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Development and Status of Data Quality Assurance Program at NASA Langley Research Center — Toward National Standards

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Abstract

As part of a continuing effort to re-engineer the wind-tunnel testing process, a comprehensive data quality assurance program is being established at NASA Langley Research Center (LaRC). The ultimate goal of the program is routine provision of tunnel-to-tunnel reproducibility with total uncertainty levels acceptable for test and evaluation of civilian transports. The operational elements for reaching such levels of reproducibility are: (1) *statistical control*, which provides long-term measurement uncertainty predictability and a base for continuous improvement, (2) *measurement uncertainty prediction*, which provides test designs which can meet data quality expectations within the system's predictable variation, and (3) *national standards*, which provide a means for resolving tunnel-to-tunnel differences. The paper presents the LaRC design for the program and discusses the process of implementation.

Introduction

About three years ago, the NASA Langley Research Center (LaRC) wind-tunnel establishment committed itself to a cultural shift from largely supporting the internal research of individual Branches, each organized around one or more wind tunnels, to supporting national programs developed in partnership by various NASA centers, other government organizations and industry. This shift has required entirely new levels of customer trust in the results produced by the tunnels[1] and led to consolidation of tunnel assets, originally involving eight different facility cultures in five Branches (Figure 1), into a single Research Facilities Branch (RFB) in the Aerodynamics Division (AD).

The consolidation was accompanied by a far-reaching change agent, *Re-Engineering Wind Tunnel Testing at LaRC*. The re-engineering effort[2,3] has been specifically tasked with developing a uniform customer-focused culture, increasing tunnel productivity, reducing costs and test process time, and improving data quality[†] to levels suitable for national standards.

Out of the initial re-engineering design work, five major efforts having an influence on data quality assurance DQA) were established:

- Test Processes
- Information Management
- Wall Interference and Correction
- Facility Operations and Implementation
- Measurement Uncertainty

Each team is accountable for identifying current practice for, standardizing, documenting and improving all of the processes assigned to it. The teams are also responsible for any training and certification required for the processes for which they are accountable. In this paper, I will describe RFB work involved in measurement uncertainty and statistical control only, although all of the re-engineering effort, including the work of several other divisions which support the wind tunnels, has an impact on the data quality assurance (DQA) program.

The key elements of the LaRC DQA program, as it is understood now, are presented in the next section. The program consists of four phases (Figure 2) which have been considerably revised and expanded during the two years since the beginning of the present level of effort as the participants have learned more about measurement uncertainty practice in the real world of high-productivity wind-tunnel testing and have begun to determine the process changes which appear to be required to achieve the program goals.

The Key Elements description is followed by four

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†For the purposes of this paper, the measurement uncertainty goals are the levels which would be acceptable for test and evaluation of civilian transports. For example, typical single-test *total* uncertainty requirements for the lift, pitching-moment and drag coefficients at transonic cruise conditions might be ±0.01, ±0.001 and ±0.0001 respectively.

sections describing the implementation so far of each phase of the project. The paper concludes with a final comment. The nomenclature used is intended to be consistent with the definitions used in references 4-7.

Key Elements of the Program

Statistical Control

The operational philosophy underlying the new program is the *measurement process* as taught by Churchill Eisenhart[8] and his colleagues[6,9] at the former National Bureau of Standards (NBS), now the National Institute of Standards and Technology (NIST). Eisenhart's distinction of a measurement process is derived from the *statistical control* and continuous improvement work of Shewhart[10] and his famous successor, W. Edwards Deming[11]. Although Eisenhart was referring to instrument calibration systems[8], his definition applies just as well to the system composed of the wind tunnel, its instrumentation and data systems, the personnel running the systems and performing the procedures, and the metrology support system. Since he defined the distinction so eloquently[8], I will simply quote him here:

> "Measurement is ordinarily a repeatable operation, so that it is appropriate to regard measurement as a production process, the 'product' being the numbers, i.e., the measurements, that it yields; and to apply to measurement processes in the laboratory the concepts and techniques of statistical process control that have proved so useful in the quality control of industrial production.
>
> "Viewed thus it becomes evident that *a particular measurement operation cannot be regarded as constituting a measurement process unless statistical stability of the type known as a state of statistical control has been attained.*"

(The italics are mine.) In reference 6, Taylor and Oppermann of NIST define statistical control to be *"the attainment of a state of predictability* [such that] *the mean of a large number of measurements will approach a limiting value (limiting mean) and the individual measurements should have a stable distribution, described by their standard deviation."*

Clearly, wind-tunnel testing is a process and all processes have inherent variation. Data quality assurance is basically the structure with which that process is managed to produce measurement uncertainty levels which are in statistical control within the limits desired. The biggest advantage of this approach is that such a measurement process is predictable.

For the LaRC DQA program, the core measurement process is the acquisition of a data polar, i.e. a sequence of data points taken in a prescribed manner with just one of the independent variables changing. The most typical polar in RFB is an angle-of-attack sweep with angle of sideslip, Mach number, Reynolds number and configurational geometry held nominally constant. Following the definition given in reference 7, the repeatability of this process is found by repeating the polar over a *short time* with no changes to the system. Hence, the repeatability is found by obtaining back-to-back polars with unchanged conditions except for the cycling of the one independent variable which is allowed to change.

Such repeatability, of course, is insufficient for either incremental or absolute testing and a hierarchical sequence of such processes yielding the desired *reproducibility*[7] over time and space must be considered. The reproducibility sequence that LaRC intends to use to establish and maintain statistical control is given in Figure 3. Back-to-back polars and repeats of those data sets over the course of a test entry are not sufficient to establish statistical control for the rest of the reproducibility hierarchy since the limiting mean would change with each model tested. Hence, it is necessary to use a check standard model in each tunnel to determine reproducibility for multiple entries and national check standards for establishing tunnel-to-tunnel reproducibility. This approach is, of course, just standard practice at a NIST-qualified laboratory.[6]

A secondary, but no less valuable, advantage of the statistical control approach is that economical and predictable continuous improvement can be planned and carried out.

Measurement Uncertainty Prediction (and Reporting)

The second critical element of the LaRC program is an insistance on measurement uncertainty prediction early enough in the test planning process to allow for a proper selection of instrumentation, test strategy, and, if necessary, test objectives.[4,12,13] The importance of credible prediction in the satisfaction of customer expectations cannot be emphasized too strongly.

National Standards

The third critical element of the LaRC program arises from the realization that the ultimate goal for a wind-tunnel measurement uncertainty standard must be tunnel-to-tunnel reproducibility for the same model (national check standard) corrected to the same free-air conditions. Resolution of any discrepancies will involve not only credible statements of measurement uncertainty for each tunnel engaged in the comparison but also will demand some sort of agreement (i.e. national standards) to resolve residuals.

Implementation Phases

With the above three legs driving the program, together with a need to get interim results as soon as possible, not only for customer negotiations but also to help support the creation of a uniform culture oriented toward statistical thinking and customer satisfaction, the decision was made to divide the program implementation into the following four phases (Figure 2):

I. Simplified Uncertainty Prediction and Reporting
II. Detailed Uncertainty Analysis and Statistical Control
III. Certification and National Standards
IV. Continuous Improvement

with work presently proceeding on Phases I and II simultaneously. As part of Phase II, the Test Processes Team is working to delineate all of the important processes involved in the wind-tunnel testing enterprise with the goal being to determine what's so now and to eventually standardize the processes for the purpose of statistical control as meant by Eisenhart, Shewhart and Deming. Of course, RFB's experience is that the sum total of processes for each tunnel has attained some level of statistical control even if it is not known exactly what that level is. So the program participants are refraining from "tampering" (in the sense of Deming[14]) with the present processes affecting measurement uncertainty until the work of the Test Processes Team is complete.

Phase I - Simplified Uncertainty Prediction and Reporting

Phase I could also be called "Getting Started." Although considerable effort[15-20] in the areas of assessing measurement uncertainty and improving data quality had been conducted in the National Transonic Facility prior to the formation of the Research Facilities Branch and the start of the present program, no comprehensive *systemic* changes had been implemented. Adopting the point of view that statistical thinking and designing wind-tunnel tests using uncertainty analysis are fundamental paradigm shifts,[21] the program participants elected to proceed using a bootstrap process somewhat similar to historical cultural shifts in the area of precision measurement.[22] Such shifts have usually proceeded through phases similar to those adopted for the LaRC program: (1) recognition of the need and the first, somewhat crude (in hindsight), efforts, (2) increased attention on the complexity of the problem and improved analysis and control of the process, (3) resolution of lingering conflicts through the development of standards, and (4) continual improvement as understanding increases and better instrumentation becomes available.

It should be understood that the personnel developing and implementing the program had either no prior or only modest experience with or training in statistical thinking[8-11,14] or modern measurement uncertainty.[4,12,13,23] Hence, the bootstrap process also allowed personnel to implement first-order assessment methods while simultaneously learning appropriate strategies and gathering increasingly detailed information about the tunnel systems and procedures.

The actual steps followed in Phase I were as follows:

1. Presentations of the short course, "Experimentation and Uncertainty Analysis," by Hugh W. Coleman and W. Glenn Steele, Jr., to all RFB test engineers and data specialists and about half of the AD researchers.
2. Application of General Uncertainty Analysis[4] to specific tests with difficult measurement uncertainty requirements.
3. Creation of spreadsheets for each tunnel for prediction of total uncertainty and single-test repeatability based on a simplified analysis.
4. Adoption of an interim RFB Data Quality Prediction and Assessment Procedure.

Presentation of Short Course

The short course presentations in the Summer and Fall of 1994 brought about a general increase in awareness of the subject of measurement uncertainty and the distinctions of bias, precision and uncertainty propagation for derived quantities. However, the heightened awareness did not bring about a general increase in measurement uncertainty activity and it became clear that training without application and appropriate management direction would be insufficient.

Application of General Uncertainty Analysis to Specific Tests

In the Fall of 1994 and the Spring of 1995, four tests in three different tunnels were supported with simplified uncertainty analysis predictions in the spirit of the General Uncertainty Analysis for test planning suggested in Chapter 3 of reference 4. Such an analysis ignores the details of the bias and precision components and concentrates on the effect of each instrument's overall contribution to the uncertainty of the derived coefficients of interest. Despite the simplified nature of the prediction methodology, it was clear to the test engineers and customers that the chosen instrumentation for each test would be inadequate to achieve the stated test objectives. In two cases, the instrumentation was changed. In the rest, the test objectives were changed.

The importance of these initial applications of the simplified analysis should not be underestimated. The results led to a heightened awareness of the value of predictions however crude, to a sense of urgency in program implementation, and, ultimately, to the decision to implement as quickly as possible the simplified methodolgy for prediction *and* reporting for all of the RFB tunnels. It is understood that this interim approach does not conform to present standards for reporting measurement uncertainty,[7, 23-25] but it does allow LaRC to derive considerable benefits from its present, immature, knowledge while the detailed information and statistical control needed for reporting according to the standards is obtained.

Spreadsheets for Simplified Analysis

The uncertainty prediction spreadsheets are based on the notion of a General Uncertainty Analysis[4] as noted in the previous subsection. The spreadsheets are based on a simple model of the data reduction process for measurement of forces and moments corrected for base and cavity pressure effects, but not corrected for wall or support interference. For example, the instruments included in the simple model for a typical transonic tunnel test are the six components of the force balance, the angle-of-attack sensor, the base and cavity pressure sensors, the tunnel total pressure, the static pressure in the plenum which surrounds the slotted test section, and the tunnel total temperature. For total uncertainty predictions, bias and precision limits for each instrument are lumped together in a single number estimated by agreement of the test engineers in each facility. The spreadsheets display on each page the effect of the uncertainty of each instrument, reference quantity and transfer distance on the uncertainties of the tunnel parameters and the derived coefficients of interest for a single set-point condition.

The effect of the total uncertainty prediction is mostly tutorial, i.e. it serves to educate the customer and test engineer to probable test-to-test and tunnel-to-tunnel reproducibility problems. The same spreadsheets are also used to estimate single-test reproducibility. These predictions are presently made for three reasons: (1) some of RFB's customers have specific single-test reproducibility requirements and need to be informed if the selected instrumentation and test conditions will meet their objectives, (2) a set of reproducibility measurements made during the test can be used to test and update the simplified prediction model, and (3) the knowledge that a test's uncertainty objectives are difficult but possible to meet based on previous facility experience alerts test personnel to use procedures which are known to produce the best data quality but which may consume significantly more time. It has not been uncommon for a customer to have to accept a reduction in the size of the test matrix and/or a change in the test conditions to meet uncertainty objectives.

Interim Data Quality Assessment Procedure

It is the interim policy of the Research Facilities Branch that the following four types of simplified analyses should be performed for each wind-tunnel test:

1. *Pre-Test Prediction of Total Uncertainty* - Use the simplified uncertainty propagation equations (see previous subsection), together with estimates of the total uncertainty for each primary measurement process in the equations. This analysis is especially important for customers who are interested in using the data for CFD validation, for development of data bases for simulations, or for test technique development, e.g. semispan testing.

2. *Pre-Test Prediction of Reproducibility During a Single Test Entry* - Use the simplified uncertainty propagation equations, together with estimates of the precision for each primary measurement process in the equations. This analysis estimates the reproducibility likely to be achieved during the test, especially if it is based on historical data for that tunnel.

3. *Post-Test Reproducibility Analysis* - Analyze the set of repeat polars obtained during the test so that the range of variation can be estimated to one significant figure. This result, and how it was obtained, should be included in the data transmittal and stored in the tunnel archives for interim tracking of statistical control. The suggested repeat-polar schedule is to obtain three back-to-back polars at the beginning, middle and end of the test (nine polars in all) on a baseline configuration and a set of test conditions of greatest interest to the customer. If a suitable repeat-polar set is not obtained, no uncertainty statement will be included in the data transmission to the customer.

4. *Post-Test Statement of Bias Limits*- Use the simplified uncertainty propagation equations to estimate the bias limit for each derived quantity of interest (usually the balance coefficients, Mach number,

Reynolds number and angle of attack) using the best available guess of the measurement process biases. This information should be included on the data transmittal file if the customer so desires. (See caveat in previous paragraph.)

Phase II - Detailed Uncertainty Analysis and Statistical Control

The purpose of a detailed uncertainty analysis is to investigate the contributions of the individual bias and precision error sources and combine them into overall bias and precision limits for the (derived) experimental results of interest.[4] This is a huge task for a typical wind-tunnel operation and the LaRC program has just begun to go beyond the simplified analyses described above. Batill[15] conservatively estimated that 250,000 pieces of information are acquired and processed to make a single drag-coefficient calculation at the National Transonic Facility. Consequently, it seems appropriate to continue the bootstrapping process originally adopted. In other words, the program will attempt to obtain an increasingly more accurate model of the measurement process in an iterative manner, considering the most obvious sources of variability first.[26] Of course, such models will be meaningless if statistical control is not demonstrated for each level considered.[9]

The four major elements of the RFB plan (Figure 4) for achieving and monitoring statistical control are (1) tunnel calibration, (2) test-section flow characterization, (3) characterization of wall and support interference, and (4) characterization of precision and bias limits. The individual elements are discussed in the following subsections, together with appropriate time scales for each activity (Figure 4).

Tunnel Calibration

There are many activities associated with what is called "Tunnel Calibration" at LaRC. But here we shall consider only those measurements which are connected with determining and monitoring the calibration constants for derivation of the test-section Mach number and dynamic pressure and for estimating the empty test-section axial pressure gradients (Figure 5). For subsonic and transonic tunnels, the calibration constants and axial pressure gradients would be inferred from infrequent (every five to ten years) centerline pipe measurements. In the past, such measurements would be obtained once for each set of tunnel conditions of interest. In the future, such measurements should be repeated over several tunnel and data acquisition system cycles to help determine the uncertainty of the constants.

For statistical control of the tunnel, measurements should be taken at least annually to check the calibrations.[27] In this regard, LaRC intends to use centerline pitot-static probes, following the approach used at the Boeing Transonic Wind Tunnel.[27] The probes should be considered to be working standards and should be treated with great care.[27]

Test-Section Flow Characterization

Figure 6 shows four flow-characterization activites that are considered to be important in the LaRC DQA program for statistical control and measurement uncertainty. The use of model check standards to annually obtain upwash and sidewash on the tunnel centerline and the location of boundary-layer transition help to establish test-to-test reproducibility levels and verify statistical control. Once an historical data base has been obtained, the annual measurements can be used to determine if action is required to clean the screens, etc., during the next maintenance period.[27]

Test-section flow-field surveys, conducted on an infrequent basis (see Figure 4), are helpful for a variety of experiments which are not conducted on the tunnel centerline. For example, the results can be used to make rough estimates of bias due to local flow angularity and can point to possible improvements in the flow-straightening system.

Although no such effort has been yet established at LaRC, it is believed that on-line monitoring of flow quality at selected locations would be helpful in determining critical aspects of process variation and point to possible out-of-statistical-control situations.

Characterization of Wall and Support Interference

A full discussion of present LaRC activities in wall and support interference is beyond the scope of this paper. However, it is clear that certain statistical control activities are required (Figure 7). First, it is imperative that the correction models used be checked on an infrequent basis (Figure 4) by testing different sizes of some check standard. Secondly, the reproducibility of the corrections should be checked frequently. This entails testing both with the tunnel empty and with a check standard installed.

Characterization of Precision and Bias

Reproducibility sufficient for a credible measurement uncertainty statement depends, at a minimum, on traceable configuration control and repeat-polar measurements during a test entry as shown in Figure 8. It seems also rather clear that frequent tests of a check standard and regular recalls of instrumentation are necessary for statistical control. But it should also be apparent that some kind of statistical control must be established for the execution of procedures by test personnel. In this regard, standardization of procedures, clear and easy-to-use documentation, and frequent training and certification are necessary. If possible, regular random checks on the output of critical procedures should be conducted. If a range of individuals are involved in the execution of a given procedure, it is important that the variation across the set of individuals be established.

Phase III - Certification and National Standards

Although no significant work has been conducted in Phase III, it is believed that the elements shown in Figure 9 are required, as a minimum, to establish credible tunnel-to-tunnel reproducibility. To the author's knowledge, nothing like this in the area of wind-tunnel testing has been achieved before. Yet it seems essential if today's data quality requirements are to be met. Any effort in this area will likely require that credible statistical control, according to some kind of national standard, be established for each tunnel participating. Furthermore, a committee would have to be created to resolve the residuals left after the testing of national check standards. The resolution would probably lead to the selection of a composite standard to which all of the tunnels are biased by a known correction together with its uncertainty.

Phase IV - Continuous Improvement

At the end of Phases I and II and statistical control will have been achieved, the data quality limits of present instrumentation and processes will have been reached and further improvement in data quality levels is unlikely without fundamental changes in processes or major instrumentation. In this regard, the author suggests using the Shewhart Cycle[14,28] for rational, economical, continuous improvement (see Figure 10). The value of the Shewhart approach (known as the Deming Cycle in Japan) has been demonstrated repeatedly in complex industrial processes and should prove just as valuable for wind-tunnel testing.

Final Comment

The Data Quality Assurance program described in this paper is composed of many elements, all of which have been described previously in the literature or are being used in other facilities (e.g. the Boeing Company[27]). Hence, none of them are new. The chief contribution of the LaRC program has been to use simplified analyses to get started and to emphasize statistical control in the manner promoted by the National Institute of Standards and Technology.

Having said that, I feel compelled to underscore here several points made in the paper:

1. The implementation (and even conception) of a data quality program of the type described here involves a cultural change of huge proportions. The problem is that, at the beginning, it will not appear to be a shift (and, hence, require new thinking) to the participants. Consequently, training by itself is insufficient. All involved will have to apply the ideas and methods in various situations to apprehend the purposes and techniques of the program.

2. Although the major authors in the engineering application of measurement uncertainty[4,12,13,23] have repeatedly stressed the value of uncertainty predictions in the design of experiments, it is not yet an idea whose time has come. Let me just say that it has been the program participants' experience that even the simplest measurement uncertainty analysis produces value far beyond the effort required.

3. Viewed under the Eisenhart, et al, spotlight, it becomes obvious that *changes* in wind-tunnel testing measurement uncertainty levels for a system in statistical control cannot be produced on demand (e.g. "Quality by Exhortation"). Since credible measurement uncertainty levels are a product of a process in statistical control, they can only be improved by making systemic changes in the process itself.[10,11]

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References

[1]Rubbert, Paul E., "CFD and the Changing World of Airplane Design," AIAA Wright Brothers Lecture, ICAS-94-0.2, September 1994.

[2]Putnam, L. Elwood, "Wind Tunnel Productivity and Improvement Activities at Langley Research Center," AIAA Paper 96-2260, June 1996.

[3]Putnam, L. Elwood, "Re-Engineering Wind Tunnel Testing at NASA LaRC," *Symposium of the International Test and Evaluation Association*, Huntsville, AL, October 2-5, 1995.

[4]Coleman, Hugh W., and Steele, W. Glenn, Jr., *Experimentation and Uncertainty Analysis for Engineers*, Wiley, 1989.

[5]Castrup, H. T, et al, "Metrology---Calibration and Measurement Processes Guidelines," NASA RP 1342, June 1994.

[6]Taylor, John K., and Oppermann, Henry V., "Handbook for the Quality Assurance of Metrological Measurements," NBS Handbook 145, November 1986.

[7]Taylor, Barry N., and Kuyatt, Chris E., "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," NIST TN 1297, 1994 Edition.

[8]Eisenhart, Churchill, "Realistic Evaluation of the Precision and Accuracy of Instrument Calibration Systems," in *Precision Measurement and Calibration,* Harry K. Ku, Editor, NBS SP 300, Vol. 1, February 1969.

[9]Mandel, John, *The Statistical Analysis of Experimental Data*, Dover, 1984.

[10]Shewhart, Walter A., *Statistical Method from the Viewpoint of Quality Control*, Dover, 1986.

[11]Scherkenbach, William W., *The Deming Route to Quality and Productivity,* CEEPress Books, 1991.

[12]Moffat, Robert J., "Using Uncertainty Analysis in the Planning of an Experiment," *Journal of Fluids Engineering*, Vol. 107, June 1985, pp. 173-178.

[13]Kline, S. J., "Closure on 1985 Symposium on Uncertainty Analysis," *Journal of Fluids Engineering*, Vol. 107, June 1985, pp. 181-182.

[14]Deming, W. E., *Out of the Crisis,* MIT Center for Advanced Engineering Study, 1982.

[15]Batill, Stephen M., "Experimental Uncertainty and Drag Measurements in the National Transonic Facility," NASA CR 4600, June 1994.

[16]Wahls, Richard A., Adcock, Jerry B., Witkowski, D. P., and Wright, Frank L., "A Longitudinal Aerodynamic Data Repeatability Study for a Commercial Transport Model Test in the National Transonic Facility," NASA TP 3522, August 1995.

[17]McPhee, J. R., "Electrical Noise Reduction Techniques Contributing to Improved Data Quality at the National Transonic Facility," NASA CR 4193, November 1988.

[18]Stewart, Pamela N., "Data Quality Analysis at the National Transonic Facility," NASA CR 4303, July 1990.

[19]Al-Saadi, Jassim A., "Wall Interference and Boundary Simulation in a Transonic Wind Tunnel With a Discretely Slotted Test Section," NASA TP 3334, September 1993.

[20]Kemp, William B., Jr., "Wall Interference Assessment in NTF Using Tared Wall Pressures," Final Report for NASA Contract NAS1-18585, ViGYAN, September 1991.

[21]Kuhn, Thomas S., *The Structure of Scientific Revolutions,* 2nd Ed., University of Chicago Press,, 1972.

[22]Wise, M. Norton, Ed., *The Values of Precision,* Princeton University Press, 1995.

[23]Abernethy, R. B., et al, "Measurement Uncertainty," ANSI/ASME PTC 19.1-1985.

[24]Anon., "Guide to the Expression of Uncertainty in Measurement," International Organization for Standardization (ISO), 1993.

[25]Anon., "Assessment of Wind Tunnel Data Uncertainty," AIAA Standard S-071-1995.

[26]Belanger, Brian, "Measurement Assurance Programs: Part I - General Introduction," NBS SP-676-I, May 1984.

[27]Wright, Frank L., Private Communication, June 1995.

[28]Holmes, Susan, and Ballance, Judy, Eds., *Process Improvement Guide,* Air Force Quality Institute, (2nd Ed.), September 1994.

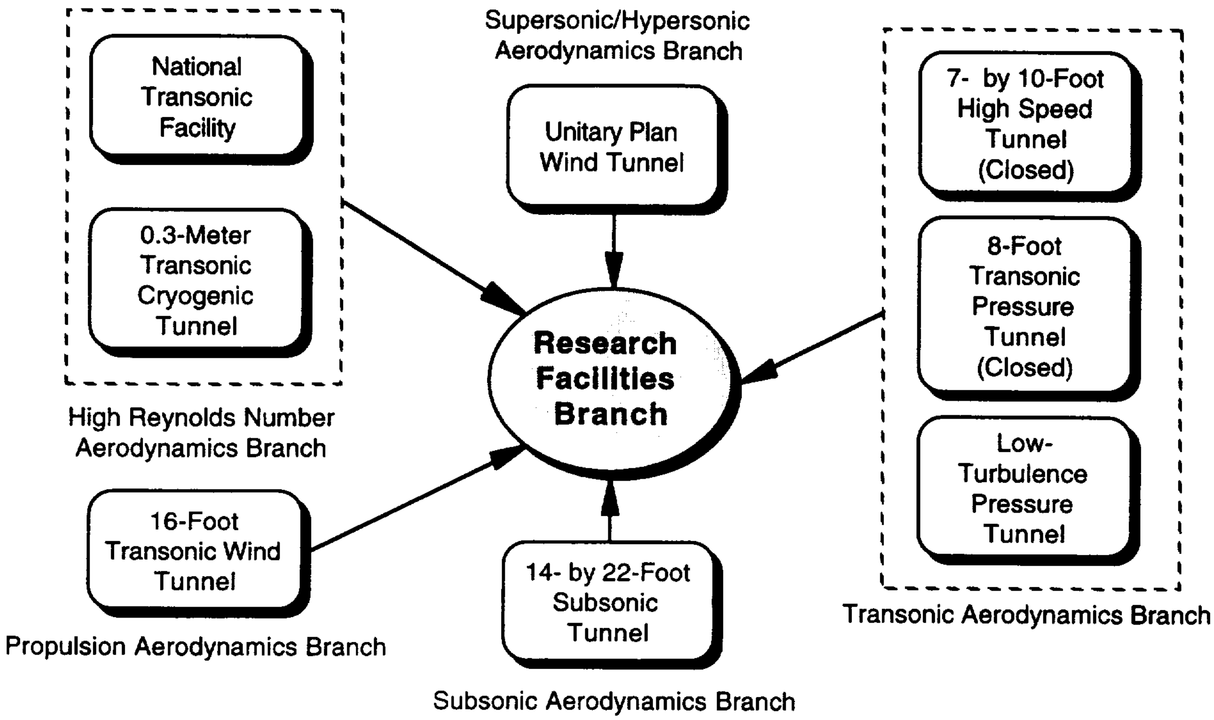

Figure 1. - 1994 Consolidation of LaRC Aerodynamics Division Wind Tunnels.

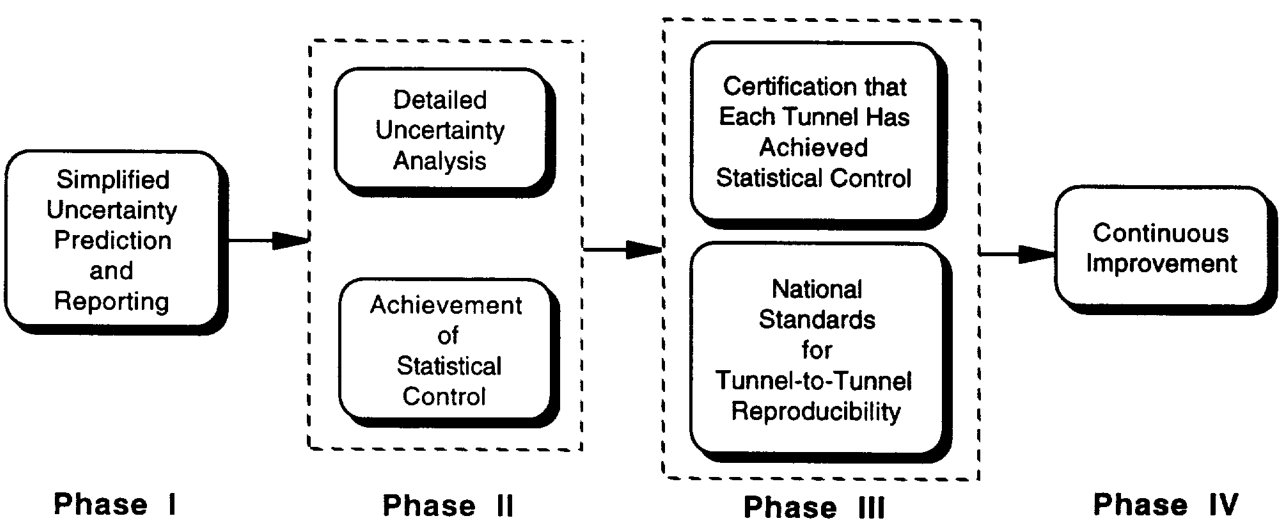

Figure 2. - Implementation Phases of LaRC DQA Program.

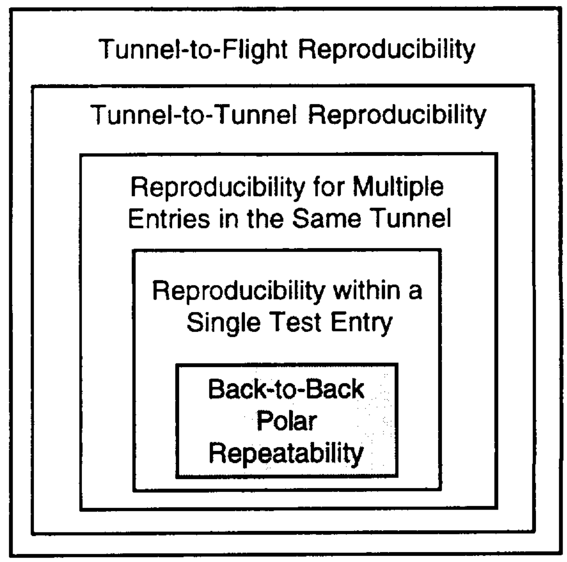

Figure 3. - Hierarchy of Reproducibility Levels Required for Incremental and Absolute Testing

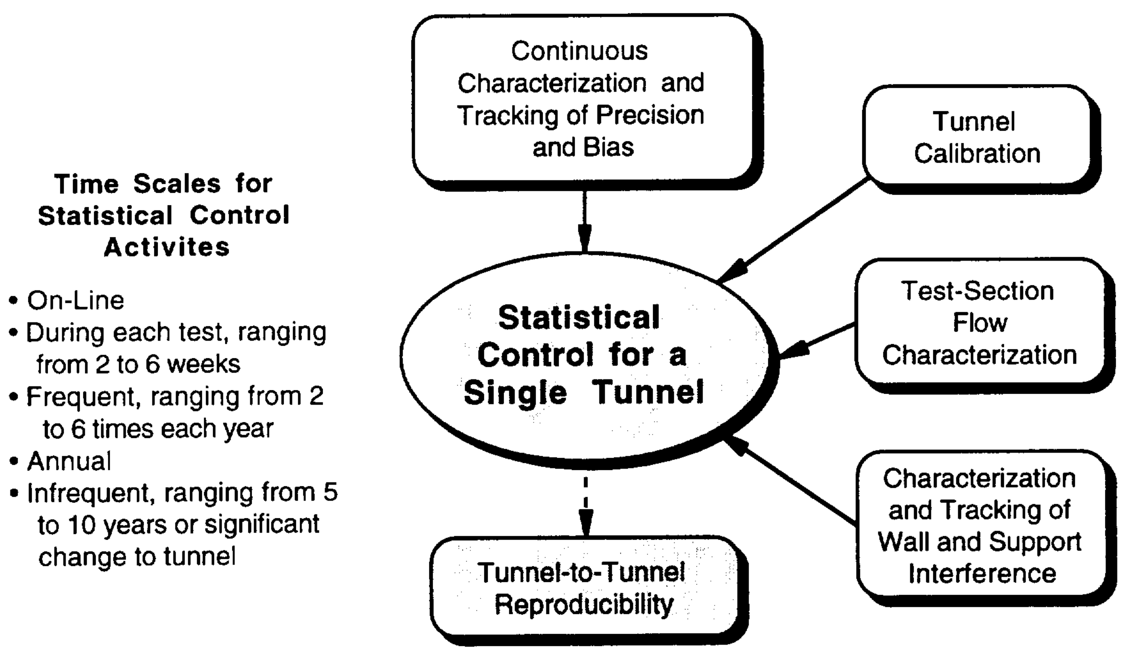

Figure 4. - Phase II - Major Statistical Control Activities and Definition of Associated Time Scales.

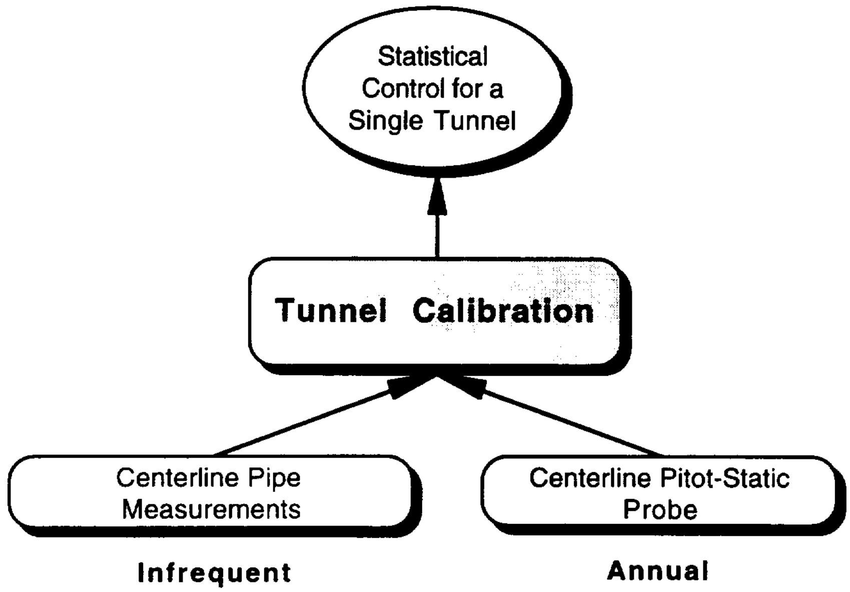

Figure 5. - Elements of Tunnel Calibration Activity

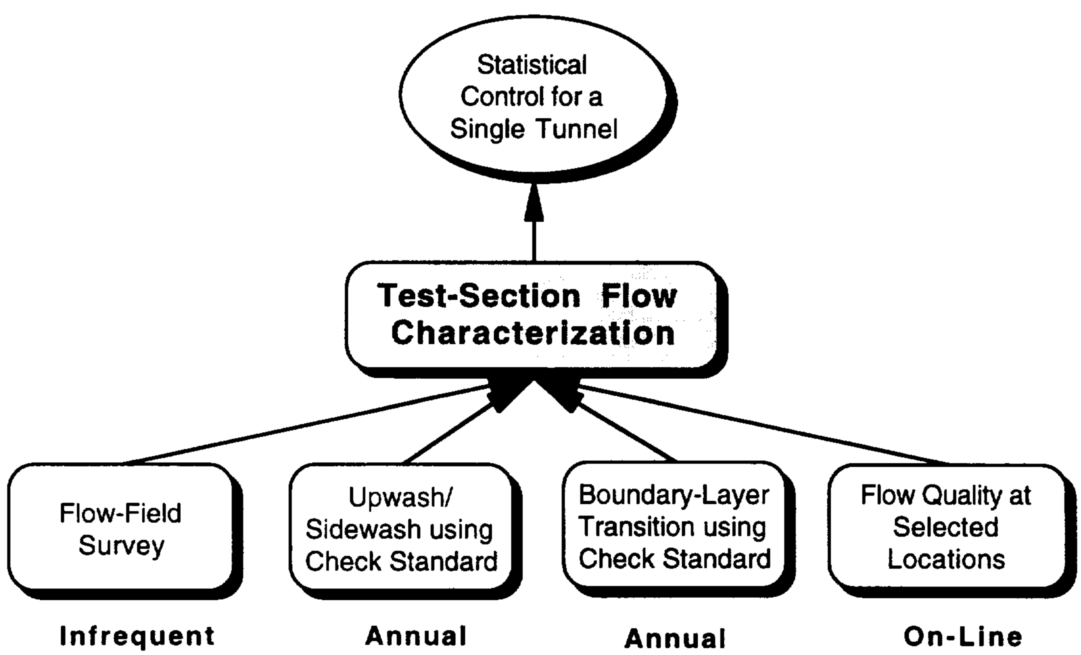

Figure 6. - Elements of Test-Section Flow Characterization Activity

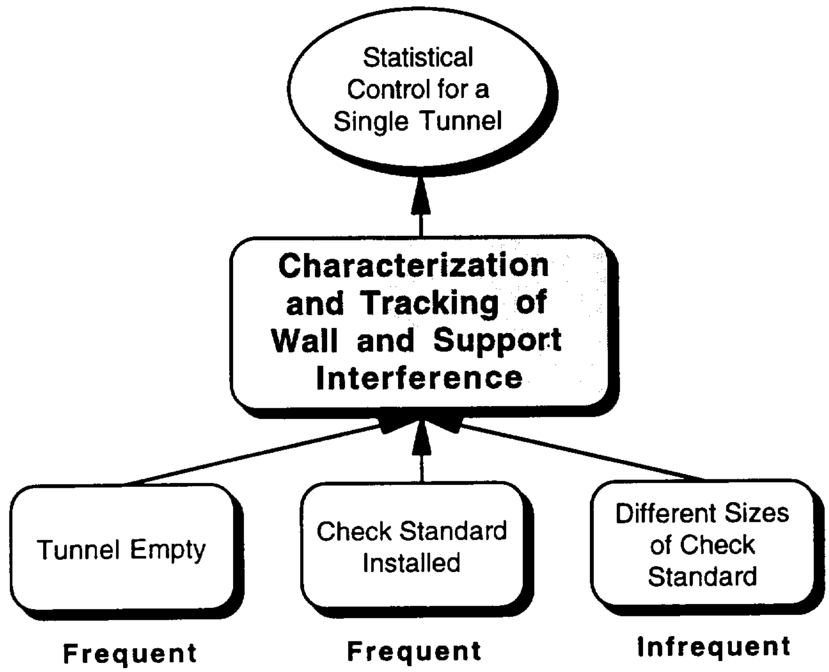

Figure 7. - Elements of Characterization and Tracking of Wall and Support Interference

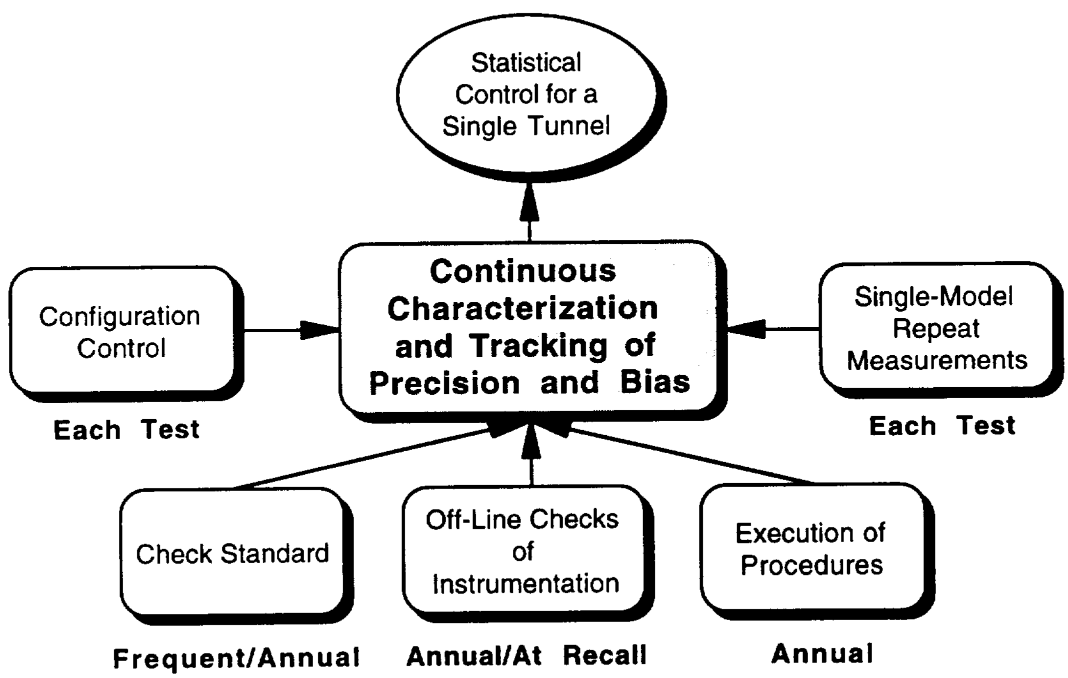

Figure 8. - Elements of Continuous Characterization and Tracking of Precision and Bias

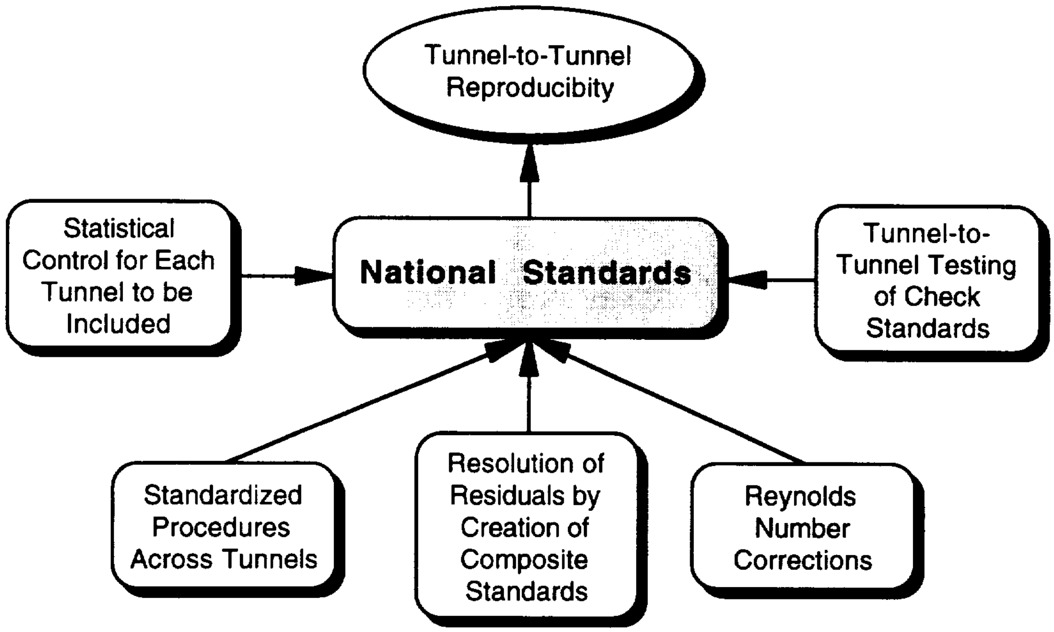

Figure 9. - Phase III - Creation of National Standards and Tunnel-to-Tunnel Reproducibility

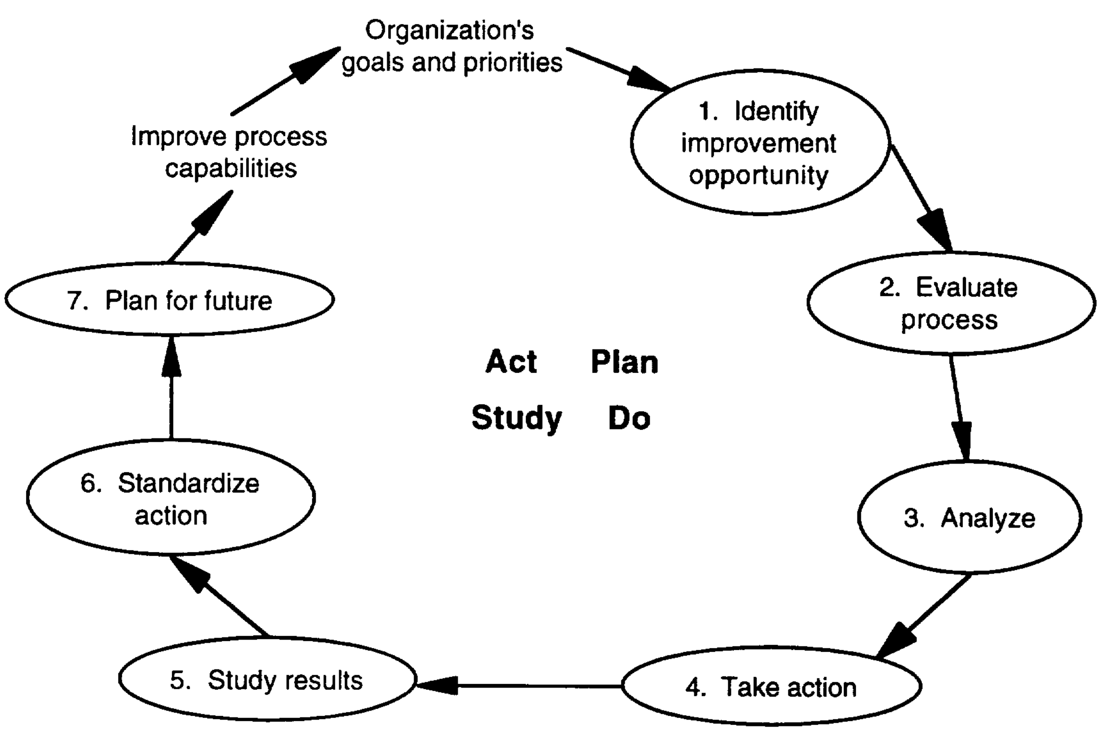

Figure 10. - Phase IV - Implement Shewhart/Deming Cycle for Continuous Improvement.