Using Statistical Process Control To Improve Yield and Traceability for Automated Production Test

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Abstract

Historically, automated test within Agilent has consisted of racks of measuring and test equipment (test systems) operated remotely by humans via software programmes. Certain tasks requiring manual intervention still remain in such a test environment and may include; initiating test programs, making the appropriate connections to the device under test and calibrating/zeroing power sensors.

With increasing demands for lower manufacturing overhead costs (MOH) and increased production capacity, a fully automated production environment was designed which allows 24/7 testing without the need for human intervention.

In principle the intention was straightforward, but a number of different and unforeseen problems associated with the automation conspired to reduce the automated operational performance beyond acceptable limits.

This paper describes how a method of statistical process control (SPC) was employed to identify these problems and allow for almost continuous station operation (near 100% process yield) in the automated environment, fully traceable to national standards.

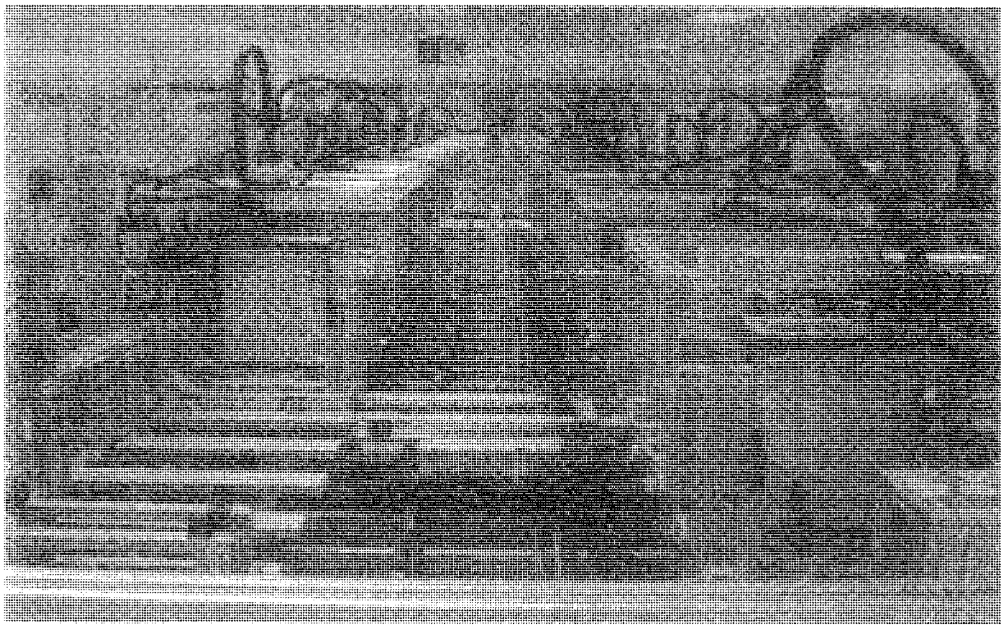
1. Introduction

Two years ago the test equipment products manufactured on production lines within the RF Communications entity at Agilent's European manufacturing plant were still tested to specification by processes comprising a number of function specific test systems operated by test engineers. Typically, test engineers were responsible for 'walking' a product through each step of the production test process, ensuring that the appropriate test schedule was followed for the product and managing various on-line demands from the test systems. This has been the model of production test process for many years and although increased product complexity has driven greater test capability, the implementation has remained largely the same.

A typical production environment

With increasing demands being placed on production, this model was found to be inadequate in meeting targets for production yield and therefore capacity. It was apparent that a number of factors were limiting the performance of the production process; repeatability of calibrations, 'no faults found', manual processes and frequent test system calibration. Factory costs associated with the capital investment in test hardware and the overhead cost of production personnel were becoming increasing unsustainable.

The decision was made to change the mode of operation to one of near complete automation where the task of testing a product would be handled by a robotic system. This system, (locally named Yellowstone) had been proven elsewhere in Agilent on products of a more simple nature and the infrastructure was readily available at reasonable cost.



Yellowstone production test environment

The main advantages of operating a system such as Yellowstone are;

- Maximum utilisation of assets through continuous production increases return on invested capital (ROIC)
- Reduction in test operator overhead (MOH)
- Redeployment of skilled test engineering staff to more value added work (instrument rework & repair)
- A manufacturing test process that is more consistent and repeatable.
- Easing of production congestion and bottlenecks through defined automation rules
- Greater control of processes leading to a more predictable output.

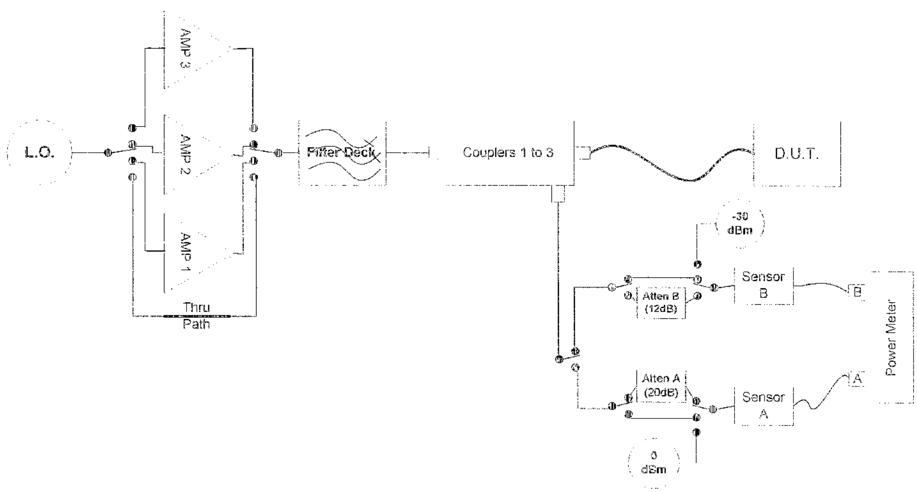
This paper focuses on the evolution of one particular production test system from a '*legacy*' type system to the fully automated version currently in use in Yellowstone.

2. Testing for CW Power Specification

The production test system in question 'Power', is used to verify the accuracy of CW power detector circuitry within RF receivers. This system is key to meeting the requirements of customer specifications on wireless communications products. Typically, test systems such as this present 'bottlenecks' to the production testing process, with the demand for tighter customer specs resulting in a reduced tolerance interval for production test.

This system is capable of characterising a product's power detector against a traceable standard over ranges of Freq: 100kHz to 4GHz and Ampl: –30dBm to +40dBm, with typical uncertainties of 0.1dB (95.5% confidence). This performance has been achieved through careful attention to system design, mismatch contributors, harmonic content, the accuracy and drift of power sensors and reference. Algorithms for the calibration of the RF path losses within the test system and monitoring of certain performance parameters are an integral part of the operation of this test system.

ET42803 Simplified Block Diagram



2.1 To Automate or Not?

The proposed automation of the Power test system coincided with demands for improved RF detector specifications in a flagship wireless communications product. An investigation was performed in order to assess the feasibility of the proposal. A measurement uncertainty (MU) analysis using the general s-parameter model for a 3 port device, based on the paper "Understanding Microwave Power Splitters" by R.A. Johnson, was carried out for the measurements. The MU analysis was based on the ISO GUM method.

By comparing the weighted contributions of the various terms of this expression, potential problem areas were identified with the new system. These anticipated problems might be summarised as follows:

i. the increase in length (1m to 2m) of the primary RF cable connecting the device under test (DUT) to test system would increase the uncertainty due to mismatch (VSWR), and repeatability (flexure) without careful selection.

ii. push-fit N Type connections between the test system and DUT, power sensors and power references might experience greater repeatability than torqued connectors.

iii. stand-alone reference sources for 1mW and 1μW would be required since the manual calibration & zeroing of power sensors no longer possible.

Solutions to these problems were identified in the form of armoured cabling of high specification (i), specially adapted metrology grade connectors mounted on a mobile 'vehicle' with force control (ii) and the availability of new reference source products intended for standalone use (iii). Based on these solutions, the decision to automate was agreed.

2.2 The Outcome

Whilst none of the anticipated problems caused any significant effects in the implementation of the automated Power station, it was apparent that the performance of the system was significantly less than those systems still operating in the manual environment. The cause(s) of the degraded performance was not obvious. The intention of a more robust and repeatable measurement had therefore, not been realised and the Power test systems had to be withdrawn from the Yellowstone environment.

In order to determine the causes of the poor system performance without extensive experimentation undertaken by a team of engineers, some form of reference measurement was essential in order that the comparison of station measurement performance against a known good value could be facilitated.

The use of statistical process control (SPC) had been employed on production lines at Queensferry for some years, but in nearly every case the purpose of this had been to indicate trends or relative movement in the performance of a test system over a period of time. A product, representative of those being manufactured, was generally used as the nominal reference for this testing. In trying to identify the cause of the Power test system problems, employing such a method and standard was insufficiently accurate or repeatable to provide the measurement resolution required. Therefore, in order to facilitate the investigation of the unacceptable performance of the Power station, a more rigorous testing program employing a more fundamental standard was required.

3.0 SPC Introduction

The realisation now existed that a tool like SPC, which would help engineers to identify and then monitor/control test system performance issues had wider potential. In addition, a means of comparing a number of similar test systems against a single reference would be highly desirable. With a reference calibrated at a standards lab, this might further enable direct traceability from production measurements to national standards.

There are a number of possible gains built on the foundation of this form of SPC:

- Calibration of test system RF paths driven by SPC rather than maintenance schedule.
- Test system downtime reduced due to increased calibration interval
- Maximum test system yield (target > 99%)
- Clear identification and segregation of product and test process problems
- Confidence in measurements is maintained (ISO 17025 requirement)

3.1 SPC Building Blocks

The elements necessary in order to realise the foundation of SPC include:

3.1.1 Measurement System Understanding

The key parameter that SPC is required to verify is the test system measurement uncertainty. This requires the engineer to have a comprehensive understanding of system operation down to the smallest contributor of uncertainty such as switch repeatability, connector repeatability, power sensor drift and so on. The investment in time by the engineer is not insignificant.

3.1.2 The Reference or 'Gold Standard' Instrument

The proper selection of the Gold standard instrument is fundamental to implementing the SPC process. The repeatability of the instrument must be significantly less than the test system uncertainty for the SPC process to add value. For this reason, the more traditional approach of selecting a representative product is in most cases not appropriate. The criteria that must be considered when selecting the Gold standard include:

- The Gold standard must operate over the parameters and range of the test system.
- Must have a 2 sigma repeatability that is less than the system MU
- Calibration uncertainty requirements will be driven by the system MU
- To maintain confidence in the Gold standard, the calibration interval should be shorter than the interval prescribed in the product manual
- Cost (two Gold standards provide cover when one is being calibrated)

Gold Standard operational requirements

- The unit should be continually powered on, even whilst not in use
- Frequent maintenance should be performed e.g. connectors gauged and cleaned, fans cleaned etc
- The Gold standard must not be opened, adjusted or used for diagnostics
- Will be handled, stored and transported in a manner that will not affect the calibration or physical condition of the instrument.

3.1.3 The SPC Limits

For warranted customer specifications, the SPC limits should be no greater than the MU value.

Type-B MU analysis will yield 95.5% confidence limits that are generally more conservative, but apply to a number of test system of the same type throughout the recommended calibration interval. Type-A analysis on the other hand may only be valid for a single system with defined system trace equipment, Gold standard and environment. Variation from system to system needs also to be accounted for.

Multiple Gold standards will introduce further variation and may be necessary to add a term to the SPC limit values to account for this.

3.1.4 SPC Test Time and Frequency

Adding SPC to an existing test process will impact production time. The cost of running and maintaining an SPC process must be balanced against the risk to quality though incorrectly calibrated product. It is therefore important that the smallest number of test points that will fully exercise the system through its entire operating range are selected.

A similar argument applies to the frequency at which the SPC is run and consideration should be given to the following:

- Production volume fluctuations
- A daily interval for guaranteed customer specifications
- Consider bi-daily or weekly intervals for non-critical specifications

3.1.5 SPC Failures

An SPC failure can have many possible causes; operator error, extraneous signals, contaminated connectors, cable wear etc. The process of flagging a failure must take into account all the failure mechanisms and drive a corrective action process. An SPC process failure has been defined as two consecutive SPC runs, which do not pass all test points. In the automated environment the Yellowstone controller immediately puts the test system off-line.

3.1.6 Reporting SPC Results

Trends in performance and SPC failures are clearly seen with results presented in graphical format. This aids the engineer trying to detect anomalies in system performance, the prediction of system drift or when a test system requires calibration. Reviewing large data sets on a frequent basis is however, time consuming and prone to error and so test support personnel are notified automatically by the system when an SPC failure occurs. Such a reporting system balances the need for prompt remedial action with the collection of data for analysis.

3.2 SPC Implementation

The implementation of a robust SPC process for the purposes of guaranteeing station performance requires the measurement of key test points with a repeatable working standard, in effect, an accurate calibration of the test system itself. This provides an error value at the key operating conditions, which in turn gives an indication of the 'health' of the system. The instrument selected as the Gold standard was an Agilent E4419B power meter and 8482A power sensor. Because of the requirements for automated connections, the sex of the power sensor was changed from N Type male to female creating unique calibration requirements.

Test & Station	Equipment Model No.	Equipment Description	Test Points	Required Uncertainty	Test Proc. or Cal Lab.
Yellowstone Stations					
SPC	ET54001 E4419A/B N-Type(m)	Power Meter	As manual except for 1mW Ref. Output. Use 478A N (f) for Stds Lab calibration.	< 0.4%	ET54001-90001
SPC	ET30896 8482A N-Type(f)	Power Sensor 100kHz - 4.2GHz	Cal. Fact & VSWR 0.1, 0.3, 0.5, 1, 3, 5, 10, 30, 50, 100, 200, 300, 500, 650, 800, 1000, 1500, 1800, 2000, 2500, 2600, 3000, 3500, 3700, 4000, 4200	Cal Factor < 0.7% Input VSWR As Manual	Nat Stds Lab ET30896-90001
SPC	ET30897 5065-4616	1mW Reference Oscillator	Output power level	< 0.4%	ET30897-90001

Table 1. Calibration Requirements of Gold Standard

Both the sensor and power meter are mounted on permanently powered cart (UPS Cart), which never leaves the Yellowstone system. In order to facilitate the automatic calibration of the 8482A power sensor by the Yellowstone robot, the power meter 1mW reference was replaced with standalone reference located at one of the Power test systems. Limits of ±0.015dB were applied to the automated sensor calibration in order that any problems with the UPS Cart may be detected.

1mW reference source on a mobile device

Gold Standard E4419B, 8482A in UPS cart

The test points covered by the SPC program were selected to ensure that the majority of the operating conditions and critical RF paths were exercised. The SPC test plan covers the ranges of paths by amplitudes, couplers and filters.

ET42803 and ET42932 Station Path Matrix								
STATION PATHS			PATHS USED TESTING PRODUCT					SPC
Coupler	Amplifier	Filter No.	Filter Freq (MHz)	Product A Pre-Test	Product A Final Test	Product B Pre-Test	Product B Final Test	SPC Test Freq (MHz)
1	1	1	0.4					
1	1	2	1					
1	1	3	10			used	used	10
1	1	4	15					
1	1	5	20					
1	1	6	30			used	used	**Note 1**
1	1	7	50			used	used	40
1	1	8	80			used	used	60
2	1	9	100			used	used	100
2	1	10	150	used	used			**125**
2	1	11	200	used	used			**175**
2	1	12	300	used	used			**250**
2	1	13	500	used	used			**400**
2	1	14	800	used	used			**650**
2	1	15	1000	used	used			**950**
2	2	16	1500	used	used			**1250**
2	2	17	2000	used	used			**1850**
3	3	18	3000	used	used			**2720**
3	3	19	4000					
Note 1:	No calibration point exists to allow SPC to be done for this path.							

Table 2. Test System Conditions for SPC

For the SPC limits, the initial thought was to use the MU values of ±0.1dB. However, as the SPC process effectively repeats the measurement of the system RF path loss carried out during a test system calibration, analysis of the measurement equation indicated that a number of the uncertainty contributors cancel out. The resultant MU analysis for the SPC test, still based on the original GUM analysis indicated that limits of ±0.05dB were appropriate.

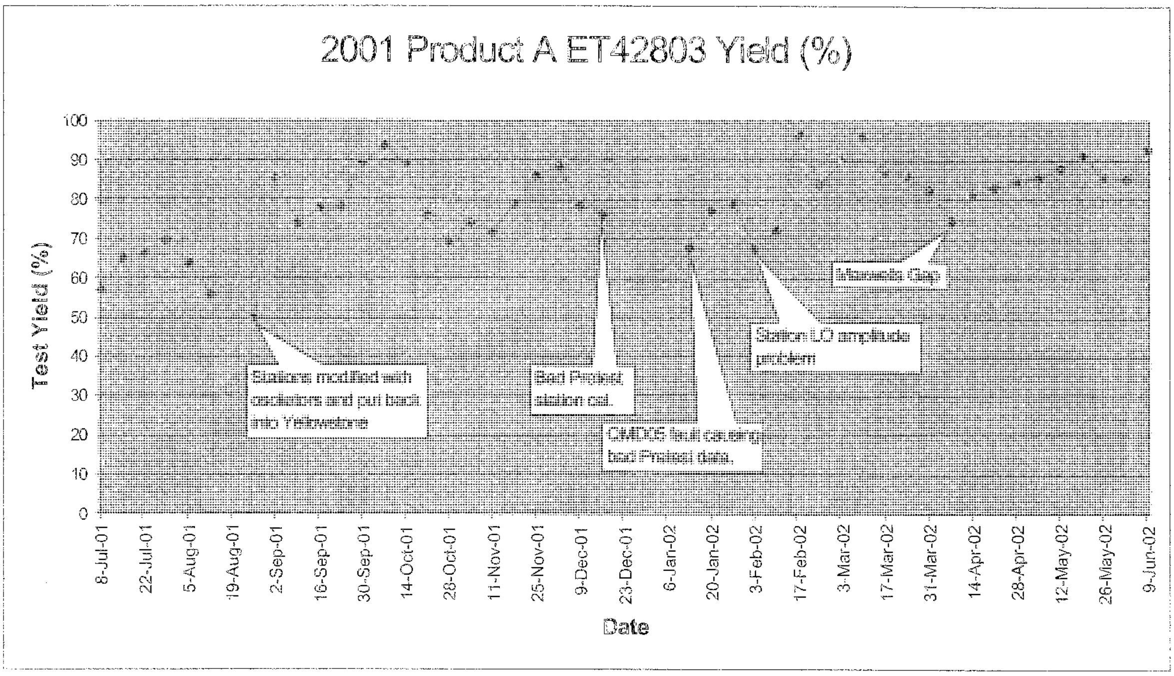
3.3 SPC Outcome

As discussed in (2.2), a variety of implementation problems over and above those known or anticipated had seriously impacted the performance of the fully automated Power test system. Immediately after the introduction of SPC to the automated version of the system, using the Gold standard and method described in the previous section, it was found that the SPC failure rate was almost daily. This confirmed that as previously suspected the Power test system within the Yellowstone environment was out of control. Using the SPC process as a tool and observing the calculated SPC limits of ± 0.05dB, investigations produced the following causes:

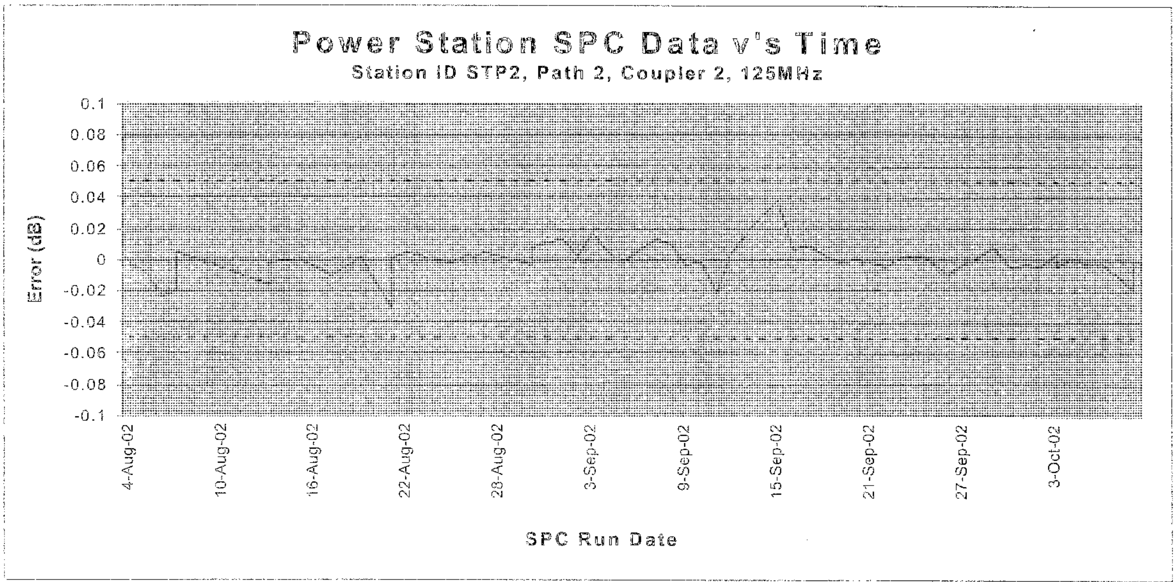
i. The primary system RF cable is attached to the DUT or Gold standard, using a metal plate housing the metrology grade push-fit N Type connector (mobile device). The robot uses an electromagnet to pick up and locate the plate and then maintain the connection during measurement. It was found that heat transfer was taking place from the plate, through a Delron connector mount, the N Type connector itself and finally, to the 8482A thermocouple sensor. When calibrating the system, DUT or Gold standard this caused a temperature related drift in the measurement, inducing an offset in the results. To overcome this, 12V fans were fitted to the electromagnets.
ii. The connection of two additional power sensors (Sensors A and B) to N Type bulkhead connectors mounted on the test system had been replaced with mobile devices, held in position during test by passive magnets. The 8lb force of connection with a spring-loaded N Type (f) was insufficient to ensure good repeatability. This arrangement was replaced with the two power sensors permanently located in the test system. With switched paths for measurement, sensor zeroing (50Ω termination) or sensor calibration (reference source), there is no disconnection of the power sensor, and repeatability is minimised to that of only the matrix RF switch.
iii. Test operators initially performed the manual calibration of the Gold standard 8482A power sensor to the 1mW reference. This was subsequently replaced with a robot assisted calibration, found to be considerably more repeatable and consistent.
iv. High power RF amplifiers used in the Power test system were found to be generating DC offsets when not in circuit. This became more apparent when the intermittent problem of sensor damage was not eliminated within the robot controlled Yellowstone environment. Additional terminated switch paths were added to prevent destructive discharges.
v. With improving consistency and performance of the automated system, the effects of RF switch repeatability, connector grades/maintenance and cleanliness issues became more apparent. Component changes, previously deemed insignificant were carried out and the production maintenance program was modified to minimised to prevent contamination of connectors.

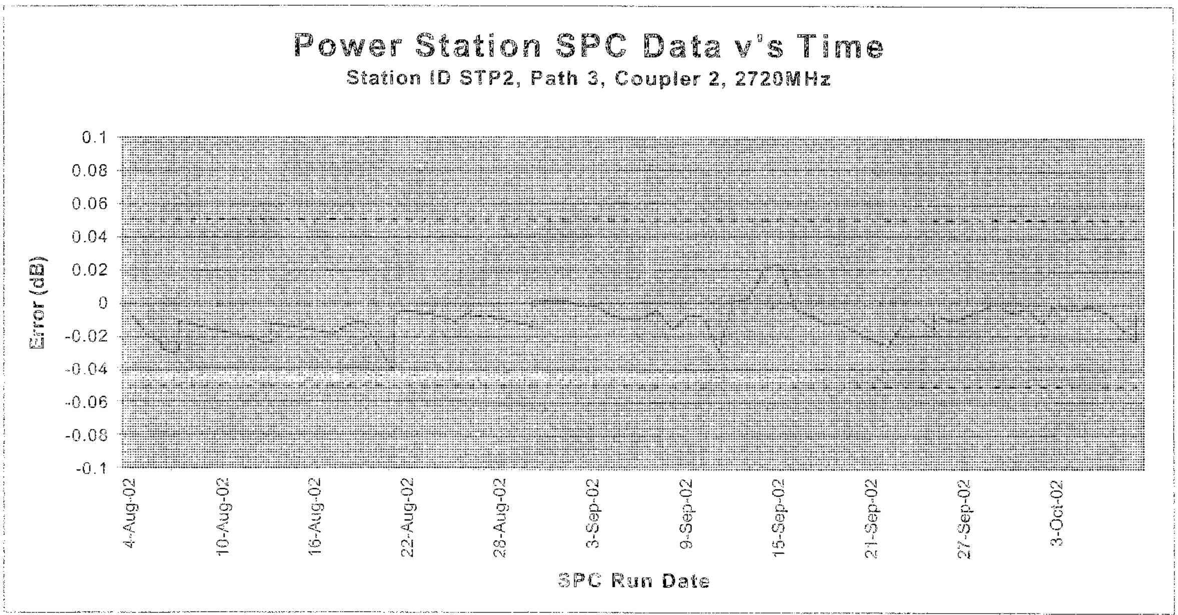
As performance problems became identified, the fixes were rolled out across the large number of Power test systems, both within and outside the Yellowstone environment. The performance of the systems, monitored through daily SPC runs, produced hitherto unrealisable test process performance, specifically:

i. Yield increase from around 50% to 90% for the product test at the Power test system.
ii. A reduction in the number of test systems from 11 to 7, an effective saving of 30% in capital expenditure.
iii. The MU of the test system has been reduced by around 20% to ±0.072dB (±0.082dB below –27dBm)
iv. Manufacturing tolerance interval reduced by around 20%, in line with demands for similar reductions in the customer specification on a key product.
v. The calibration interval for the Power test system is now driven by SPC as the drift in the test system performance can be clearly monitored through the results of the daily SPC run. The interval is currently 1 month with no SPC fails. Limited experimentation indicates that an interval of 8 week and possibly more may be achievable.
vi. By being able to effectively separate the performance of the test system and product (DUT), the number of 'no fault found' conditions has decreased dramatically. If the Power test system can pass the exacting demands of the daily SPC run, then the confidence in the measurement and test process is very high, with any production Fail, now attributed to product.
vii. Manufacturing and production resource can be more effectively utilised.



Yield for Power Test System in Yellowstone Environment





The SPC philosophy described here has realised the intention of helping to identify the problems associated with automating the Power test system and subsequently, has provided a means of keeping the test process in control with a high degree of confidence.

This process can be applied to any test system to monitor the performance of over a period of time relative to a known good operating condition. It is the relative 'drift' in the measurements and the growth in uncertainty from that point that is under examination and if the measurement exceeds the SPC limits, then there is either an immediate and (hopefully) identifiable problem or possibly the calibration of the system is due.

Looking forward, if the reported results of the SPC test rather than the calibration of the Gold standard power meter and sensor, could be traced directly to national standards, then it is unlikely that confidence in the production measurements can be further improved upon. In effect, the SPC run is calibrating the test system against a higher standard at frequent intervals, through the Gold standard (transfer standard). This method could be considered to be an inter-lab comparison (ILC).

4 Inter Lab Comparison

The potential implications of performing a frequent ILC where one body is, for example a national standards laboratory such as NPL or NIST, and the other body is Agilent production are;

- Extended calibration intervals of test system equipment due to increased confidence in measurement through SPC and ILC.
- Direct traceability of measurement through the Gold standard, rather than multiple items of test equipment in the system implies that test systems may not need to leave the production line for scheduled equipment calibration.

4.1 ILC Specifics

An ILC process is a comparison of calibrations carried out by two participating calibration entities. In this case the two calibration bodies might be Agilent Queensferry production (Power test system), a national standards laboratory and the artefact itself, the Gold standard unit. Previously it has been stated that one of the criteria for selecting a Gold standard was repeatability. This is critical to achieving the most accurate comparison for an ILC.

Specified parameters, test conditions, instrument settings and associated uncertainties first need to be agreed, essential as the standards laboratory will almost certainly use different methods and equipment in order to perform the measurements. The ability of the laboratory to make measurements at all of the required test conditions may not in some instances be possible. The ILC should be carried out whenever the Gold standard unit has been calibrated, as this will provide an absolute reference of the least uncertainty at that point in time.

4.2 Comparison of Results

With the ILC measurements completed by both parties, a comparison of the results generated by the Power test system and from the standards laboratory may be made. Calculating the difference between the reported values will not in itself indicate useable information, unless accompanied by some form of acceptance limits. These limits will be calculated by combining in some manner, the expanded uncertainties from both parties. In doing this, the performance of both measurement systems is accounted for in a single term. The repeatability of the Gold standard also needs to be taken into account.

A possible method for defining acceptance limits involves taking the RSS of the two uncertainties related to the parameter being measured.

$$\text{ILC Result} = \text{Diff}\left(\text{Results}_{\text{Power Test System}} - \text{Results}_{\text{Standards Lab}}\right)\Big|_{\text{Freqency, Amplitude, Instrument Settings}}$$

$$\text{Acceptance Limits} = Factor \times \sqrt{MU_1^{\,2} + MU_2^{\,2} + \text{Repeatability}_{\text{Gold Standard}}^{\,2}}$$

where; MU_1 and MU_2 are the expanded uncertainties of both parties and *Factor* is to be determined, depending on the confidence required.

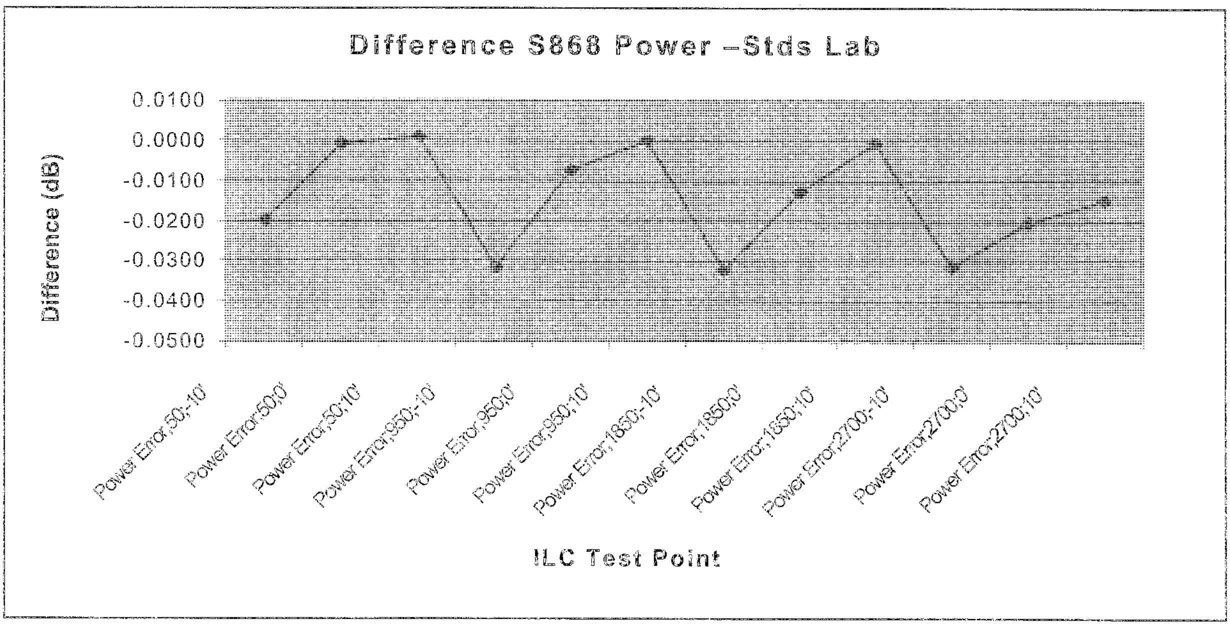
The value of *Factor* must be small enough (< 1.0) to reflect the fact that the acceptance limits apply to the difference of the two measurements. Additionally, the limits must assure the required confidence in measurement traceability of the Power test system.

If the ILC results generated by the multiple Power test systems fall within the acceptance limits then we can be confident that each is making absolute measurements correctly. If however any of the test systems generates results outwith the acceptance limits, then there is a problem with the measurement and the test system will be put out of commission until corrective action has been carried out. The results in the table below indicate the ILC carried out for the first Power test system.

Freq (GHz)	Indicated Power (mW)	Standards Lab		SQF (Manual) Power System S868		Difference S868 Power –Stds Lab	Possible Acceptance Limits
		Power Diff (Inc–Ind) (%)	MU (%)	Power Diff (Inc–Ind) (%)	MU (%)	(%)	(%)
0.05	0.1	0.3	0.5	-0.15	1.7	-0.45	1.2
	1.0	0.2	0.4	0.18	1.7	-0.02	1.2
	10.0	0.0	0.4	0.03	1.7	0.03	1.2
0.95	0.1	1.4	0.6	0.67	1.7	-0.72	1.2
	1.0	1.2	0.5	1.03	1.7	-0.17	1.2
	10.0	1.0	0.5	1.00	1.7	0.00	1.2
1.85	0.1	2.4	0.7	1.64	1.7	-0.74	1.2
	1.0	2.3	0.6	2.00	1.7	-0.29	1.2
	10.0	1.9	0.6	1.88	1.7	-0.01	1.2
2.70	0.1	5.3	0.7	4.54	1.7	-0.72	1.2
	1.0	5.2	0.6	4.71	1.7	-0.47	1.2
	10.0	5.0	0.6	4.64	1.7	-0.34	1.2

Table 3. Initial ILC Result for Power Test System

The ILC results indicated by the Difference term in the above table may be seen more clearly in the chart below.



The chart shows that the measurements made by the S868 Power test system are within 0.74% (0.032dB) of those carried out by the standards lab. The chart also shows that it may be possible to make further improvements to system performance by investigating what may be a systematic effect, present at levels less than 10mW.

The ILC has enabled acceptance limits to be placed around the absolute performance of the Power test system. When monitored and controlled with the regime of SPC testing, the performance of the system can be traced directly to the standards lab on an ongoing basis with a high degree of confidence.

5. Conclusion

The concept of applying a more metrologically based SPC process has provided a means of identifying, and then controlling test system performance issues within well defined and exacting limits. This method met the original aim of solving the problems associated with the automation of one particular test system, critical to the RF Communications production test process. Benefits to production have been realised in the form of reduced capital equipment requirement, improved system performance (quality and yield) and finally, the redeployment of production resource. This work has had a positive impact on the factory cost of Agilent products, and provides a clear justification for extending this philosophy to other production process within Agilent Queensferry.

By introducing the inter-lab comparison, the traceability for the measurements carried out is now more direct than an unbroken chain of comparison. The possible implications of this will be fully realised in the future.

6. Acknowledgement

The authors would like the acknowledge the time and effort given by the engineers and metrologists of manufacturing engineering, PL13 production and the Queensferry standards lab that have allowed this work to be carried out.

7. References

1. "Understanding Microwave Power Splitters", R.A. Johnson Hewlett Packard Company, Application Note 1975.
2. "Guide to the Expression of Uncertainty in Measurement" 1993 (E), International Organisation for Standardisation.