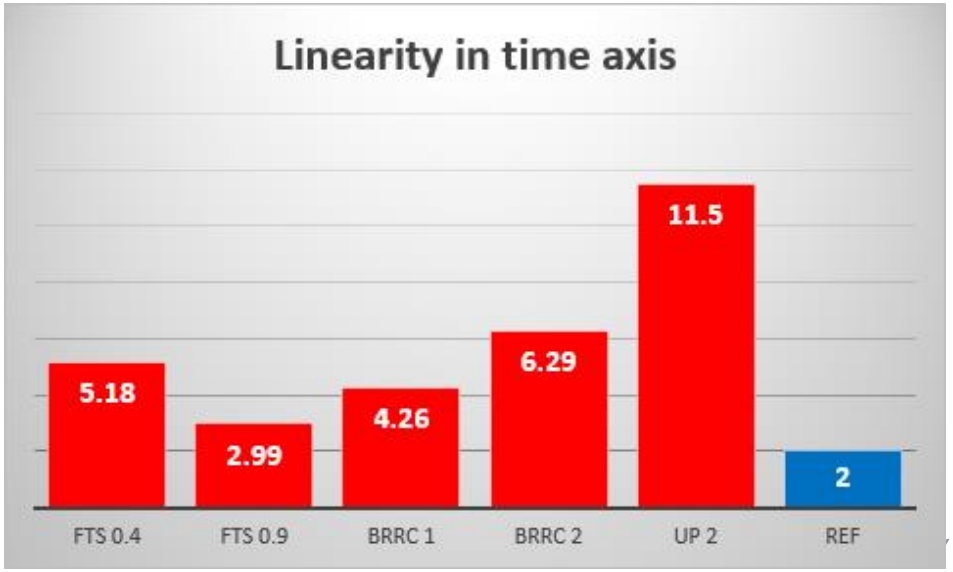
- raw data

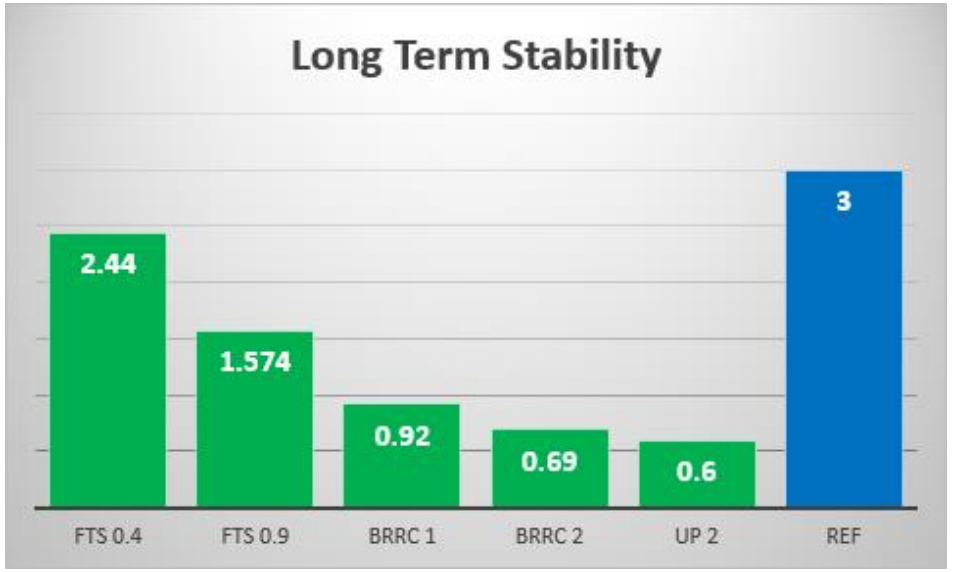
- filtered data

Tresholds?


Signal to Noise Ratio
10.58
12.48
7.24
22.21
17.64
20.80
15.81
16.21
20
FTS 0.4
FTS 0.9
BRRC 1
LNEC 1 512
LNEC 1 1024
LNEC 1.8 256
LNEC 1.8 1024
BRRC 2
REF


Signal Stability
7.914
2.879
10.61
7.56
7.42
3.65
3.92
4.51
1.2
1
FTS 0.4
FTS 0.9
BRRC 1
LNEC 1 512
LNEC 1 1024
LNEC 1.8 256
LNEC 1.8 1024
BRRC 2
UP 2
REF


Linearity in time axis
5.18
2.99
4.26
6.29
11.5
2
FTS 0.4
FTS 0.9
BRRC 1
BRRC 2
UP 2
REF


Long Term Stability
2.44
1.574
0.92
0.69
0.6
3
FTS 0.4
FTS 0.9
BRRC 1
BRRC 2
UP 2
REF

Tresholds?

- After the testing performed by various COST participants proposed values are:
  - Test 1: Signal-to-Noise Ratio **> 10 (20dB)**
  - Test 2: Signal Stability **< 8%**
  - Test 3: Linearity in the Time Axis **< 6.5%**
  - Test 4: Long-Term Signal Stability **< 2.5%**
- Before these values are accepted as the final ones:
  - Tests could be repeated
  - More antennas could be tested
  - Check the history of tested antennas
  - Test brand new antennas…

Thank you

TU1208 Education Pack

COST Action TU1208

Civil Engineering Applications of Ground Penetrating Radar

www.GPRadar.eu

info@GPRadar.eu

www.cost.eu

www.facebook.com/COSTActionTu1208/

COST is supported by the
EU Framework Programme Horizon2020