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ANAMET-991:
TDNA Measurement Comparison Exercise

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REPORT

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ANAMET-991: TDNA MEASUREMENT COMPARISON EXERCISE

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1. INTRODUCTION

For several years, there has been a growing interest within the ANAMET community in the time-domain capability now available on most modern VNAs. Following a request made at a recent ANAMET meeting, a comparison exercise was organised by NPL to investigate the between-laboratory reproducibility of TDNA (Time Domain Network Analyser) measurements. The comparison was given the identifier ANAMET-991, in line with other exercises in the ANAMET series of comparisons.

Four items were constructed by joining together selected coaxial components to provide composite items with interesting and distinctive time-domain responses. These items were then wrapped in 'gaffa' tape for two reasons: firstly, the tape significantly reduced the chance of the items coming apart during the exercise; and secondly, the tape shielded the identity of the constituent parts so that it was not possible to relate aspects of the time-domain trace with the device's construction (i.e. the devices were effectively 'black-box' items).

As this was the first time ANAMET had conducted a TDNA comparison, it was decided that the exercise would take the form of a small pilot study. The comparison was undertaken free of charge and, to facilitate this, was restricted to a small number of UK resident laboratories. As the items were inherently fragile (being composite items), the comparison artefacts were transported to and from the participants by hand (by one of the authors). This had the added advantage in that the comparison was completed within a six week period.

This report presents the results obtained by the exercise, and is similar to the report issued to the participants (except the identity of the participating laboratories' results is not revealed). Generally, the results look very encouraging, showing good agreement between the majority of participants. There are some unusual results, however, indicating that there is scope for significant further investigation into this type of measurement.

2. THE PARTICIPANTS

The six participants, denoted as 'lab 1' to 'lab 6' in the data, were as follows:

- DERA Aquila, Bromley;
- BAE SYSTEMS, Warton;
- National Physical Laboratory, Teddington;
- Agilent Technologies, South Queensferry;
- BAE SYSTEMS, Towcester;
- Agilent Technologies, Winnersh.

It should be noted that the order in which the laboratories appear in the above list is arbitrary and does not correspond to the labels assigned as lab 1, lab 2, etc.

3. THE ITEMS

The comparison items comprised four 'home made' one-port GPC-7 artefacts, each constructed from a number of coaxial components. These items were designed to have distinctive TDNA characteristics.

4. THE MEASUREMENTS

The measurement technique for the exercise was not specified, allowing the participants to measure the items using their own preferred methods.

For each item, results were supplied in terms of (i) magnitude VRC and, (ii) time from the test port to the most prominent discontinuities. In addition, the magnitude VRC at the test port (time = 0 s) was also supplied.

5. THE METHODS OF MEASUREMENT

The measurement configurations used by each laboratory are listed below.

Lab 1 used a Hewlett-Packard 8722D VNA with port one calibrated using a Short, Open, Sliding load, Lowband load scheme in GPC-7 over a frequency range of 2 GHz to 18 GHz with 401 frequency points. Band-pass mode was used to interpret the data in the time-domain.

Lab 2 used a Hewlett-Packard 8510C VNA. A Short, Open, Broadband load calibration was used, with precision 3.5 mm connectors on port 1 over a frequency range of 2 GHz to 18 GHz with 401 frequency points. A 3.5 mm to GPC-7 adaptor was then used to provide a suitable test port for the items. The electrical length of this adaptor was found by attaching a high reflect termination to the end to establish the electrical delay. This delay was then extracted from the final results, effectively transforming the test port reference plane to the end of the GPC-7 adaptor. Band-pass mode was used to interpret the data in the time-domain.

Lab 3 used a Hewlett-Packard 8510C VNA. A Short, Open, Broadband load calibration was performed in GPC-7 on port 1 over a frequency range of 2 GHz to 18 GHz with 201 frequency points. Band-pass mode was used to interpret the results in the time-domain.

Lab 4 used a Hewlett-Packard 8510C VNA. A Through, Reflect, Line calibration was used in GPC-7 over a frequency range of 2 GHz to 18 GHz with 201 frequency points. Band-pass mode was used to interpret the results in the time-domain.

Lab 5 used a Hewlett-Packard 8510C VNA. A Short, Open, Broadband load calibration in GPC-7 was used on port 1 over a frequency range of 2 GHz to 18 GHz with 201 frequency points. Results were interpreted in the time-domain using the band-pass mode.

Lab 6 used a Hewlett-Packard 8510C VNA. A Short, Open, Broadband load calibration was used at the end of a cable in precision 3.5 mm connectors over a frequency range of 66 MHz to 26.5 GHz with 801 frequency points. To make the measurements, a 3.5 mm to GPC-7

adaptor was used. The adaptor 'length' was extracted using the same method as Lab 2. Results were interpreted in the time-domain using the low-pass impulse mode.

6. THE STATISTICAL ANALYSIS

It is usual, when analysing measurement comparison data, to provide some form of statistical summary of the results. This, for example, is usually an average value (e.g. the mean) and a measure of the scatter in the data (e.g. the standard deviation). For a comparison of frequency-domain measurements, the statistical analysis is performed at each frequency, as frequency is part of the definition of the measurand. I.e. it is meaningful to compare participants' values at a common frequency, but not necessarily so at different frequencies.

Generally, in a TDNA measurement, the time (or distance) values are not defined directly, but rather are a consequence of the frequency domain settings. This means that in a TDNA measurement comparison exercise, there is a degree of variation in the time values as well as the S-parameter values. This has the effect that it is not always obvious which values should be used for each analysis. Clearly, only a single value from each participant should be included in each separate analysis, but there may be confusion over which value to use, especially when values appear to be outlying or when the discontinuities being measured are close together.

The above situation has led to a degree of discretion being used when analysing the data in this comparison. The aim has been to identify regions, in the magnitude VRC/time plane, where a given grouping of measurement results indicates a consensus between the participants that these are measurements of a common discontinuity[1]. Such groupings are then analysed separately, i.e. it is assumed that the measurements contained within each grouping all refer to the same measurand. Measurements not contained within a clear grouping do not form part of the analysis. In a sense, such measurements are assumed to be outliers, and are not included in the analysis.

7. THE RESULTS

The results are presented in terms of two graphs and a table for each device. The first graph shows the measured values superimposed on a sample trace for the item. This facilitates the identification of the data groupings, mentioned above, which are subsequently analysed separately. Each grouping is nominally located around each of the item's discontinuities. The second graph shows the measurement values selected for each grouping, which are analysed subsequently to produce the summary statistics.

The table presented for each device contains the participants' measurement values along with the summary statistics, i.e. the mean and sample standard deviation (SD) of each set of values for each recorded discontinuity. The measurement values are presented in the tables to the same number of decimal places as was supplied by the participants. Where a participant's value was not contained in any of the identified groupings, the table entry has been left empty (and shaded grey).

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[1] Purely objective methods of establishing and analysing 'clusters' of data in a plane have been reported in the literature. Their suitability for analysing the type of data presented in this comparison exercise will be investigated in the future.

8. OBSERVATIONS

In general, there is good agreement between the results supplied by the participants. The exception to this is the results supplied by Lab 6, which were often not contained within the identified groupings (and hence values were omitted from the results tables). Examining the method of measurement used by Lab 6 (as given in section 5), it is clear that this laboratory was the only one to use the low pass impulse mode of measurement as well as the only lab to include measurement data above 18 GHz (this being the recommended top frequency for the 7 mm coaxial line size). Both of these differences could be the cause of the unusual results reported by Lab 6, although the latter issue (i.e. data above 18 GHz) is thought by the authors to be the more likely cause.

However, since the majority of laboratories showed good agreement (and suspect data was effectively excluded for the analysis), the results can be further analysed to provide a 'quality indicator' for typical TDNA measurements. To do this, the standard deviations given in the tables can be taken as equivalent to reproducibility standard deviations [1], s_R, since it is expected that the within-laboratory standard deviation (i.e. repeatability) of the measurements will be small compared with the between-laboratory standard deviations presented in the tables. A technique presented in [2] can be used to establish an upper limit, called the Reproducibility Limit, for the differences that might be expected between results obtained by different laboratories. Such a technique has been used previously in ANAMET to establish the Reproducibility Limit for coaxial connector dial gauge measurements [3].

The Reproducibility Limit, R, for a probability level of 95% is given by the following approximate formula:

$$R \approx 2.8 \times s_R$$

8.1 <u>Magnitude VRC values</u>

The largest value of s_R for the $|\Gamma|$ values presented in the results tables is 16 mU. Therefore, for $|\Gamma|$ values, we have:

$$R \approx 2.8 \times 16 \approx 45 \text{ mU}$$

This tells us that, in general, the difference between $|\Gamma|$ time-domain results reported by any two laboratories (performing measurements competently) can be expected to be less than 45 mU. *I.e.* in the absence of any traceability, this is a typical degree of variation we can expect for this type of measurement.

8.2 <u>Location values</u>

The largest value of s_R for the location values presented in the results tables is 0.021 ns. Therefore, for location values, we have:

$$R \approx 2.8 \times 0.021 \approx 0.06 \text{ ns}$$

As with the $|\Gamma|$ values, this tells us that the difference between time-domain location values reported by two laboratories (performing measurements competently) can be expected to be less than 0.06 ns. Again, in the absence of any traceability, this is a typical degree of variation we can expect for this type of measurement.

9. CONCLUSIONS

This report has presented results obtained by the recent ANAMET-991 TDNA measurement comparison exercise. The results have generally shown good agreement and have suggested a typical degree of variability of the order of 45 mU for $|\Gamma|$ time-domain measurements, and 0.06 ns for location time-domain measurements. However, considerable additional work, including further measurement comparison exercises, will need to be undertaken to substantiate these values. Finally, one laboratory's results did depart significantly from the other participants, and the reasons for this will need to be further investigated.

10. REFERENCES

[1]   ISO 5725-1, "Accuracy (trueness and precision) of measurement methods and results Part 1: General principles and definitions", *International Organization for Standardization*, 1994.

[2]   ISO 5725-6, "Accuracy (trueness and precision) of measurement methods and results – Part 6: Use in practice of accuracy values", *International Organization for Standardization*, 1994.

[3]   N M Ridler, "How much variation should we expect from coaxial connector dial gauge *ANAlyse Note No 14*, February 1996.
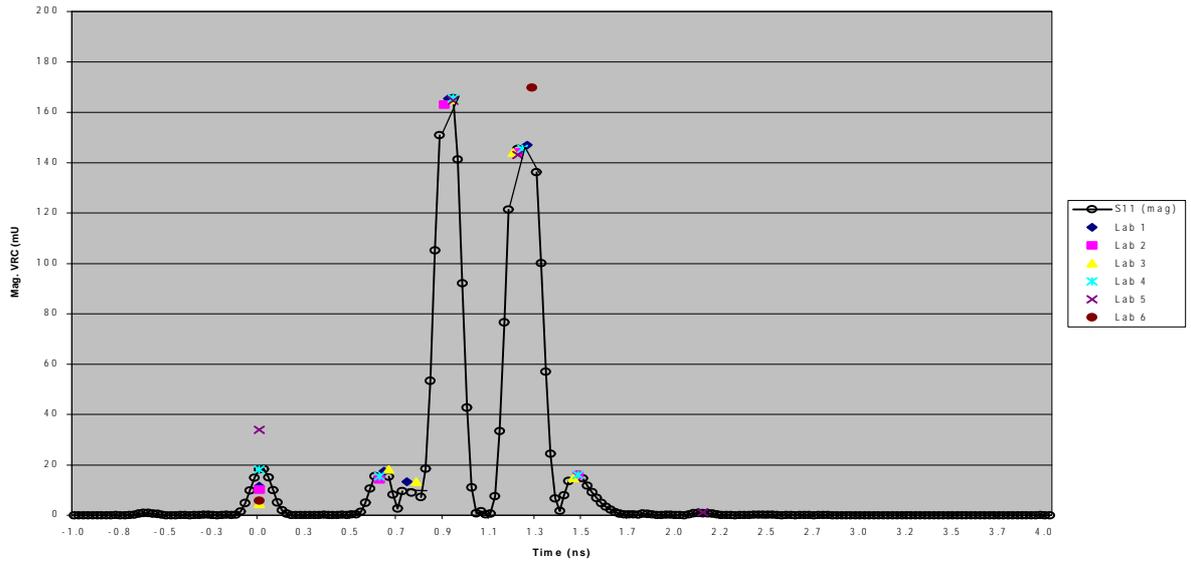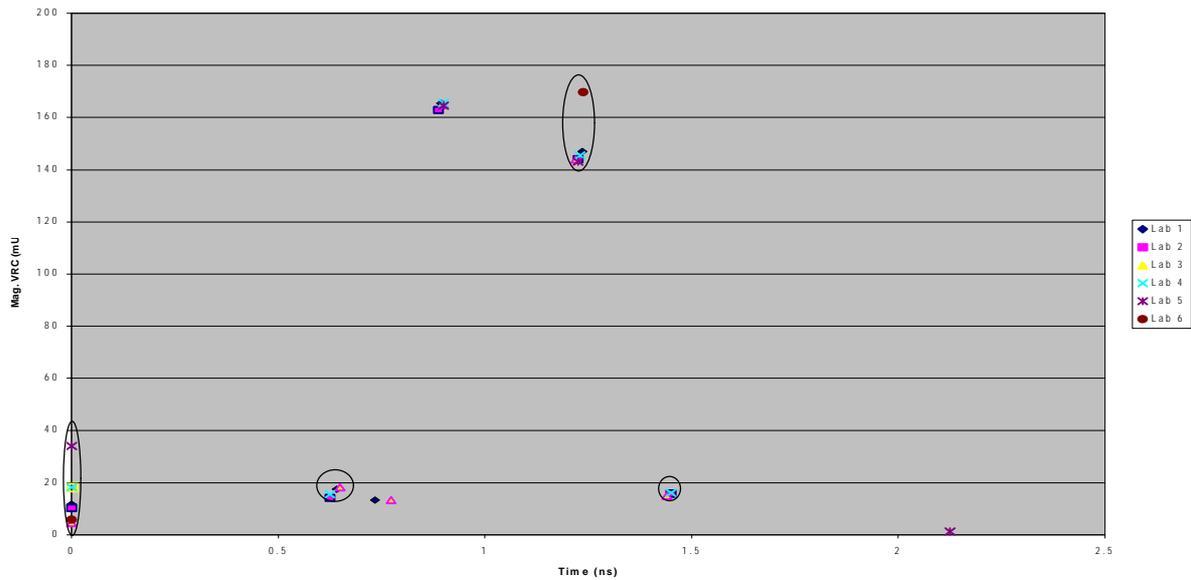
fig 1: Item 1 data and sample trace

fig 2: Item 1 data groupings

Discontinuity No. (Arbitrary)		Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6		Mean	SD
1	Location	Test Port							N/A	N/A
	$\lvert\Gamma\rvert$ (mU)	11.6	10.3	4.6	18.2	34	5.8		14	11
2	Location (ns)	0.642	0.625	0.65	0.625				0.636	0.013
	$\lvert\Gamma\rvert$ (mU)	17.5	14.2	18.2	15.5				16.6	1.9
3	Location (ns)	0.894	0.888	0.9	0.9	0.9			0.8963	0.0056
	$\lvert\Gamma\rvert$ (mU)	165.5	163	165	165.7	164.6			164.8	1.1
4	Location (ns)	0.124	0.123	0.122	0.123	0.123	0.124		0.12288	0.00068
	$\lvert\Gamma\rvert$ (mU)	147	144.1	144	145.5	143.1	169.8		145	11

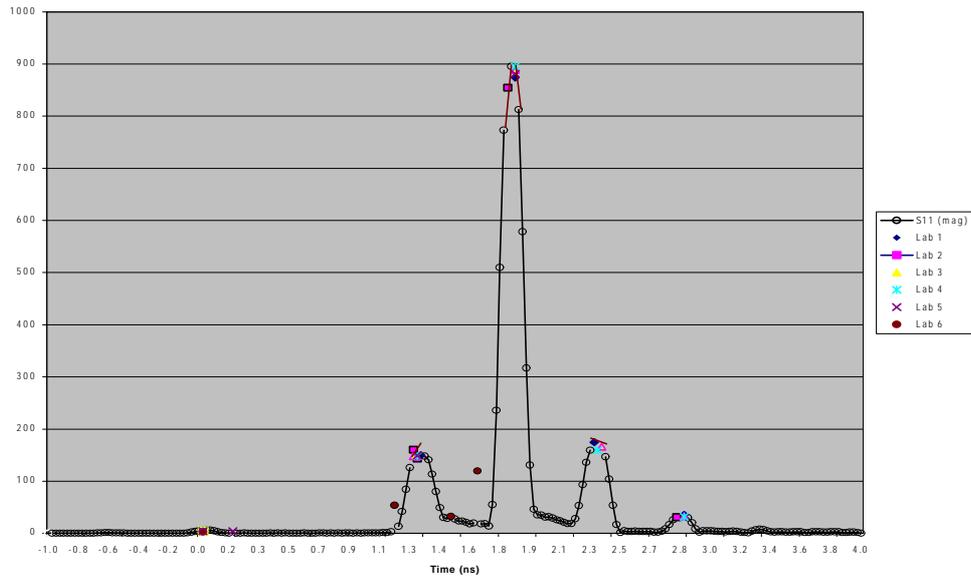table 1: Item 1 data and summary statistics

fig 3: Item 2 data and sample trace
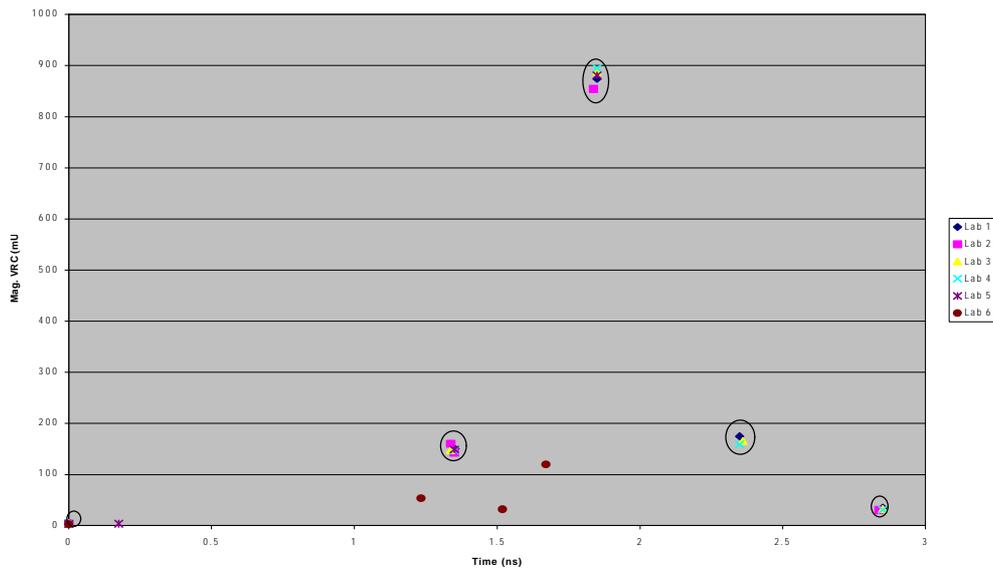
fig 4: Item 2 data groupings

Discontinuity No. (Arbitrary)		Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6		Mean	SD
1	Location				Test Port				N/A	N/A
	$\lvert\Gamma\rvert$ (mU)	5.1	4.5	4.8	4.3	3.5	2.8		4.17	0.87
2	Location (ns)	1.352	1.35	1.3375	1.35	1.35			1.3479	0.0059
	$\lvert\Gamma\rvert$ (mU)	149.8	143.2	148	147.4	148.7			147.4	2.6
3	Location (ns)	1.85	1.8375	1.85	1.85	1.85			1.8475	0.0056
	$\lvert\Gamma\rvert$ (mU)	874.24	854.6	889	895.355	881.00421			879	16
4	Location (ns)	2.85	2.8375	2.85	2.85				2.8469	0.0063
	$\lvert\Gamma\rvert$ (mU)	35	30.9	32.4	31.3				32.4	1.9

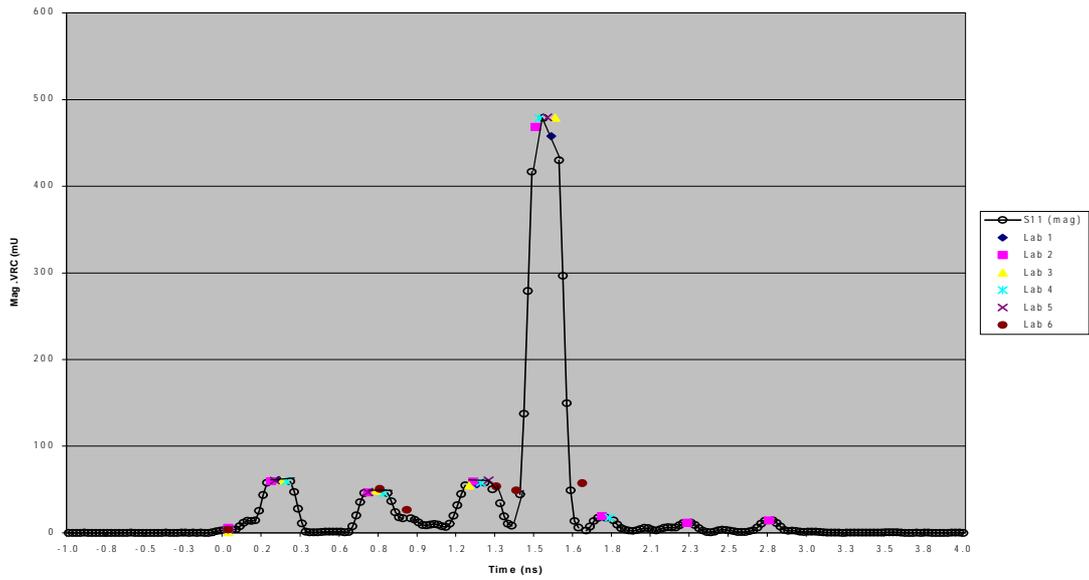table 2: Item 2 data and summary statistics

fig 5: Item 3 data and sample trace
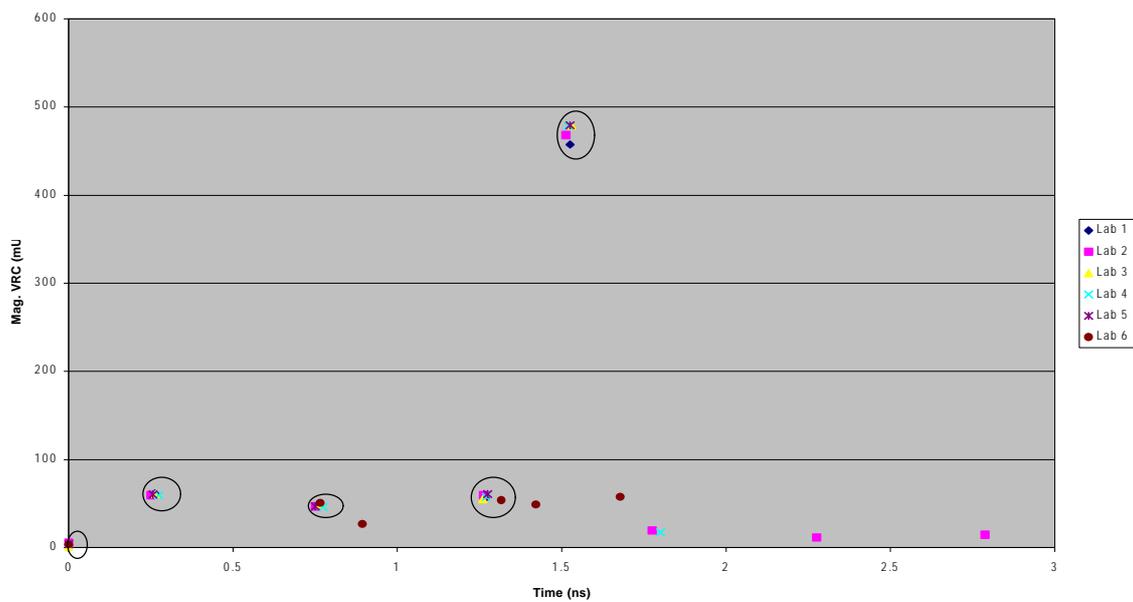
fig 6: Item 3 data groupings

Discontinuity No. (Arbitrary)		Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6		Mean	SD
1	Location	Test Port							N/A	N/A
	$\lvert\Gamma\rvert$ (mU)	3.1976	5.8548	1.26	3.447	3.98057	3.61907		3.6	1.5
2	Location (ns)	0.262	0.25	0.263	0.274	0.257			0.2612	0.0088
	$\lvert\Gamma\rvert$ (mU)	61.463	59.593	60.7	59.406	60.34732			60.30	0.84
3	Location (ns)	0.76	0.75	0.763	0.774	0.75	0.7652233		0.7604	0.0093
	$\lvert\Gamma\rvert$ (mU)	47.763	46.801	48.8	46.062	46.88896	50.5733		47.8	1.7
4	Location (ns)	1.266	1.2625	1.26	1.27	1.275	1.3160983		1.275	0.021
	$\lvert\Gamma\rvert$ (mU)	56.205	59.46	54.9	57.699	60.82848	53.7509		57.1	2.8
5	Location (ns)	1.526	1.5125	1.53	1.52	1.525			1.5227	0.0068
	$\lvert\Gamma\rvert$ (mU)	457.48	468.34	479	478.638	479.3606			472.6	9.7

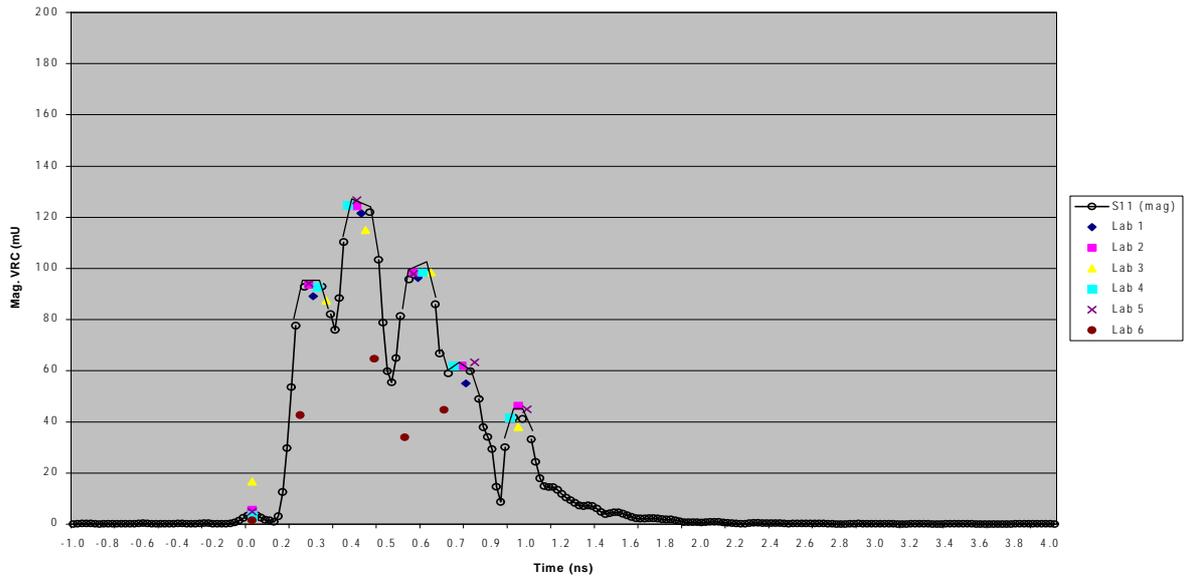**table 3: Item 3 data and summary statistics**

fig 7: Item 4 data and sample trace
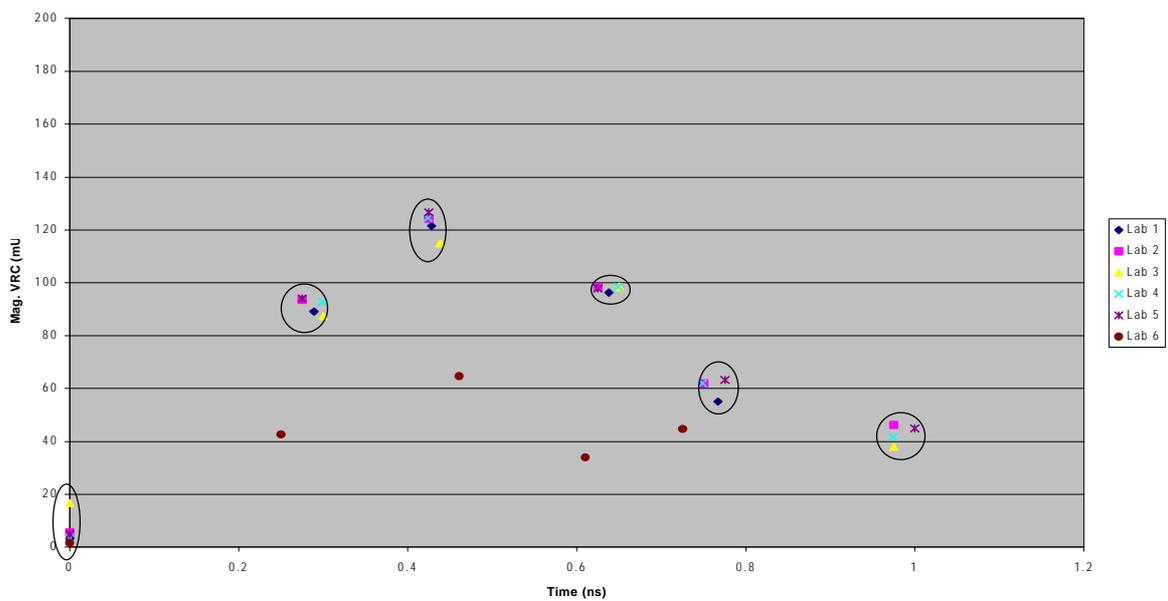
fig 8: Item 4 data groupings

Discontinuity No. (Arbitrary)		Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6		Mean	SD
1	Location	Test Port							N/A	N/A
	$\lvert\Gamma\rvert$ (mU)	3.2	5.6	16.7	3.4	4.9	1.6		5.9	5.5
2	Location (ns)	0.289	0.275	0.3	0.299	0.275			0.288	0.013
	$\lvert\Gamma\rvert$ (mU)	89.168	93.651	87.5	92.831	94.1611			92	3
3	Location (ns)	0.428	0.425	0.438	0.424	0.425			0.4280	0.0058
	$\lvert\Gamma\rvert$ (mU)	121.47	124.27	115	124.538	126.582			122.4	4.6
4	Location (ns)	0.638	0.625	0.65	0.649	0.625			0.637	0.013
	$\lvert\Gamma\rvert$ (mU)	96.349	98.45	98.5	98.484	97.806			97.92	0.93
5	Location (ns)	0.767	0.75		0.749	0.775			0.760	0.013
	$\lvert\Gamma\rvert$ (mU)	55.093	61.998		61.983	63.3106			60.6	3.8
6	Location (ns)		0.975	0.975	0.974	1			0.981	0.013
	$\lvert\Gamma\rvert$ (mU)		46.217	38	41.645	44.9272			42.7	3.7

table 4: Item 4 data and summary statistics