VERIFICATION – ELECTRIC PROPULSION'S ACHILLES HEEL

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Abstract: Despite all the progress of the last decade the majority of the space community still believe that electric propulsion is expensive and high risk. Lengthy, expensive life tests and qualification results which are not fully consistent with earlier development performance measurement add to the perception. Further variation when an electric propulsion system is integrated to a spacecraft has also deepened suspicion about the technology amongst customers. They therefore add large margins which drive up the cost or wait until there is considerable very expensive space heritage adding enormously to the sunk costs in future production. The electric propulsion community bears much of the responsibility for this unfortunate perception. Current verification procedures and processes are fallible and the majority do not conform to current international standards. Reversing the perception of high cost and risk is a significant challenge. Unless the electric propulsion community takes the initiative the challenge is likely to prove permanent. The starting point is to overcome the weaknesses in the current verification practices and to demonstrate reliable, affordable processes to develop and qualify competitive products. The principles are straightforward. Performance measurement must be consistent, accurate and repeatable. Measurement practice must be fully compatible with ISO/IEC 17025 (General Requirements for the competence of testing and calibration in laboratories) and should follow the 'Guide to the Expression of Uncertainty in Measurement (International Organization for Standardization, Geneva, ISBN 92-67-10188-9). It is also a fundamental requirement for test results from different test facilities to be comparable. This means that test results can be referred to a common baseline which can equally be referenced to in-space operating environment. This paper sets out an electric propulsion verification strategy to overcome the flaws in current practice. This includes methods for managing difficult aspects of measurement uncertainty and establishing common references.

Nomenclature

Abbreviations:
- ECSS – European Cooperation for Space Standardization
- GUM – Guide to Uncertainty Measurement
- ISO – International Standards Organization
- VIM - International Vocabulary of Metrology

Measurement Terms
- Accuracy: Closeness of the agreement between the result of a measurement and a true value of the measurand [note the term precision should not be used as an alternative to accuracy].
- Calibration: Set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards.
- Traceability: Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties (VIM definition).
- Resolution: Smallest difference between the indications of a displaying device that can be meaningfully distinguished.
- Repeatability: Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.
- Sensitivity: Change in the response of a measuring instrument divided by the corresponding change in the stimulus.
- Random Errors. Where randomly different results are achieved from repeated measurements or repeated simulated measurements (Monte Carlo simulation) in the form of a random, uniform or other distribution.
- Systematic and all other sources (Type B). Where the same influence affects the result for each of the repeated measurements, in practice all types and sources of uncertainty other than random.
- Uncertainty: Parameter associated with the result of a measurement which characterizes the dispersion of values that could reasonably be attributed to the measurand. [From the "Guide to the expression of uncertainty in measurement"].
- Standard (Measurement) Uncertainty. A margin of plus or minus one standard deviation.
- Combined (measurement) Uncertainty. The summation of all the standard deviations in a measurement process by summation in quadrature or another recognised process and expressed at one standard deviation.
- Expanded Combined (measurement) Uncertainty. A Combined Uncertainty expanded to two or three standards deviations.
- Correlation Coefficient. A measure of the relative mutual dependence of two variables (equal to the ratio of their covariances to the positive square root of the product of their variances).
- Independence**.** Two random variables are statistically independent if their joint probability distribution is the product of their individual probability distributions.

I. Introduction

Space electric propulsion has achieved over half a million hours of successful in-orbit operation on commercial satellites. It is making possible new missions to explore our solar system and its unique, precision performance has made it possible to map the Earth's geoid with unprecedented accuracy. Ambitions for large distributed aperture formation flying missions are unlikely to be realised without it. It can still trim commercial operating margins to new levels of competitiveness and open new horizons in space exploration.

Despite this many spacecraft operators and manufacturers still consider the technology to be expensive and high risk. A key contributor to this perception is verification testing. Test facilities are expensive to operate and maintain and test results often appear inconsistent with previous tests or tests in other test facilities. Further or re-testing, particularly for long duration tests, to investigate apparent anomalies can add significantly to cost and schedule. It also undermines confidence in results however thorough the investigation.

Electric propulsion verification testing is complex and technically challenging. All performance measurement is affected to a greater or lesser extent by the test environment and is different to what is actually achieved in-orbit. A test result depends on a range of measurements each of which has an associated degree of uncertainty and between which there can be significant dependency. This can be small and well defined when diagnostic instruments are readily calibrated but many tests rely on specialist diagnostic equipment for which calibration is difficult or not possible to a recognised independent standard. Further problems can occur when diagnostic equipment is prone to drift from the calibration.

Accurate, consistent, repeatable test results and the ability to compare results from different test facilities can only be achieved through the application of common procedures and international standards of measurement practice. These are founded on common, universally accepted definitions, full traceability and compatibility with ISO/IEC 17025 (General Requirements for the competence of testing and calibration in laboratories). Equally important is observance of the 'Guide to the Expression of Uncertainty in Measurement (International Organization for Standardization, Geneva, ISBN 92-67-10188-9) to quantify confidence in test results.

The application of these principles requires a strategy for assessing the measurement uncertainty associated with all diagnostic equipment used to measure the equipment under test and the test environment. The purpose of the strategy is to establish realistic, quantified confidence in the results. For comparison purposes it is also necessary to be able to refer all measurements to a common reference. The strategy must take account of dependencies which requires a thorough understanding of the relationship between the equipment under test and the test environment. The main focus of this paper is on the management of measurement uncertainty because this is perceived to be the greatest impediment to achieving consistent, comparable verification test results.

II. Verification Principles

A. Rationale.

The purpose of the proposed verification strategy is to reduce the cost and risk of failure in electric propulsion verification by test by establishing an unambiguous basis for customer and supplier test requirements specification and test result evaluation. The benefits include:

- High confidence the test specification and results will be fit for purpose,
- Reducing or avoiding the risk of expensive re-test,
- A route to full traceability to international measurement standards,
- Facilitating increasing confidence in comparison between tests in different facilities and with in-orbit performance.

To be unambiguous the scope of verification testing must be consistent so that there can be comparison, to a high degree of confidence, between the results of the following different tests:

- The same equipment in the same test facility,
- The same equipment in different test facilities,
- Different equipments in the same test facility,
- Different equipments in different test facilities,
- In-orbit performance measurement.

For a valid comparison performance measurement must be to common procedures and measurement standards and to a common reference. Common procedure standards can be achieved through the application of common, agreed definitions and compliance with international measurement standards and practice. Ideally the common reference is the performance in the in-orbit environment. Alternatively it can be an agreed terrestrial test environment. In either case the measured performance must be adjusted to take account of differences between test environments.

B. Challenges.

The following challenges have been identified:

- Definitions. Definitions must be fit for purpose for electric propulsion and commonly agreed and applied; digression must be fully documented together with the rationale. It has been observed that organisations have developed interpretations of commonly used definitions which from time to time vary sufficiently to distort comparisons between test results. An example is when one plume shape measurement is to one σ of the ion current density and another measurement is to 2σ of the ion current density. Another is where instantaneous Isp is compared with Isp averaged over a period of time.
- Measurement. International measurement standards and practices are created to give a basis for consistent, traceable measurement results. The key principles and challenges are:
  1. Calibration. Traceability to international measurement standards is a fundamental requirement. Where this is not possible the effect on the measurement uncertainty must be calculated or estimated from first principles. In most cases the complexity of this task can be reduced by traceable calibration of as many aspects of diagnostic equipment that can be calibrated. For example the electronics associated with a Faraday cup can be calibrated even though this may not be possible for the collector itself. Other diagnostic devices, such as vacuum gauges and propellant mass flow meters, are notoriously difficult to calibrate and are prone to drift between calibrations. In such cases normal calibration may have to be supplemented by data from empirical tests or calculations from the literature. A lack of consistency in establishing the measurement uncertainty due to difficult or no calibration has been observed.
  2. Measurement Uncertainty. Measurement uncertainty analysis is fundamental to establishing quantified, realistic confidence levels for performance measurement. The application of uncertainty analysis is not well understood particularly for more complex aspects such as facility effects and dependencies and there is a tendency to ignore it.
  3. Dependencies. Dependencies are at the heart of most electric propulsion performance measurement. The correlation between different test parameter measurements is better understood for say the relationship between current and voltage input, propellant flow rate and thrust. Correlation between facility effects, such as background pressure and thrust, is complex and much less well understood.
  4. Margins and Confidence Levels. In reality measurement uncertainty dictates that performance can only be assessed to a confidence level; for example a 95% confidence level (2σ). If the analysis is not done correctly tolerance bands are not always set to the appropriate performance confidence levels, requirements are not based on the most efficient technical solution and testing may be made unnecessarily complex or insufficiently rigorous, leading to expensive re-test.
- Test Facility Effects. To understand how the test environment affects performance it is necessary to measure the test environment and to have a thorough knowledge of the equipment under test's susceptibility to thermal, vacuum, charging (including grounding arrangements), radiation, EMI/EMC and contamination. Current practice tends to be to set up the test facility to create a specific test environment and to record the extent to which the environment was achieved. The practice needs to be extended in two ways: to incorporate analysis of the test environment measurement uncertainty; and to use the equipment knowledge to derive the performance against a common reference.
- In Orbit Performance Measurement. In principle in-orbit performance is the standard to which all performance measurement should be referred. In practice larger measurement uncertainties may result because the scope for in-orbit diagnostic equipment is more limited and calibration more difficult.

C. Proposed Methodology.

A strategy to meet these challenges is embodied in recommendations for updating Electric propulsion Verification by Test ECSS Standards based on:

- Use of common agreed definitions,
- Fully traceable test procedures based on recognised test requirements,
- International measurement best practice for both the equipment under test and the test environment,
- A recognised, traceable methodology for referring individual test result to a common reference.
- A common understanding between customer and supplier of the test requirement, procedure, measurement practice and results.

III. Implementation

A. Definitions

The common agreed definitions require some modification and addition to those currently in ECSS-E30-Part 5.1A – Mechanical – Part 5.1 Liquid and Electrical propulsion for Spacecraft. These will be proposed for review in 2012. However, it is recognised that evolving technologies and circumstances do not allow for a perfect universal set of definitions. Conformance to the standard is generally helpful in creating confidence in results and facilitating comparison with other test results. In principle, digression, if necessary, can be managed provided that the assumptions and differences from the standard are accurately recorded.

B. Test Procedures

Test procedures must be tailored to the requirements of a particular test. The scope must include all relevant aspects of the equipment under test and the test environment. Equally important is to measure and record all the information required to give full traceability. Consultation with the European electric propulsion community has facilitated a compilation of their experience in the form of a draft handbook, entitled the Outline Instructions for Electric Propulsion verification by Test. The purpose is to offer a check-off reference for ensuring that all the elements necessary to achieve the required scope and traceability have been included in the test planning and execution. It illustrates the steps to be considered, the list of common definitions and advice on diagnostic equipment characteristics and operation. A key feature is to give advice on the management of measurement uncertainty associated with diagnostic equipments and the methodology for calculating and presenting results. The draft handbook will also be put forward for review in 2012.

C. Managing Measurement Uncertainty

1. Rationale

If customer and supplier are to have reasonable expectation that the test will be successful a preliminary measurement uncertainty analysis should be made using representative data from earlier tests or design data. If the analysis indicates that the expanded, combined uncertainty measurement margin falls outside or very close to the required tolerances the test is likely to be high risk. This provides an opportunity to identify key sources of measurement uncertainty and to investigate ways to reduce it. It also provides an opportunity to review whether the tolerances and confidence levels are fully optimised for the application and the electric propulsion equipment or if a more suitable test environment is required.

If the customer and supplier proceed without a reasonable expectation of success then the likely outcome is at best a lengthy investigation and at worst lengthy re-test, re-design or rejection of the product. The unique benefit of the preliminary uncertainty analysis is to give a quantified forecast of the measured performance margin at a defined confidence level. Analysis of the potential sources of measurement uncertainty also give the opportunity avoid overlooking and minimising the effects of important contributors. In short, it greatly increases the likelihood that we can 'know what one does not know'.

2. Practice

The measurement uncertainty for a single parameter is derived from the result of taking the measurement a number of times, establishing the mean value, corrected for any systematic error, and the standard uncertainty. The standard uncertainty is based on the standard deviation of the distribution of the readings about the mean for a purely random distribution or by dividing a uniform distribution by $2\sqrt{3}$.

In its most straightforward application the measurement uncertainty of a process is derived by summing the systematic measurement errors and taking the square root of the sum of squares of the individual measurement standard uncertainties (summation in quadrature). This establishes a corrected overall mean value and the margin of the distribution of the measurement uncertainty at a 65% confidence level. Assuming a normal distribution the margin at higher confidence levels can then be calculated.

This approach is only correct if two conditions are satisfied: the standard uncertainties are converted to the same units and the sources of measurement uncertainty are <u>not</u> inter-dependent or *correlated*.

If, for example, we use a metal ruler for measurement, errors may emanate from the calibration of the ruler and from changes in temperature. The error caused by temperature variation must be converted to how it affects the length of the ruler before calculating the overall measurement uncertainty.

3. Electric Propulsion

In space electric propulsion design is based on achieving thrust levels by the application of voltages and currents and propellant mass flow rate. The measurement of all these have their own measurement uncertainty. Similar features, coupled with the physical properties of the thruster structure are designed to give the required exhaust plume characteristics. The purpose of verification is to demonstrate that the required thrust and plume characteristics are achieved with the design inputs. At the same time performance is also affected by the test environment whose properties in turn are also a source of measurement uncertainty. To illustrate the measurement task a simplified schematic of a thrust test procedure is in Figure 1.

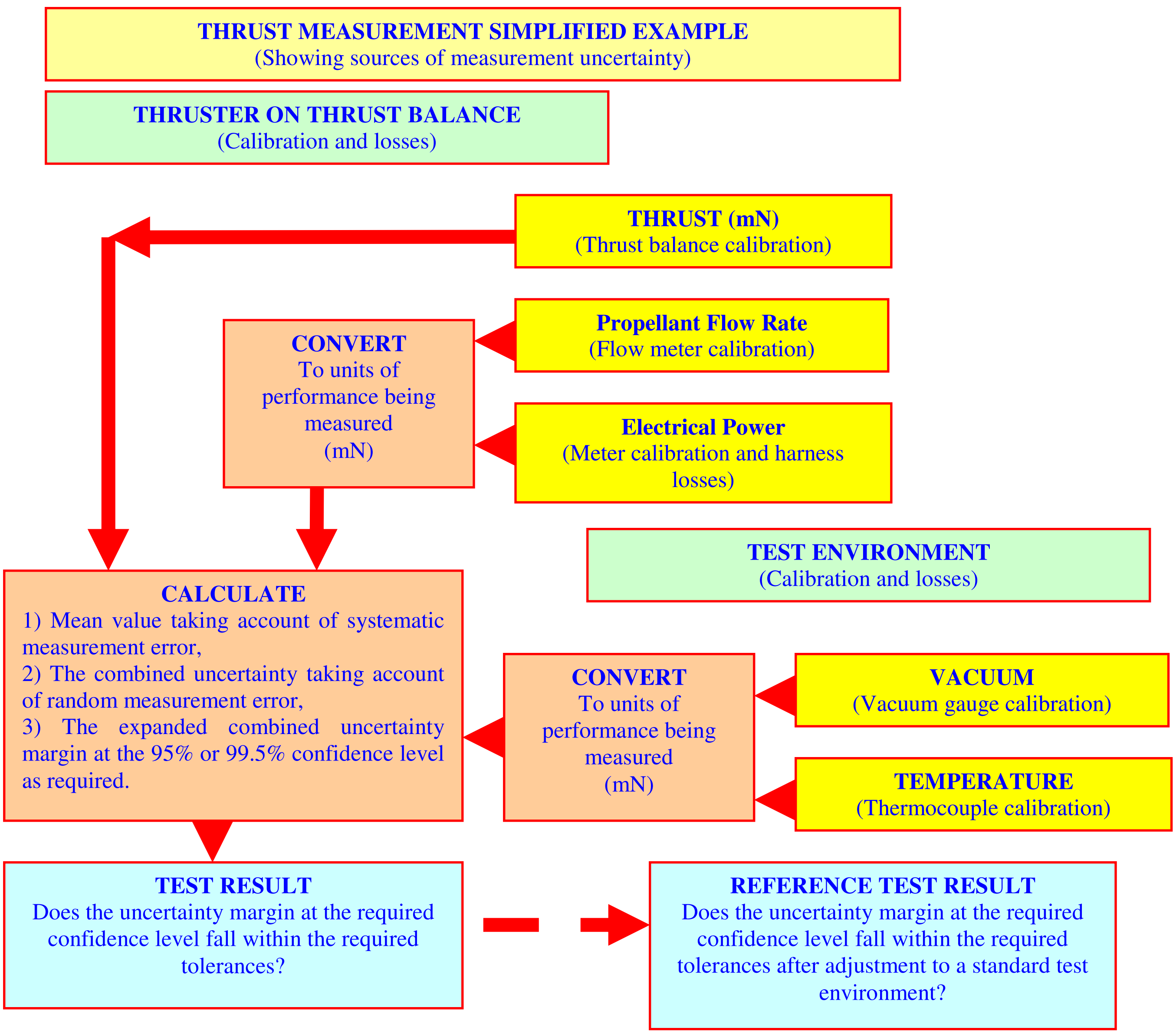

Figure 1. Schematic of Simplified Thrust measurement Process.

D. Dependencies and Correlation

1. General.

In practice, input quantities are often correlated (dependent) because the same physical measurement standard, measuring instrument, reference datum, or even measurement method having a significant uncertainty is used in the estimation of their values. Correlation can also be expected if significant systematic errors (including subjective ones) are to be considered.

A simple example is the determination of a rectangular area by measuring the length and the width with the same measuring instrument. In this case one would expect any calibration error to affect both measurements in the same way. Summation in quadrature of all the uncertainties is not necessarily valid in this case.

In any measurement process it is therefore necessary to identify dependencies and the degree of correlation between them. One must also distinguished between "logical"(non-statistical) and statistical correlation. The former is caused by a dependence of two or more quantities on one or more common ("third") quantities such as in the area measurement example. The latter appears in situations where quantities are repeatedly measured such as comparing weights, electrical resistances etc. by means of a comparator. In the latter case correlation tends to be negative and results in a decrease of uncertainty. Unfortunately in many instances "logical" correlation is positive and adds to the overall uncertainty to a degree depending on the level of correlation.

2. Applied to Electric Propulsion

For a thrust measurement, for example, account must be taken of the uncertainty in measuring both the thrust (with a thrust balance) and the applied voltages, currents and mass flow rates, at a defined operating temperature, applied to achieve it. Together the voltage, current, mass flow rate and temperature measurement uncertainties contribute to the thrust balance measurement uncertainty. (Temperature may also contribute to measurement uncertainty in both the thrust balance and the design performance of the thruster.) There are defined, logical relationships, or correlation, between the voltages, currents, mass flow rate and temperature and the thrust delivered. However it is possible for all to be measured with different diagnostic instruments, calibrated to independent standards and by different methods. Equally it could be argued that significant systematic errors can occur from say unreliable propellant mass flow rate measurement.

A common factor to consider is the method applied to convert the units, in which voltage, current, propellant mass flow rate and temperature are measured, to units of thrust to enable uncertainties to be combined. In most cases it is reasonable to assume that this is a design model validated by development testing. The relationships may be logical but complex and non-linear. If the relationships between voltage, current and propellant mass flow rate are accurately defined then correlation factors can be equally accurately defined.

In practice a similar analysis must also be applied to a wider test environment, particularly facility effects. There can be significant measurement uncertainty associated with determining the background pressure and temperature as seen by the thruster and the thrust balance. Correlation from design models and development testing is normally less easily defined and can vary for reasons such as test chamber geometry as well as vacuum gauge design, pumping characteristics, temperature profiles, sputtering or charging effects

Plume characteristic measurement for a particular thrust is subject to measurement uncertainty from all the properties contributing to a thrust measurement together with that associated with thruster physical characteristics and the plume measuring diagnostic equipment. Variation of physical properties with temperature, such as grid movement on a gridded ion engine or expansion of magnetic coils in HETs for example, must also be taken into account.

3. Managing Dependencies

Dependencies introduce unwanted complexity into the determination of measurement uncertainty and are best avoided if possible. However at first sight there would appear to be significant correlation between many of the properties to be measured to determine electric propulsion thrust or plume characteristics. A first step is to establish independence of physical measurement standard, measuring instrument or reference datum. The second step is to minimize or eliminate measurement methods having a significant uncertainty or significant systematic errors (including subjective ones). A third step is to seek independence in the methodology by which units are converted to the units in which the process is being measured; eg thrust or plume ion current density.

Independence of measurement standards, instruments of datum should be achievable in most cases. Temperature can affect several measurements but independence of measuring devices and calibration may be able to overcome this. Reducing significant measurement uncertainty and systematic errors in some cases, for example propellant flow rate or vacuum at the thruster exit plane, can be more challenging but bring huge benefit. The methodology for converting the units is highly complex and can only probably be dealt with on a case by case basis. However, it may be possible to demonstrate for some measurements that a combination of low correlation coefficient and standard uncertainties make negligible contribution to the overall (combined expanded) measurement uncertainty.

Where dependencies are unavoidable the following should be considered:

- Adding the Standard Uncertainties Arithmetically. This is the safest approach because it is based on the worst case but it leads to the highest combined uncertainty. For wide tolerances this may not present difficulties but it may make it difficult to establish required confidence levels for precision performance requirements. Inherent in this approach is the assumption that correlation is positive and adds to the combined measurement uncertainty. Independent standard uncertainties may be summed in quadrature and the square of the combined standard uncertainty added to the square of arithmetically added dependent standard uncertainties where there is a mixture of the two.
- Applying Unambiguous Correlation Coefficients. Where the correlation is well know it can be applied as an additional standard uncertainty (as a function of the individual standard uncertainties and the relationship between them) in the summation by quadrature. The advantage is that the lower the correlation coefficient the lower the combined standard uncertainty. Alternatively correlation coefficients may be given a Gaussian propagation.
- Introducing Auxiliary Quantities. Another approach is to formally introduce an auxiliary quantity that "represents" a correlated fraction of the quantity because correlation is always related to systematic effects. In some cases, if the physics of the measurement is well known, this allows the straightforward resolution of the correlation by explicitly modelling the dependence of two or more input quantities on the same systematic effect expressed by the auxiliary quantity.
- Whole System Uncertainty Modelling. Although complex for electric propulsion testing it may be possible to include known effects of correlation explicitly in the whole system measurement equations (probably in the form of a model), and either perform a Monte Carlo simulation or a GUM standard uncertainty analysis on the equations, or model, to determine combined measurement uncertainties in the normal way.

4. Summary

The complexity of applying uncertainty analysis to electric propulsion verification testing is not underestimated but it can be made manageable. The first principle is to ensure that all potential sources of measurement uncertainty are considered and to recognise those which are most likely to contribute significantly to the combined uncertainty. Reducing their contribution to uncertainty through calibration or other means can then pay dividends. The most difficult aspect of all is to identify and manage dependencies by making best use of design and development information.

E. Comparability

Adjustment of the measurement results to a standard test environment must be tailored to the type of comparison to be made. For repeat tests in the same facility it may be possible to demonstrate that the test environment diagnostic equipment measurement uncertainty is not significant. For comparison between terrestrial and in-orbit testing an analysis of the correlation between the test facility and the space environments effect on the electric propulsion equipment will be essential. For comparisons between tests in different terrestrial test facilities a corresponding correlation will also be required. The precaution of a preliminary analysis using representative data from previous tests or design data can reduce the risk of inappropriate correlation and unmanageable measurement uncertainty.

Comparability can be significantly helped if the correlation coefficients derived for the uncertainty analysis associated with test facility effects form the basis of comparison between different test environments. As increasing information about in-orbit performance becomes available there is scope to extend the correlation to in-space performance. This opens the way to a universal basis for performance comparison. It is considered that sufficient electric propulsion verification test and in-orbit data now exists for the validity of such an approach to be investigated.

IV. CONCLUSIONS AND RECOMMENDATIONS

A strategy for better electric propulsion verification testing is recommended to convince the space community that the technology is affordable at acceptable risk and very competitive. Study of current practices concludes that relatively modest improvements to definitions and test procedures are required in the majority of cases. The main source of improvement depends upon the acceptance of international measurement practice, particularly in the form of measurement uncertainty analysis. By understanding the causes of measurement uncertainty their effects can controlled or minimised to achieve higher quality, first time results while minimizing lengthy and expensive testing. The principles also can be extended to improve the comparability of tests in different test facilities and with in orbit performance.

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