Enclosure 6

ON-ORBIT METROLOGY AND CALIBRATION REQUIREMENTS FOR SPACE STATION ACTIVITIES DEFINITION STUDY

FINAL REPORT

BY

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FOREWORD

The work described in this report was conducted by Martin Marietta Manned Space Systems, New Orleans, Louisiana 70189 for the National Aeronautics and Space Administration, Space Station Freedom Program Office, Reston, Virginia in accordance with the requirements of Contract NAS14-303. The objective of this program was to evaluate the on-orbit metrology and calibration requirements for the Space Station. The period of performance for this contract was November 1, 1988 to April 30, 1989.

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EXECUTIVE SUMMARY

The National Aeronautics and Space Administration is in the process of initiating an operational Space Station during the 1990s. The Space Station is the focal point for the commercial development of space. The long term routine operation of the Space Station and the conduct of future commercial activities suggests the need for in-space metrology capabilities analogous when possible to those on-earth. The ability to perform periodic calibrations and measurements with proper traceability is imperative for the routine operation of the Space Station. An initial review, however, indicated a paucity of data related to metrology and calibration requirements for in-space operations. This condition probably exists because of the highly developmental aspect of space activities to-date, their short duration, and nonroutine nature.

The primary objective of this study was to understand and assess the on-orbit metrology and calibration needs of the Space Station. In order to achieve this goal, the following specific tasks were performed.

- Task 1, Performance of Up-To-Date Literature Review;
- Task 2, Identification of On-Orbit Calibration Techniques;
- Task 3, Identification of Sensor Calibration Requirements;
- Task 4, Identification of Calibration Equipment Requirements;
- Task 5, Definition of Traceability Requirements;
- Task 6, Preparation of Technology Development Plans; and
- Task 7, Preparation of Final Report.

In the following paragraphs of this section, significant information and major highlights pertaining to each of the tasks is separately presented. In addition, some general (generic) conclusions/ observations and recommendations that are pertinent to the overall in-space metrology and calibration activities are presented in the final paragraphs of this section.

Task 1, Literature Review

A large number of documents were reviewed as a part of this task. A majority of these documents included various NASA publications, Space Station RFP work packages, technical papers and publications available in the open literature (public domain), and equipment manufacturers' data books. Based on this literature review and discussions with Space Station prime contractors, generic measurement and calibration requirements were identified for the purpose of this study. These requirements could change as more details of the Space Station design are developed and become available.

Primary conclusions:

- ECLSS, EVA, and EPS are examples of the systems where major calibration activities will be required.
- Certain similar calibrations (for example, voltage) are required in several of the systems/subsystems.
- Review of Soviet work (available in the open literature) provided very limited definitive data.

Primary recommendations:

- Complete definitive identification of specific measurement requirements as detailed designs become available.
- Develop integrated (common) measurement requirements that incorporate all work packages.
- Prepare an on-orbit metrology design guide.

Task 2, On-Orbit Calibration Techniques

From the generic measurement requirements identified in Task 1, specific measurement parameters (potential range and accuracy) for each category were derived from pertinent, available NASA documents. In cases where this information was not available, other related publications were utilized. Based on this information, identification of measurement/calibration techniques and an assessment of their on-orbit applicability were performed. State-of-the-art as well as some emerging techniques were included in this evaluation.

Primary conclusions:

- Calibration techniques for several measurement categories are currently available, though not in a completely optimized condition.
- Calibration techniques for some measurement categories (for example, mass, micro-g) are either not currently suitable or need to be developed

Primary recommendations:

- Conduct detailed evaluation of current calibration techniques.
- Improve accuracy and extend calibration life through enhanced techniques.

Task 3, Sensor Calibration Requirements

An assessment of sensors that could potentially be used for various on-orbit measurements is a primary output of this task. Data on specific sensors (for example, platinum resistance thermometer, quartz thermometer) were included for each measurement category (for example, temperature). Comments on advantages and limitations for each sensor were given, which could assist in evaluating potential sensors for specific applications. Inputs for this task were derived from results of Task 2, manufacturers' data books, and related metrology documents.

Primary conclusions:

- Several hundred sensors could be used aboard the Space Station; pressure, flow, and temperature sensors could be the most abundant.
- Accuracy of sensor measurements are affected by various extraneous conditions (for example, electromagnetic interference).
- Effects of on-orbit natural environment on sensor measurement accuracy are not completely understood.

Primary recommendations:

- Calibration techniques should include verification of sensors' primary function (for example, pressure to voltage conversion).
- Sensor applications must provide for calibration access and interfaces.

Task 4, Calibration Equipment Requirements

An assessment of available calibration equipment was conducted. Results of Tasks 1, 2 and 3 provided the inputs for this task. In addition, information obtained from equipment manufacturers' data books, metrology documents, and discussions with equipment manufacturers was utilized in this assessment. Results included the identification of calibration equipment needed for each type of measurement and their description, and an evaluation of equipment compatibility for on-orbit application.

Primary conclusions:

- Vast majority of available calibration equipment will need at least some redesigning and repackaging to reduce weight or size.
- Additional design modifications may be required to minimize redundancies (for example, separate power supplies for each equipment).
- Deficiencies that are equipment-specific need to be addressed in design activities (for example, gravity dependence, sensitivity to natural environment).

Primary recommendations:

- Identify in detail the calibration equipment required for sustained operation.
- Develop an equipment commonality list to aid in the integration process.

Task 5, Traceability Requirements

Evaluation of traceability requirements was conducted based on the information developed in Tasks 1, 2, 3 and 4. In addition, information obtained from metrology literature as well as discussions with metrologists in industry and government was included in this evaluation. Both the near term and the long term scenarios for traceability were developed.

Primary conclusions:

- Traceability for initial operation will be provided by the use of on-ground precalibrated instrumentation.
- Near term traceability can be provided by secondary standards transported between the station and the earth.
- Long term traceability will require the development of on-orbit primary standards to reduce the cost of repeated transportation of secondary standards.

Primary recommendations:

- Develop detailed traceability approaches for near term operation.
- Develop techniques for providing resident (on-board) primary reference standards.
- Investigate methods for better utilizing the in-space natural environment as primary reference standards.

Task 6, Technology Development Plans

The performance of Tasks 2, 3, 4 and 5 identified on-orbit deficiencies in calibration technology that cannot be satisfied using ground-based methods. The deficiencies represent technology development needs for in-space operations. Technology Development Plans were prepared for major categories. Information presented here is intended for enhancements and long term reliability of on-orbit measurements. It appears that for most part the initial safe operation can be accomplished through the use of existing technologies.

Primary conclusions:

- Major technology gap exists in gravity dependent measurement techniques (for example, mass).
- Additionally, technology gap exists in those techniques that are sensitive to in-space natural environment (micro-g measurements in micro-g background).

Primary recommendations:

- Develop gravity independent techniques.
- Develop more complete understanding of the effects of in-space natural environment on measurement techniques.
- Consider immediate initiation of crucial R&D efforts.

The **general conclusions/observations** of this study are:

- Only limited awareness currently exists for on-orbit metrology requirements.
- Involvement of metrologists in the design process is essential; To-date, it appears to be minimal.
- Innovativeness and inventiveness, needed in solving some of the fundamental problems associated with in-space conditions, will require an interdisciplinary approach; metrologists alone cannot solve all of the problems.
- Minimal attention appears to have been paid to-date in selecting specific measurement and calibration equipment.

The **general recommendations** (near term and long term) are:

Near Term

- Recommend that metrology and calibration personnel get involved in the design process at the earliest of stages; this could provide significant cost avoidance.
- Prepare an **On-Orbit Metrology Design Guide** to aid in the selection/assessment of instrumentation for on-orbit use. This would be a valuable tool in preparing preliminary design requirements for the **Preliminary Design Review (PDR)**.
- Conduct an **On-Orbit Metrology Workshop** for appropriate personnel (U. S. government and industry, international partners) to heighten the understanding, awareness and need for incorporating on-orbit metrology requirements. This would provide an international check and also challenge for future contributions to the Space Station operation.

- Generate and implement **detailed Technology Development Plans** to facilitate early identification of solutions for bridging the technology gaps. Then the candidate solutions can be evaluated and appropriate methods developed.

Long Term

- Conduct **preliminary design** study for an **on-orbit metrology system**. Study results should yield an **integrated system** design and methods of operation.
- Develop **final design** and **fabricate** the on-orbit metrology system. The effort shall include **test and checkout** of the system.

This report has attempted to emphasize the vital role played by on-orbit metrology in assuring reliable, long term, and routine operation of the Space Station. Satisfying on-orbit metrology needs, poses many unique and difficult challenges. However, these can be overcome with a systematic, cooperative and interdisciplinary effort. A detailed review of this report should provide at least some of the essential data needed towards implementing on-orbit metrology and calibration requirements.

1. INTRODUCTION

The commercial development of space is a national commitment that is being actively pursued by the National Aeronautics and Space Administration (NASA). The focal point for these activities is the development of a manned Space Station (SS) which will ultimately provide the basis for potential space related commercial enterprises. A forerunner of these commercial activities involves research and development (R&D) in a number of disciplines, such as:

- Space power;
- Space propulsion;
- Fluid behavior and management;
- Glass and ceramics;
- Automation and robotics;
- Earth and ocean observation;
- Communication and data systems;
- Life sciences and human factors;
- Space materials and structures; and
- Controls and guidance.

The installation, operation and maintenance of the SS for these activities requires calibration traceable to universal standards to assure accurate measurements. Moreover, calibration requirements must satisfy in-space functional objectives in a cost effective manner. The successful operation and maintenance of experimental payloads, orbiting platforms and satellites will depend on the adequacy of on-orbit metrology capabilities.

The daily operation of the SS presents some unique challenges in adapting current Earth-based metrology to the in-space environment. Lack of gravity, elevated radiation levels, broad temperature ranges, a 30 year use cycle, and the remoteness of space are some of the factors that create demands for new calibration equipment and methods.

Metrology, the regular calibration of measuring and testing equipment, is devoted towards an accurate and uniform system of measurement. This system is accomplished by using the seven basic and two supplementary units of measurement of the International System (SI) of units. Measurement traceability to the SI units is manifested by the ability to ultimately trace the calibration of equipment and reference standards to the basic units of measurement which are maintained by a national laboratory, e.g., the National Institute of Standards and Technology (NIST). Preparing guidelines and establishing requirements for subsequent on-orbit calibration of measurements is necessary to assure proper functioning of equipment and the acquisition of valid data. Approaches for ensuring long term traceability of calibration of appropriate reference standards should be established.

An initial review indicated that a paucity of data related to metrology requirements for in-space operations exists. The objective of this definition study was the identification, quantification, and analysis of SS operational data to better understand on-orbit metrology requirements for future routine in-space operations. The detailed scope of work involved in this study is given below and the overall approach is shown in Figure 1.

Task 1 -- Performance of up-to-date literature review

Review and analysis of select documents to identify on-orbit metrology/calibration needs of major systems/elements of the Space Station.

Task 2 -- Identification of on-orbit calibration techniques

Assessment of state-of-the-art calibration techniques based on the measurement parameters identified in Task 1.

Task 3 -- Identification of sensor calibration requirements

Evaluation of potential on-orbit sensor calibration techniques.

Task 4 -- Identification of calibration equipment requirements

Assessment of state-of-the-art calibration equipment for compatibility with on-orbit environment.

Task 5 -- Definition of traceability requirements

Definition of potential long term traceability approaches with appropriate reference standards.

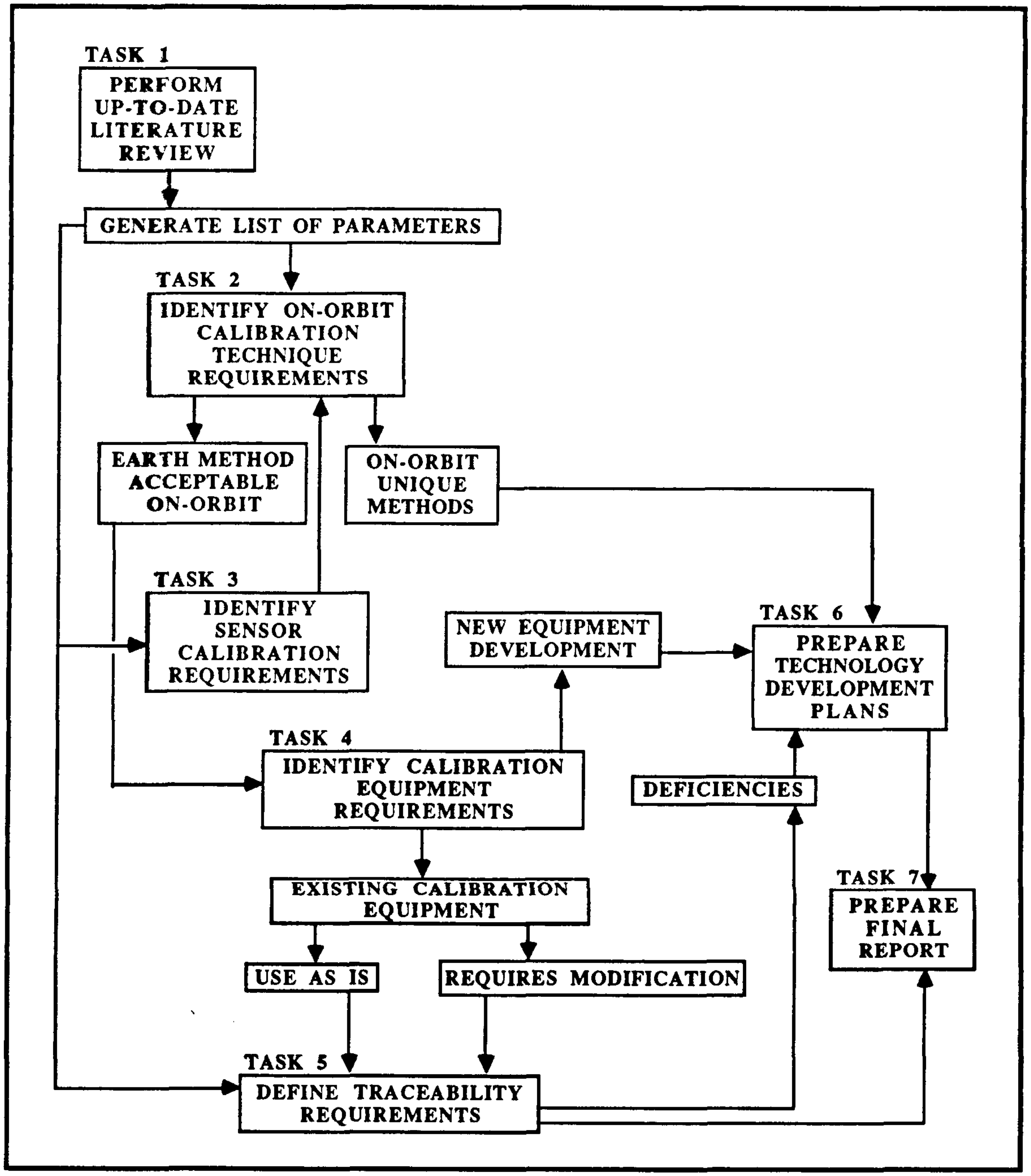

Figure 1. Overall approach.

Task 6 -- Preparation of technology development plans

Identification of deficiencies for on-orbit metrology that cannot be satisfied using ground based methods.

Task 7 -- Preparation of final report

Documentation of results and findings of the study for each of the above tasks.

2. RESULTS AND DISCUSSION

The Results and Discussion section consists of six subsections. Each subsection deals separately with the first six tasks of this study. These tasks are:

- Task 1, Performance of up-to-date literature review;
- Task 2, Identification of on-orbit calibration techniques;
- Task 3, Identification of sensor calibration requirements;
- Task 4, Identification of calibration equipment requirements;
- Task 5, Definition of traceability requirements; and
- Task 6, Preparation of technology development plans.

The data generated during the course of this study are presented in a tabular form for the majority of the tasks to provide clarity, readability and easy cross-referencing between the various tasks. In addition, the writeup for various tasks is organized in such a way that continuity is maintained as much as possible without detracting from the technical content of this report.

2.A Task 1, Literature Review

A large number of documents were reviewed for this study and these are listed in the Bibliography section. As a part of this activity several computer data bases were searched which included RECON, DIALOG, Engineering Meeting (EIM), Inspec, Engineering Index, USG/NTIS, NASA and GIDEP. Initially over 1000 references were identified. Final selection of references for review was based on their relevancy and value to this study. Only those references included in the final selection are listed in the Bibliography section.

The results presented here are based on the data obtained from:

- Various Space Station related documents (Architectural Control Documents, Space Station Program Office Documents, Johnson Space Center documents);

- Space Station RFP Work Packages #1, 2, 3 and 4;

- Discussions with NASA Space Station Prime Contractors (Boeing - Work Package #1, McDonnell Douglas - Work Package #2, General Electric - Work Package #3, Rocketdyne - Work Package #4);

- Consultations with NASA Centers (Marshall Space Flight Center - Work Package #1, Johnson Space Center - Work Package #2, Goddard Space Flight Center - Work Package #3, Lewis Research Center - Work Package #4);

- Technical papers/publications available in the open literature relating to Space Station, Shuttle, submarines and work done by USSR; and

- General metrology and calibration information (equipment manufacturers, technical data sheets, conference proceedings).

This review has yielded generic calibration/metrology requirements for the Space Station. They are presented in Table 1.1 through Table 1.13 and are organized individually for each of the following 13 major systems/elements:

- Environmental Control and Life Support System (ECLSS);
- Extra Vehicular Activity (EVA) System;
- Scientific Experiments;
- Electrical Power System (EPS);
- Data Management System (DMS);
- Mechanical Systems;
- Fluid Management Systems;
- Propulsion System;
- Servicing System;
- Guidance, Navigation and Control (GN&C) System;
- Communication and Tracking (C&T) System;
- Thermal Control System (TCS); and
- Manned Systems (Hab and Lab Modules).

Primary conclusions are:

- Majority of the calibration activities appear to be primarily concentrated in only some of the major systems, such as, ECLSS, EVA, EPS.
- Certain similar calibration requirements, for example, voltage, appear to be widely distributed throughout the station.

Primary recommendations are:

- Complete definitive identification of specific requirements throughout the station.
- Develop integrated (commonality) measurement requirements that incorporate all work packages.

Table 1.1 Task 1, Calibration Requirements for Space Station

SYSTEM: ECLSS

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Atmosphere Revitalization (AR)	Carbon dioxide content Oxygen content Trace contaminants	Concentration (%) Concentration (%) Trace concentration (ppm/ppb)
Atmosphere Control and Supply (ACS)	O2, N2 supply and flow Cabin pressure	Pressure, Flow rate Absolute and partial pressure
Fire Detection and Suppression (FDS)	Fire detection	Heat, Radiation, Temperature, Combustion by-products
Air Temperature and Humidity Control (THC)	Temperature Humidity Ventilation	Temperature Relative humidity Flow rate
Water Recovery and Management (WRM)	Temperature Water quality	Temperature pH, Conductivity, Ion concentration, Particulate content, Total organic carbon (TOC)
Waste management	Quantity	Volume (mass)
EVA support	Resource supplies (O2, N2, Water) Waste collection (CO2)	Flow rate, Pressure Pressure
Safe Haven	CO2 content O2, N2 supply Trace contaminants Humidity Water quality Waste quantity Fire detection	Concentration (%) Pressure, Flow rate Trace concentration (ppm/ppb) Relative humidity pH, Conductivity, Ion, Particulate, TOC Mass, Volume Heat, Temperature, Radiation

Table 1. 2 Task 1, Calibration Requirements for Space Station

SYSTEM: EVA

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
EVA life support	Oxygen content Oxygen reserve Nitrogen Carbon dioxide content Humidity Ventilation Pressure (internal atmosphere) Temperature (internal environment) Electrical power (reserve)	Concentration (%) Pressure Pressure, flow Concentration (%) Relative humidity Flow rate Pressure Temperature Current
Reservicing subsystem	Battery and power supply performance checkout Oxygen resupply module Heat rejection module regeneration Carbon dioxide module regeneration Humidity module regeneration EMU drying Performance trend data Nitrogen supply EMU pressure integrity Performance of pumps/fans Performance of caution/ warning devices Cooling loop gas separator performance Pressure/flow regulators EMU sensors calibration	Voltage, Current, Storage efficiency Pressure, Leak rate Fluid temperature, Fluid flow rate, Fluid leak rate CO2 removal rate H2O removal rate Moisture content A to D conversion Pressure, Leak rate Pressure, Leak rate Flow rate, Mechanical pressure, Voltage, Current, Electrical frequency Temperature, Pressure, Flow rate, Voltage and other safety related sensors Temperature, Flow rate, Pressure Pressure, Flow rate Suit temperature, Suit pressure, CO2 sensor checkout, Vent flow sensor, Primary/ secondary O2 supply sensors
Decontamination and detection subsystems	Contaminants identification	Species identification

Table 1. 2 Task 1, Calibration Requirements for Space Station

SYSTEM: EVA (Continued)

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
System interfaces		
- Hyperbaric airlock	Pressure	Absolute pressure, Rate of pressurization and depressurization
- ECLSS	Trace contaminants	Trace concentration (ppm/ppb)
	Fluid Quantity	Flow rate, Volume, Mass
	Gas quantity	Flow rate, Pressure
- Electrical power system	Power consumed and rate	Voltage, Current
- Thermal control system	Heat input	Fluid flow rate, Fluid temperature
- Fluid system	Fluid quantity	Flow rate, Volume, Pressure
- Crew tracking	Crew member position	Distance, Position
- Proximity	Range	Distance, Rate
- Docking	Range	Distance, Rate
- Electrical hazard	Residual charge	Voltage

Table 1. 3 Task 1, Calibration Requirements for Space Station

SYSTEM: Scientific Experiments

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Life sciences	Animal physiological research	Mass, Chemical composition, Temperature, Micro-g, Optical, pH, Electromagnetic dosimetry, Voltage, Current, Flow rate
	Animal ECLSS	Gas concentration, Temperature, Humidity, Pressure, Contaminants
	Botanical research	Liquid quantity, Flow rate, Mass, Temperature, Pressure, Humidity, Gas composition, Optical, Contaminants
Materials processing	Processing parameters and material properties	Micro-g, Chemical composition, Temperature, Pressure, Flow, Electrical conductivity, Hardness, Dimensions, Mass, Voltage, Flux density, Contaminants, Optical, Radiation
Earth Sciences	Atmospheric, oceonographic, geological and natural resources	Wind velocity and direction, Temperature mapping, Contour mapping, Terrestrial radiation and irradiance
Natural environment	Space environmental research	Radiation, Pressure, Temperature, Micro-g, Magnetic fields, Composition

Table 1. 4 Task 1, Calibration Requirements for Space Station

SYSTEM: Electrical Power System

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Power generation (DC)	Output power Module conversion efficiency Array pointing accuracy Temperature	Voltage, Current Solar radiation intensity Angle Temperature
Energy storage	State of charge Battery pressure Battery temperature	Reserve power Pressure Temperature
Power distribution (AC)	User voltage User current Frequency Waveform Circuit fault detection Continuity Insulation NSTS power transfer	Voltage Current Frequency accuracy Phase angle, Distortion Current Resistance Resistance Power (KW)

Table 1. 5 Task 1, Calibration Requirements for Space Station

SYSTEM: Data Management System (DMS)

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Optical data distribution (fiber optics)	Transmission reliability	Frequency, Power, Attenuation, Bandwidth, S/N ratio
Time and frequency reference	Time/frequency stability	Drift rate
A to D and D to A conversion	Conversion accuracy	Full scale, Zero stability, Linearity
Signal conditioning	Function accuracy	Gain/attenuation, S/N ratio, Bandwidth
Interfacing	Data communication rates: Time and frequency accuracy Orbital position data Attitude data Data integrity Bit error rate (electronic) Bandwidth (SSIS support) Data acquisition and distribution Telemetry MDM (A to D and D to A)	Signal timing

Table 1. 6 Task 1, Calibration Requirements for Space Station

SYSTEM: Mechanical Systems

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Alpha axis transverse boom rotary joint	Pointing accuracy Stability Jitter Search rate	Degrees Degrees Degrees Degree/second
Central radiator rotary joint	Rotational accuracy	Degrees
Umbilical mechanisms (remote operation)	3-D position accuracy Electrical continuity Leakage (gas, liquid)	3-D coordinates Resistance Leak rate, pressure
Assembly mechanisms and tools	Integrity of assembly	Torque, Stress, Strain, Tension, Straightness
End effector	Mechanical functions	Tactile force, Rotational accuracy, Torque

Table 1.7 Task 1, Calibration Requirements for Space Station

SYSTEM: Fluid Management Systems

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Integral Nitrogen System (INS)	Nitrogen quantity	Pressure, Flow rate, Leak rate, Temperature
Integral Water System (IWS)	Water quantity Water quality	Flow rate, Level, Pressure, Leak rate pH, TOC, Conductivity, Ion, Particulate
Integral Waste Fluid System (IWFS)	Waste fluid quantity Waste fluid composition	Pressure, Flow rate, Level, Leak rate Composition

Table 1. 8 Task 1, Calibration Requirements for Space Station

SYSTEM: Propulsion System

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Orbital position and attitude reorientation	Thruster performance	Force, Flow rate, Pressure, Temperature, Electrical power
Propellant reserve	Quantity gaging	Pressure, Temperature
Electrolysis unit	Electrical Generation rate	Voltage, Current, Conductivity, Temperature, Pressure
DMS interfacing	Performance data	Sensor and A to D accuracy

Table 1. 9 Task 1, Calibration Requirements for Space Station

SYSTEM: Servicing System

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Utilities	Utilities usage data	Fluid flow, Thermal load, Electrical power
Maintenance (work stations and portable equipment)	Operational performance	Voltage, Current, Resistance, Impedance, Frequency, RF Power/attenuation, Distortion, Temperature, Pressure, Flow rate, Force, Dimensional, Optical

Table 1. 10 Task 1, Calibration Requirements for Space Station

SYSTEM: Guidance, Navigation and Control (GN&C)

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Orbital attitude and position control of station, payload, and platforms	Orbital position/attitude	Latitude, Longitude, Attitude, Altitude
Collision avoidance	Distance and approach determination	Distance

Table 1.11 Task 1, Calibration Requirements for Space Station

SYSTEM: Communications & Tracking System (C&T)

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Microwave subsystems	Performance characteristics	Carrier/IF frequencies, Receiver sensitivity, Transmitted power
Signal processing subsystems	Signal characteristics	S/S+N ratio
Proximity determination	Position/range accuracy	Range, Velocity, Angle

Table 1. 12 Task 1, Calibration Requirements for Space Station

SYSTEM: Thermal Control System (TCS)

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
Waste heat acquisition, transport and rejection	Heat load (Note: Additional requirements will depend on final design)	Heat flow rate, Liquid flow, Pressure, Emissivity

Table 1. 13 Task 1, Calibration Requirements for Space Station

SYSTEM: Manned Systems (Hab & Lab Modules)

SYSTEM FUNCTION	MEASUREMENT REQUIREMENTS	CALIBRATION REQUIREMENTS
System monitoring	Pressure integrity Structural integrity Crack detection & propagation Space debris impact detection Radiation monitoring	Leak rate Stress, Strain, Elongation, Deflection Acoustics/ultrasonics Acoustics Spectral, Energy levels
Integrated workstations	System interfaces Service and repair workbench	Data aquisition Test and Diagnostic instruments (Refer to Table 1.9, Maintenance, Page 18)

2.B Task 2, On-Orbit Calibration Techniques

Information pertaining to Task 2 is presented in Table 2.1 through Table 2.13 for each of the 13 systems/elements and their respective measurement requirements identified in Task 1. The majority of the Range/Accuracy information was derived from the review of literature listed in the Bibliography section. In some cases these are best estimate values based on available information and are by no means intended to be firm or conclusive. This is believed not to affect the validity of the rest of the information presented for a specific measurement requirement. Generally, the Measurement and Calibration Techniques presented represent the state-of-the-art in measurement science for on-ground calibrations. However, some emerging techniques are also included with a view for potential on-orbit use.

The types of measurement and calibration equipment used for each technique and applicability for on-orbit use are assessed and presented. Approximate calibration intervals were estimated based on the range/accuracy requirements, current on-ground calibration practices, and a limited understanding of the effects of on-orbit natural environment on measurement accuracies. Shorter intervals may be required for higher accuracy applications. Calibration intervals are not provided for techniques that are not presently suitable for on-orbit use.

Primary conclusions are:

- Calibration techniques for several measurement categories are currently available for on-orbit use. However, many of these may not be totally optimized and in addition satisfy only a limited number of measurement criteria for each category. Some examples are given below.

    - Direct comparisons to more accurate sensors used as transfer standards (pressure sensor, flow meter, load cell),

    - Replacement of sensors with precalibrated spares (humidity, photometry),

- Existing on-orbit satellite practices (telemetry, frequency/time),
- Use of natural environment and stellar bodies (orbital position and attitude, pointing angles and stability),
- Use of stable Standard Reference Materials (pure substances, material property standards).

• Calibration techniques that are not currently suitable or need to be developed were identified for the following measurement categories.

  - Chemical composition (limited range and stability for many applications),
  - Spectrophotometry/radiometry (errors due to out-of-band responses of sensors),
  - Temperature (inaccuracies of high temperature pyrometric measurements),
  - Dimensional (lack of automation),
  - Electrical/electronic (errors induced by the natural environment),
  - Mass and derived categories such as pressure, flow and force (need for gravity independent techniques),
  - Magnetic flux (interferences from variations in magnetic field due to the periodic orbiting of the station),
  - Micro-g (need to establish validity through substantial on-orbit experimentation).

Primary recommendations are:

• Conduct additional evaluation of current calibration techniques.

- Improve accuracy and extend calibration life through enhanced techniques.
- Develop solutions for voids in calibration techniques.

Table 2.1 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: ECLSS

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Carbon dioxide (CO_2) content	pCO_2, 3-12 mm Hg 1.0 mm Hg	CO_2 specific sensor	Standard gas mixture	Standard Reference Materials (SRM's) must be resupplied. Proportional gas mixture generator could be used on-orbit.
Oxygen (O_2) content	pO_2, 115-205 mm Hg 5.0 mm Hg	Oxidizing/catalyzing/electrochemical sensor	Standard gas sensor or replaceable sensor	Calibration interval for most gas sensors limited by 2 years shelflife and 6 months useable life after first use.
		Spectral response (atomic absorbtion)	Spectrophotometer	Measurement is through quantification of spectral response. Optical sensor and spectral filters must be recalibrated or replaced every 2-3 years. Equipment needs further development for on-orbit use.
Trace contaminants	0.01-100 ppbv 10%	Gas chromatography (GC) Mass spectrometry (MS)	Chemical Composition SRM	Range of SRM's incomplete. Chemical stability may be a problem. Useful life is from 30 days to 10 years. Instrumentation may require calibration every 1-2 years.
O_2/Nitrogen (N_2) supply and	10-5000 psi 0.2-2.0 lbs/hr 3%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
		Flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.

Table 2.1 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: ECLSS (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Cabin pressure	10-14.7 psia 0.1 psi average, 0.03 psi/ minute	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
Fire detection	To Be Determined (TBD)	Ultraviolet (UV) sensor	UV Photometer (with calibrated filters and sensor)	Filters and sensors need to be calibrated on earth (2-3 years) or with a natural source (needs further evaluation and verification for calibration traceability). Diffused and scattered light must be considered for accurate measurements. Accuracies currently limited to a few percent.
		Thermographic sensor	Black body	Equipment needs further development to be practical for on-orbit use.
		GC, MS, Carbon monoxide (CO) sensor	Standard gas mixture	SRM's (pure or mixtures) must be resupplied. Some are not stable over long periods. Proportional gas mixture generator could be used on-orbit. Sensor calibration interval may be less than a year.
		Temperature sensor	Standard Platinum Resistance Thermometer (SPRT)	Calibration life depends on severity of use (1 to 5 years). High temperatures and shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.

Table 2.1 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: ECLSS (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Temperature	60-90 °F 1 Deg F	Thermistor Resistance Temperature Device (RTD)	SPRT	Calibration life depends on severity of use (1 to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.
Humidity	25-75% RH 5% RH	Optical dewpointer Replaceable Semiconductor Sensor (replace with precalibrated spares every 1-2 years as an alternative to recalibration)	Standard dewpointer Psychrometer Saturated salt solution (SRM)	Dew pointer can be recalibrated on-orbit (2-3 years). Equipment needs development to be practical for on-orbit use. Suitable for ventilation purposes. Easily recalibrated on-orbit (3-5 years). Generates reference humidity conditions for calibrating sensors. Salt may be corrosive and must be periodically resupplied.
Ventilation	5-200 ft/min (velocity) 10-125 CFM (volume) 10%	Velocimeter Venturi flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.

Table 2.1 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: ECLSS (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Water quality				
- pH	6-8 pH 0.2 pH	Hydroxyl (OH) ion probe	pH buffers (SRM)	Probe calibration intervals may be less than one year. SRM's usually are not stable in solutions. Stability in dry form can be 10 years. Solution preparation procedures may need modification for micro-g environment. Spent solutions may not be compatible with waste processing.
- Ionic species	0.01-5.0 mgm/liter 1.0%	Specific ion probe	Chemical composition SRM	
- Conductivity	10-100 micromhos/cm 10%	Conductivity probe	Electrolytic conductivity solutions	Low concentration solutions easily contaminated (e.g. CO2 in air). May require frequent preparation. Reference standard probes can be designed such that they can be verified dimensionally/electrically on-orbit. Probe calibration life can be 1-2 years.
- Total Organic Carbon (TOC)	0.1-1.0 mgm/liter 10%	TBD	TBD	TBD
- Particulates	0.2-2.0 mgm/liter 10%	Optical	Optical fiber (SRM)	Standard solutions can be prepared in advance and sealed for instrument calibrations (1-2 years). Pariculate suspension in miro-g could be different than on earth.

Table 2.1 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: ECLSS (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Waste management - Volume (mass)	% capacity 5%	Level sensor	Dimensional/electrical	Level sensors for micro-g need further development.
EVA support	Measurement requirements are similar to all items listed above in this table (2.1), pages 26 - 30.			
Safe haven				

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: EVA

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
EVA life support				
- O2 content	pO2 115-205 mm Hg 5.0 mm Hg	Electrochemical sensor	Standard gas mixture	Standard Reference Materials (SRM's) must be resupplied. Proportional gas mixture generator could be used on-orbit.
			Standard sensor	Calibration interval for most gas sensors limited by 2 years shelflife and 6 months useable life after first use.
		Spectral response	Spectrometer	Measurement is through quantification of spectral response. Optical sensor and spectral filters must be recalibrated or replaced every 2-3 years. Equipment needs further development for on-orbit
- O2 reserve	10-3000 psi 3%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
- N2 supply	10-5000psi 0.2-2.0 lbs/ hr 3%	Pressure sensor	Standard pressure sensor	
		Flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: EVA (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- CO_2 content	pCO_2, 3-12 mm Hg 1.0 mm Hg	CO_2 specific sensor	Standard gas mixture	Calibration interval for most gas sensors limited by 2 years shelflife and 6 months useable life after first use.
- Humidity	25%-75% RH 5% RH	Optical dewpointer Replaceable Semiconductor Sensor (replace with precalibrated spares every 1-2 years as an alternative to recalibration)	Standard dewpointer Psychrometer Saturated salt solution (SRM)	Dewpointer can be recalibrated on-orbit (3-5 years). Equipment needs development to be practical for on-orbit use. Continuous monitoring possible. Suitable for ventilation purposes. Easily recalibrated on-orbit. Generates reference humidity conditions for calibrating sensors. Salt may be corrosive and must be periodically resupplied.
- Ventilation	5-200 ft/min (velocity) 10-125CFM (volume) 10%	Velocimeter Venturi flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.
- Pressure	10-14.7 psia 0.1 psi average, 0.03 psi/minute	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: EVA (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Temperature	60-90 °F 1 Deg F	Thermistor RTD	SPRT	Calibration life depends on severity of use (1 to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.
- Power	1-12 amps 1%	Shunt/Analog to Digital (A to D) converter	Voltage/current calibrator	Can be a voltage and current measuring instrument or a voltage and current source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage and resistance standards. A to D converter may require recalibration every 2 to 3 years (depends on accuracy required). Calibrator can have calibration interval of up to 5 years. Equipment needs further development to be practical for on-orbit use.
Reservicing - Battery and power supply performance	0-30V 0.25% 0-10A 0.5%	Shunt/A to D converter	Voltage/current calibrator	

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use System: BVA (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- O2 resupply module				
--- Pressure	1-5000 psi 1%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated on earth periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
--- Leak rate	50 SCCM max 1%	Pressure sensor Flow meter	Standard leak Leak rate calibrator	Suitable for low flow rates only. Life span depends on flow rate. Leak rate cailibrator using volume vs pressure or proportional flow measurement techniques to measure/generate standard leak rates need further development.
- Heat rejection module				
--- Fluid leak rate	0.1 lb/hr max 2.5%	Flow meter	Leak rate calibrator	
--- Fluid temperature	0-200 Deg F 1%	Thermistor RTD	SPRT	Calibration life depends on severity of use (1 to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: EVA (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
--- Fluid flow rate	0-250 lbs/hr 2.5%	Flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.
- CO2 module regeneration	0.02-0.4 lb/hr	Flow meter	Standard flow meter	
	5%	CO2 sensor	Standard gas Mixture	Calibration interval for most sensors is limited by 2 year shelflife and six month use life after first use. Proportional gas mixture generator could be used on-orbit.
- Humidity module regeneration	5-90%RH 5%	Dew pointer	Standard dewpointer	Dew poiter can be recalibrated on-orbit (2-3 years). Equipment needs development to be practical for on-orbit use.
		Replaceable Semiconductor Sensor (replace with pre-calibrated spares every 1 to 2 years as an alternative to recalibration)	Saturated salt solution (SRM)	Generates reference humidity conditions for calibrating sensors. Salt may be corrosive and must be periodically resupplied.
- EMU drying	5-20%RH 5%			

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: EVA (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Performance trend data (sensor outputs)	0-10 V 0.1%	A to D converter	Voltage/current calibrator	Can be a voltage and current measuring instrument or a voltage and current source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage and resistance standards. A to D converter may require calibration every 2 to 3 years (depends on accuracy requirements). Equipment needs further development to be practical for on-orbit use.
- N2 resupply (engine thrusters)				
--- Leak rate	50 SCCM max 1%	Flow meter	Leak rate calibrator	Leak Rate Calibrator using volume vs pressure or proportional flow measurement techniques to measure/generate standard leak rates need further development.
--- Pressure	100-5000 psi 2%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
- EMU pressure integrity	20 psi max 1%	Pressure sensor	Standard pressure sensor	

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: EVA (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Performance of pumps and fans	1-500 pulses/sec 1%	Event counter	Frequency counter	Can measure pulse rates, frequency, time, etc. as a portable or built-in instrument. Calibrate with telemetry (interval depends on accuracy).
	0-250 lbs/hr 2.5%	Flow meter	Standard flow meter	With limited use calibration interval could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.
	0-30 V 0.5% 0-5 A 0.5%	A to D converter/ shunt	Voltage/current calibrator	Can be a voltage and current measuring instrument or a voltage and current source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage and resistance standards. A to D converter may require calibration every 2 to 3 years (depends on accuracy requirements). Equipment needs further development to be practical for on-orbit use.
- Caution and warning devices	0-10 V 0.1%	A to D converter	Voltage/current calibrator	

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: EVA (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Cooling loop				
--- Temperature	0-100 Deg C 5 Deg C	Thermistor	SPRT	Calibration life depends on severity of use (up to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.
--- Flow rate	5-200 lbs/hr 10%	Flow meter	Standard Flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.
--- Pressure	0-250 psia 5%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
- EMU pressure flow regulators and sensors calibration	Measurement requirements are similar to all the items listed above in this table (2.2), pages 31-38.			

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: EVA (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Decontamination and detection subsystems - Species identification	ppm/ppb TBD	MS, GC, UV, Infared (IR), surface sensitive techniques	Chemical composition SRM's	Range of SRM's incomplete. chemical stability may be a problem. Instruments may require calibration every 1 to 2 years.
Electrical hazard	0-200 KV 10%	Electrostatic sensor	Voltage/current calibrator (high voltage)	Can be a voltage and current measuring instrument or a voltage and current source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage and resistance standards. Calibrated accessories required for high voltage applications. Electrostatic sensor may require calibration every 2 to 3 years. Equipment needs further development to be practical for on-orbit use.
Interfacing - Hyperbaric airlock	0-5 Atm 2%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.

Table 2.2 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: EVA (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- ECLSS	Measurement requirements are similar to those listed in Table 2.1, pages 26-30.			
- Electrical power system	Measurement requirements are similar to those listed in Table 2.4, pages 51-55.			
- Thermal control system	Measurement requirements are similar to those listed in Table 2.12, page 78.			
- Fluid systems	Measurement requirements are similar to those listed in Table 2.7, pages 62-64.			
- Data management system	Measurement requirements are similar to those listed in Table 2.5, pages 56-58.			
- Communications and tracking	Measurement requirements are similar to those listed in Table 2.11, pages 76-77.			
- Guidance, navigation, and control	Measurement requirements are similar to those listed in Table 2.10, page 75.			

Table 2.3 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Experiments

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Life Sciences - Animal Physiological				
---Mass	< 100 mgms < 100 gms <100 Kgms >100 Kgms 0.01% mgms 0.01% gms 0.1% Kgms	TBD TBD TBD TBD	Mass artifacts	Long term accuracy (5 to 10 years) depends on care in handling. Measurement technique for micro-g environment (using force, velocity, or acceleration) needs further development.
--- Chemical composition	ppm 10%	Atomic Absorption (AA), X-ray fluorescence, IR, GC	Chemical composition SRM	Range of SRM's incomplete. Chemical stability may be a problem. Instruments may need recalibration every 1 to 2 years.
--- Temperature	0-50 °C 0.1 Deg C	RTD	SPRT	Calibration life depends on severity of use (1 to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.
-- Microgravity	10^{-4} - 10^{-8} g 5%	Accelerometer	TBD	On-orbit techniques need to be developed.

Table 2.3 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Experiments (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
---Optical	IR to UV, Microwatts to Watts/sq. cm 1%	Spectrophotometer	Standard sensor and spectral filter set	Spare sensor and filter set needed. Can be expendable or returned to earth for recalibration(2 to 3 years). Susceptible to damage (scratches, contamination, overexposure). Equipment needs further development for on-orbit use.
---pH	0-14 0.2 pH (7 +/- 0.05)	Wet probe Litmus paper	pH buffers (SRM)	Dry buffers exhibit long life(up to 10 years). Not stable in solutions. Probes may require recalibration at less than 1 year intervals.
--- Electromagnetic dosimetry	TBD	Radiation sensor (active or badges)	Standard radiation source	Safety, badge processing, and film storage are issues.
--- Voltage	0-10V 0.1%	A to D converter	Voltage/current calibrator	Can be a voltage and current measuring instrument or a voltage and current source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage and resistance standards (and AC to DC transfer standards for AC calibrations). A to D converters may need to be calibrated every 1 to 2 years (depends on accuracy requirements. Equipment needs further development to be practical for on-orbit use.

Table 2.3 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Experiments (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
--- Current	1 uA - 1 mA 2%	A to D Converter/ shunt	Voltage/current calibrator	Can be a voltage and current measuring instrument or a voltage and current source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage and resistance standards (and AC to DC transfer standards for AC calibrations). A to D converters may need to be recalibrated every 2 to 3 years. Equipment needs further development to be practical for on-orbit use.
Flow rate	1 Microliter/ hr to 10 Milliliters/ hr	Graduated scale/ time	Initial calibration only (currently accepted procedure)	May be limited to positive displacement techniques due to low gravity.
- Animal ECLSS	Measurement requirements are similar to items listed for Human ECLSS, Table 2.1, pages 26-30.			
- Botanical research	Measurement requirements are similar to items listed above in this table (2.3), Animal Physiological and Animal ECLSS, pages 41-42.			
Material Processing - Microgravity	10^{-4} - 10^{-8} g 1.0%	Accelerometer	TBD	On-orbit techniques need to be developed.

Table 2.3 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Experiments (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Chemical composition	ppm 1%	AA, X-ray flourescence, IR, GC	Chemical composition SRM"s	Range of SRM's incomplete. Chemical stability may be a problem. Instruments may require recalibration every 1 to 2 years.
- Temperature	Cryo (< 0 Deg C) 1 Deg C	PRT	On-board cryo liquids	O2, N2, CO2 baths (at boiling point) provide reasonable calibration reference points. Venting and gas collection may be issues.
	Furnace (up to 2000 °C) 2 Deg C	PRT (or type "S" thermocouple)	SPRT/Melting point standards	Exposures to high temperatures reduce the useful life span and alter the calibration. May require frequent replacement of PRT or type "S" thermocouple with precalibrated elements(1 year or less). Melting/freezing point standards are available at several temperatures. Best accuracy for temperature calibration. Equipment needs further development to be practical for on-orbit use.
		Optical Pyrometry	High temperature black body	Equipment needs further development to be practical for on-orbit use.
- Pressure	0-45psia 1.0%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated on earth periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.

Table 2.3 **Task 2, Assessment of Calibration Techniques for On-Orbit Use System: Experiments (Continued)**

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Flow rate	1-20 cc's/ min 5.0%	Flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary flow standard needs to be developed.
- Electrical conductivity -	1-110% IACS (International Annealed Copper Standard) 0.1%	Eddy current	Electrical resistivity and conductivity standards	SRM's available for most conducting materials. Superconductive standards need to be developed. Ageing of some materials may require resupply every 3 to 5 years.
Hardness	Plastics, Metals, Ceramics 2%	Hardness testers	Hardness standards (SRM)	Long term (5 to 10 years) standards are available over a wide range of values. Instrument calibration (prior to use) can be automated.
- Dimensions	10 Angstroms (Coatings) to 10 inches	SEM	Coating thickness standards (SRM)	Full range of SRM's (e.g. semiconductor manufacturing technology) not presently available.
	3 Angstroms to 10 ppm	Holography/laser interferometry	Self calibrating	Accuracy dependent on wavelength stability and transmission medium. Needs further development for on-orbit use.

Table 2.3 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Experiments (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Mass	mg - kgm 1.0%	Force/Acceleration	Mass artifact standard	Long term (up to 10 years) accuracy depends on care in handling. Measurement technique for micro-g environment (using force, velocity, or acceleration) needs further development.
- Voltage	0-30 KV TBD	Voltage divider/A-D converter/Inductive pickup	Voltage/current calibrator	Can be a voltage and current measuring instrument or source. Calibrated against primary voltage and resistance standards. Calibrated accessories required for high voltage applications. Due to aging of high voltage components, calibration intervels will be limited to 1-2 years. Equipment needs further development to be practical for on-orbit use.
- Flux density (magnetic)	TBD Gauss	Flux probe/Hall sensor	Flux standard	Available secondary standards lack long term stability and must be calibrated relative to primary flux standards on earth (1-3 years). Natural environment is of limited use as a standard. On-orbit primary standard (using on-ground apparatus and technqiues) is not practical.
			Standard Hall sensor	Needs further development.

Table 2.3 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Experiments (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Contaminants				
--- Effluents	ppm/ppb 10.0%	GC, MS	Chemical composition SRM's	Range of SRM's incomplete. Chemical stability may be a problem. Useful life is from 30 days to 10 years. Instruments may require calibration every 1-2 years.
--- Material purity	ppm/1.0% 5.0%	SEM, Optical microscopy, X-ray flourescence, AA		
-Optical Properties/Spectral Data				
--- Transmittance/Reflectance	0-100% 0.5% (relative) 2-5% (absolute)	Spectrophotometer	Standard sensor and filters (SRM)	Standard sensor and spectral filter set (spectrophotometer) - Spare sensor and filter set needed. Can be expendable or returned to earth for recalibration (2-3 years). Susceptible to damage (scratches, contamination, overexposure). Equipment needs further development to be practicable for on-orbit use.
--- Wavelength	IR-UV 5.0%	Spectrophotmeter	Blackbody/irradiance standard	Equipment needs further development to be practical for on-orbit use.

Table 2.3 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Experiments (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Radiation	TBD 5.0%	Geiger counter	Radiation source (SRM) Natural environment	Standard may be a safety hazard. Instrument calibration interval 1-3 years. Needs further evaluation as a calibration standard.
Earth Sciences - Wind velocity and direction	0-500 mph 2% 1-360° 5 Deg	Scatterometer	Telemetry	Measurements affected by upper atmospheric conditions. Needs further development. Calibration can be accomplished by comparison with ground measurements.
- Temperature mapping (surface)	-70 to 125 °F 0.01 Deg F (Resolution)	Infrared Radiometer	Telemetry	
- Contour mapping	0-10 Kilometers 0.3 meters	Radar and Laser Altimeters	Ground targets Telemetry	
Terrestrial radiation and irradiance	TBD	Radiation and optical sensors	Black body/irradiance standard Natural environment	Equipment needs further development to be practical for on-orbit use. Calibration in natural environment needs further evaluation.

Table 2.3 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Experiments (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Natural environment				
– Electromagnetic radiation	10^{-4} to 10^{-14} Angstroms TBD Microwatts - Watts per sq. meter TBD	Electromagnetic sensor/semiconductor sensor/ion chamber	Radiation source (SRM) Standard sensor	Wide range of SRM's available. May present a safety hazard. Sensors may require recalibration every 2-3 years. Interference from out-of-band radiations may generate errors.
– Pressure (vacuum)	10^{-4} to 10^{-10} torr 5.0%	Pressure sensor Ion gage	Spinning rotor gage	Not practical for on-orbit use. High vacuum standard needs to be developed.
– Temperature	-200 to +400 deg F 2 Deg F	Thermistor RTD	SPRT	Calibration life depends on severity of use (1 to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.
– Micro-g	10^{-4} to 10^{-8} g 1.0%	Accelerometer	TBD	On-orbit techniques need to be developed.

Table 2.3 Task 2, Assessment of Calibration Techniques for On-Orbit Use System: Experiments (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Magnetic field	TBD TBD	Flux probe/Hall sensor	Standard Hall sensor	Hall sensor needs further development, possibly as primary standard.
- Composition of induced environment	TBD TBD	GC MS	Chemical composition SRM's	Range of SRM's incomplete. Chemical stability may be a problem. Useful life is from 30 days to 10 years. Instruments may require recalibration every 1-2 years.

Table 2.4 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Electrical Power System

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Output power - Voltage	0 - 440 V 0.5%	Voltage transformer/A to D converter	Voltage/current calibrator	Calibrator can be a voltage and current measuring instrument or source calibrated against primary voltage, resistance, and AC to DC transfer standards. Calibrated accessories required for high power/current/voltage. Transformers exhibit long term stability, but A to D may require recalibration every 2-3 years. Equipment needs further development to be practical for on-orbit use.
- Current	0 - 300 A 0.5%	Current transformer/A to D converter	Voltage/current calibrator	
Module efficiency - Solar radiation intensity	0 - 0.15 Watts/sq. cm. 1.0%	Photometer	Standard sensor and spectral filter set	Spare sensor and filter set needed. Can be expendable or returned to earth for recalibration (2-3 years). Susceptible to damage (scratches, contamination, overexposure). Equipment needs further development for on-orbit use.
Array pointing accuracy - Angle	+/- 55 deg 0.5 Deg.	Sun sensor (peak intensity)	Natural standards (stellar bodies)	Standard satellite practice.

Table 2.4 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Electrical Power System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Temperature				
- Photovoltaic (PV)	-25 to +105 Deg. C 0.2 Deg. C	PRT	SPRT	Calibration life depends on severity of use (up to 5 years). One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.
- Solar Dynamic (SD)	0 to 750 Deg. C 10 Deg.	PRT	SPRT	Exposures to high temperatures reduce the useful lifespan and alter the calibration. May require frequent replacement of PRT or type "S" thermocouple with precalibrated elements (1 year or less).
State of charge (Reserve power)	0-81 amphrs 2.0%	Current and voltage sensors	Voltage/current calibrator	Can be a voltage and current measuring instrument or source calibrated against primary voltage and resistance standards. Calibrated accessories required for high power/current. Recent improvements in semiconductor sensors may extend calibration up to 5 years (for less accurate applications). Equipment needs further development to be practical for on-orbit use.

Table 2.4 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Electrical Power System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Battery pressure	0-2000 psig 2%	Strain gage (integral)	Initial calibration only	ORU replacement/recalibration.
Battery temperature	-100 to +200 Deg. F 0.5%	RTD	SPRT IR thermometer	ORU/sealed unit. Calibration technique needs evaluation.
User voltage	0-440 V 0.5%	Voltage transformer/A to D converter	Voltage/current calibrator	Can be a voltage and current measuring instrument or source calibrated against primary voltage, resistance, and AC to DC transfer standards. Calibrated accessories required for high power/current/voltage applications. A to D converters may require recalibration every 2-3 years. Equipment needs further development to be practical for on-orbit use.
User current	0-300 A 0.5%	Current transformer/A to D converter	Voltage/current calibrator	
Frequency	20 +/- 1 KHz 0.1%	Phase locked loop	Frequency counter	Recalibrated through telemetry (1-5 years).

Table 2.4 Task 2, Assessment of Calibration Techniques for On-Orbit Use

System: Electrical Power System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Waveform				
- Phase angle (power factor)	0 +/- 180 Deg 2 Deg	Phase detector	Waveform generator	Phase angle variations at user points may require multiple measurements. Function/frequency generator required to calibrate many AC measuring instruments (1-3 years). Equipment needs further development to be practical for on-orbit use.
- Distortion	0-3% 0.3%	Distortion analyzer	Waveform generator	
Circuit fault detection	0-300 A 1%	Built in circuitry (verification of safety functions should be performed every 1-3 years)	Voltage/current calibrator	Calibrator can be a voltage and current measuring instrument or source calibrated against primary voltage, resistance, and AC to DC transfer standards. Calibrated accessories required for high current. Equipment needs further development to be practical for on-orbit use.
Continuity (resistance)	0-1 ohm 0.001 ohm	Milliohm meter Built In Test (BIT) circuitry	Standard resistor	Trouble shooting aid for ORU replacement. Meter may require manual testing. BIT will require additional wiring or circuitry. Standard resistor calibration interval can be up to 10 years, milliohm meter from 1-3 years.

Table 2.4 Task 2, Assessment of Calibration Techniques for On-Orbit Use

System: Electrical Power System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Insulation (Resistance)	10^5 to 10^{10} ohm 10.0%	Megohm meter Built In Test (BIT) circuitry	Standard resistor	High resistance standards are not stable. Recalibration may be required every 1-2 years.
NSTS power transfer	0 - 200 V 0.5% 0 - 50 A 0.5%	Voltage transformer Current transformer	Voltage/current calibrator	Can be a voltage and current measuring instrument or source. Calibrated against primary voltage, resistance, and AC to DC transfer standards. Calibrated accessories required for high power/current/voltage applications. Equipment needs further development to be practical for on-orbit use. NSTS on-board instrumentation can be used as transfer standards for on-orbit calibration.

Table 2.5 Task 2, Assessment of Calibration Techniques for On-Orbit Use

System: Data Management System (DMS)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Transmission reliability (fiber optics)				
- Frequency	TBD	Phase locked loop	Frequency counter	Can be used to measure pulse rates, frequency, time, etc. as a portable or built in instrument. Recalibration can be easily accomplished (1 to 5 years).
- Power	TBD	Optical power sensor	Photometer (fiber optic)	Filters and sensors calibration on earth(2-3 years) or with a natural source (needs further evaluation and verification for calibration traceability). Accuracies currently limited to a few percent. Fiber optic systems are usually totally closed, must open the system to calibrate.
- Attenuation	TBD	Optical power sensor	Photometer (fiber optic)	
- Bandwidth	TBD	Signal analyzer	Waveform/signal generator	Function/frequency generator required to calibrate many AC measuring instruments every 1 to 3 years. Equipment needs further development to be practical for on-orbit use. Possible commonality with other system requirements (C&T, GN&C).
- S/N ratio	TBD	Signal analyzer	Waveform/signal generator	

Table 2.5 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: DMS (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Time/frequency stability (Drift rate)	TBD	Phase locked loop	Frequency counter	Can be used to measure pulse rates, frequency, time intervals, etc. as a portable or built in instrument. Recalibration on-orbit is easily accomplished (1 to 5 years).
A to D & D to A conversion accuracy				
- Full scale/zero stability and linearity	0 - 10 V 0.02%	8-16 Bit A to D converter	Voltage/current calibrator	Calibrator can be a voltage and current measuring instrument or source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage, resistance, and AC to DC transfer standards. Equipment needs further development to be practical for on-orbit use.
Signal conditioning accuracy				
- Gain/attenuation	Ratio (10^{-2} to 10^{3}) 0.02%	Resistive divider/ operational amplifier/ A to D converter	Voltage/current calibrator	Numerous input channels, widely distributed through the station. Possibly the highest voltage accuracy requirement for on-orbit calibration. High accuracy A to D converters may require recalibration every 1 to 2 years.

Table 2.5 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: DMS (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- S/N ratio	Varies with application <2 db	TBD	TBD	On-orbit requirements need to be better defined. Technique needs development for dynamic measurements. Numerous input channels widely distributed.
- Bandwidth	TBD TBD	TBD	TBD	
Interfacing (signal timing)	10 microseconds to 50 milliseconds	Design characteristic	Data/word generator	On-orbit data communication testing requirements need to be better defined. The use of telemetry and/or Built In Test (BIT) circuitry would be applicable to on-orbit use.

Table 2.6 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Mechanical Systems

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Alpha axis - Pointing accuracy	0 to +/- 55 deg 0.5 Deg.	Sun sensor	Natural standard (stellar bodies)	Standard satellite practice.
- Stability	TBD	Star tracker	Natural standard (stellar bodies)	Dependent on accuracy requirements.
- Jitter	TBD	Accelerometer Star tracker	TBD Natural standard (stellar bodies)	On-orbit techniques need further development. Dependent on accuracy requirements.
- Search rate	TBD	Star tracker	Natural standard (stellar bodies)	Standard satellite practice.
Thermal radiator - Rotational accuracy	0 to +/- 55 deg 3 Deg.	Sun sensor Star tracker	Natural standard (stellar bodies)	Standard satellite practice.

Table 2.6 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Mechanical Systems (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Umbilical				
- 3-D position	0-300 meters TBD (similar to orbitor arm)	Built in encoders Radar Laser	Calibrated targets	Initial calibration of target position on earth. May need recalibration on-orbit depending on the structural stability of the space station (5 to 10 years). Equipment recalibration (1 to 2 years).
- Electrical continuity	0-1 ohm 0.001 ohm	Milliohm meter (BIT)	Standard resistor (calibration plug)	Milliohm meter may require calibration every 2 to 3 years. BIT will require additional wiring or circuitry.
- Leakage (gas, liquid)	50 SCCM max 1.0%	Pressure sensor	Standard leak	Standard leak suitable for low flow rates only. Life span depends on flow rate. Pressure sensor and flow meter may require recalibration every 2 to 3 years.
	0.1 lb/hr max 2.5%	Flow meter	Leak rate calibrator	Volume vs pressure or proportional flow measurement techniques to measure/ generate standard leak rates needs further development.
Assemblies and mechanisms				
- Torque	1 inch oz - 100 ft lbs 2%	Torque wrench/ load cell (hand tools)	Standard load cell	Calibration of assembly/maintenance tools. Calibration interval depends on frequency of use, may be 1 to 5 years.

Table 2.6 Task 2, Assessment of Calibration Techniques for On-Orbit Use System: Mechanical Systems (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Stress, strain, tension	TBD TBD	Strain gage	Initial calibration only Holography	Associated electronics can be recalibrated on-orbit (2-3 years) for exchangeability and to minimize redundancy. Potential self calibration, technique needs further development.
- Straightness (alignment)	TBD TBD	Optical	Laser interferometry (self calibrating)	Equipment needs further development to be practicable for on-orbit use.
End effector - Tactile force	0-100 lbs 2.0%	Force sensor Load cell Strain gage	Standard load cell	On-orbit calibration can be facilitated by fixtured load cell for force and position calibration of external robotics. Standard load cell should be recalibrated every 2 to 3 years.
- Rotational accuracy	0 - 360 deg (3 degrees of freedom) 1 Deg.	Encoder	Functional test	360 Deg. digital encoders usually require only functional testing. Less than 360 Deg. requires an angular standard.
- Torque	1 inch oz to 100 ft lbs 2%	Torque/load cell (end affector)	Standard load cell	Used for the calibration of robotic assembly/maintenance tools (1 to 3 years).

Table 2.7 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Fluid Management Systems

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Nitrogen quantity				
- Pressure	0-5000 psi 2%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
- Flow rate	<100 SCFM 2.0%	Flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.
- Leak rate	TBD	Analysis of above 2 items	Leak rate calibrator	Volume vs pressure or proportional flow measurement techniques to measure/ generate standard leak rates needs further development.
- Temperature	-200 to 400 Deg. F 5 Deg. F	RTD	SPRT	Calibration life depends on severity of use (1 to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.

Table 2.7 Task 2, Assessment of Calibration Techniques for On-Orbit Use System: Fluid Management Systems (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Water Quantity				
- Flow rate	0-20 lbs/min 5.0%	Flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.
- Level	% capacity 5.0%	TBD	TBD	On-orbit liquid level measurement techniques need further development.
- Pressure	0-100 psi 5.0%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
- Leak rate	TBD	Analysis of above 3 items.	Leak rate calibrator	Volume vs pressure or proportional flow measurement techniques to measure/ generate standard leak rates needs further development.
Water Quality	Measurement requirements are similar to items listed in Table 2.1, ECLSS, Water Quality, Page 29.			

Table 2.7 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Fluid Management Systems (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Waste fluid quantity				
- Pressure	0 - 100 Psi 5.0%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
- Flow rate	0 - 20 lbs/min 5.0%	Flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.
- Level	% capacity 5.0%	TBD	TBD	On-orbit liquid level measurement techniques need further development.
- Leak rate	TBD	Analysis of above 3 items	Leak rate calibrator	Volume vs pressure or proportional flow measurement techniques to measure/generate standard leak rates needs further development.
Waste fluid composition	TBD (depends on type of waste)	TBD	Chemical composition SRM's	Range of SRM's incomplete. Chemical stability may be a problem. Useful life from 30 days to 10 years.

Table 2.8 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Propulsion System

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Thruster performance				
- Force	0 - 100 lbs 1.0%	Load cell	Standard load cell/ force calibrator	Primary standard for on-orbit force calibration needs development.
- Flow rate	0 - 1 lb/hr 2.0%	Flow meter	Standard flow meter	With limited use calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. Primary standard needs to be developed.
- Pressure	0-500 psi 2.0%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
- Temperature	Cryo to 2000 deg F 20 Deg. F	PRT Type "S" thermocouple	SPRT Type "S" thermocouple	Exposures to high temperatures reduce the useful life span and alter the calibration. May require frequent replacement of PRT or type "S" thermocouple with precalibrated elements. Reduced accuracy may allow calibration interval of up to 3 years.

Table 2.8 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Propulsion System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Electrical power	0-1 A 5.0%	Current transformer	Voltage/current calibrator	Can be a voltage and current measuring instrument or a voltage and current source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage and resistance standards (and AC to DC transfer standards for AC calibrations). Equipment needs further development to be practical for on-orbit use.
Propellant reserve				
- Pressure	0-3000 psi 2.0%	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy recalibrated on earth periodically (2-3 years). Primary standard (force x area) for on-orbit calibration needs to be developed.
		Strain gage	Initial calibration only	Probably ORU candidate.
- Temperature	-200 to 400 Deg. F 2.0%	RTD	SPRT	Calibration life depends on severity of use (1 to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.

Table 2.8 Task 2, Assessment of Calibration Techniques for On-Orbit Use System: Propulsion System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Electrolysis unit				
- Voltage	0 - 50 V DC TBD	Shunt/A to D converter	Voltage/current calibrator	Can be a voltage and current measuring instrument or source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage, resistance, and AC to DC transfer standards. Shunt/A to D converter calibration interval depends on accuracy requirements. Equipment needs further development to be practical for on-orbit use.
- Current	0 - 10 A TBD	Shunt/A to D converter	Voltage/current calibrator	
- Conductivity	0.01 to 0.1 mhos TBD	Resistive bridge and probe	Electrolytic conductivity standard	Low concentration solutions easily contaminated (e.g., CO_2 in air). May require frequent preparation. Reference standard probe can be so designed that it can be verified dimensionally/electrically on-orbit (1-2 years).
- Temperature	0 - 200 deg F TBD	RTD	SPRT	Calibration life depends on severity of use (1 to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.

Table 2.8 Task 2, Assessment of Calibration Techniques for On-Orbit Use System: Propulsion System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Pressure	0-1200 psia TBD	Pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
DMS interfacing - Sensor and A to D accuracy	0-10 V 0.25%	A to D converter	Voltage/current calibrator	Can be a voltage and current measuring instrument or source. Self contained display and data interface for manual and automated use. Calibrated against primary voltage and resistance standards. Calibration interval for A to D converter can be 2-3 years. Equipment needs further development to be practical for on-orbit use.

Table 2.9 Task 2, Assessment of Calibration Techniques for On-Orbit Use

System: Servicing System

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Fluid flow (liquid, gas)	0-100 lbs/hour 2.0%	Flow meter	Standard flow meter	When used on a limited basis calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. On-orbit primary standard needs to be developed.
Thermal load	0 - 10 KW 5.0%	Calorimetric temperature measurement	SPRT	Calibration life depends on severity of use (1 to 5 years). High temperatures and shock can alter accuracy. One point re-calibration of SPRT (e.g., ice point) can provide reasonable accuracy.
Electrical power	0 - 10 KW 5.0%	ORU maintenance	Voltage/current calibrator	Voltage/current calibrator can be a multipurpose voltage and current measuring instrument (and source) calibrated against on-board primary voltage, resistance, and AC to DC transfer standards. This device could be used for the calibration, maintenance and repair of on-board electrical/electronic equipment. Calibrated accessories will be required for high power/current/voltage measurements. Depending on accuracy requirements and equipment stability, the calibration interval could be up to 5 years. Long term primary standards and automated calibration equipment need further development to be practical for use on-orbit.

Table 2.9 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Servicing System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Basic electrical (AC/DC)				
- Voltage	0-440 V 0.1%	Digital multimeter (DMM)	Voltage/Current calibrator	DMM would be used to support various on-orbit functions. The calibration interval would depend on the accuracy required. An interval of 3 to 5 years should be possible for the troubleshooting or maintenance of most systems (accuracy limited to 0.1%). A shorter interval would be required for more accurate applications. Voltage/current calibrator can be a voltage and current measuring instrument (and source). A self contained display and data interface would allow manual and automated use in calibrating various instruments (such as a DMM) and performing maintenance of various electrical/ electronic equipment. The calibrator could contain built-in primary voltage, resistance and AC to DC transfer standards and use automated calibration techniques to improve accuracy. Calibrated accessories could be included for high power/ current/voltage applications. Equipment needs further development to be practical for on-orbit use.
- Current	0-300 A 0.1%			
- Resistance	1 mohm to 100 Mohm 0.1%			

Table 2.9 Task 2, Assessment of Calibration Techniques for On-Orbit Use System: Servicing System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
– Capacitance/ Inductance (Reactance)	10 pF to 1000 uF 0.1% 10 nH to 100 mH 0.1% 0.1 ohm to 1 Mohm 1.0%	Impedance bridge (test and diagnostic equipment)	Standard capacitor/ inductor	Automated calibration could be accomplished by using internal long term standards recently developed (solid dielectric capacitors and thick film inductors). The calibration interval without internal standards would be limited to 1 - 2 years. Equipment needs further development to be practical for on orbit use.
High frequency electrical - Frequency/ time	1 Hz to 18 GHz 0.1 nsec to 30 years 10 ppm	Frequency counter	Atomic frequency standard Telemetry	A cesium atomic frequency standard provides the best possible accuracy. Space qualified equipment is presently in use. Propagation errors limit accuracy of telemetry. Calibration of frequency counters and other RF equipment can be performed continuously by interconnecting to standard.

Table 2.9 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Servicing System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- RF Power level/attenuation	-130 to +40db (continuous) 0.5 db 30 to 70 db (pulsed) 2.0 db	Power sensor/ spectral analyzer (test and diagnostic equipment)	Standard power sensor/standard attenuator	Background radiation may be a problem. Automated multifunction RF equipment lacks long term stability. Equipment may need recalibration every 2-3 years. Further development required.
- Distortion	0.1 to 10% 3.0%	Distortion analyzer (test and diagnostic equipment)	Precision sine wave generator/ narrow band filter	Function/frequency generator required to calibrate many AC measuring instruments (1-2 years). Equipment needs further development for on-orbit use.
Physical - Pressure	0-5000 psi 0.25%	Presision sensor Vacuum gages	Standard pressure sensor (accuracy better than 0.1%)	Long term high accuracy standards for on-orbit use are not currently available. Quartz pressure sensor can be used for high accuracy requirements but calibration interval is limited to 2 - 3 years. On-orbit primary pressure standard needs to be developed.

Table 2.9 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Servicing System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Temperature	Cryo to 250 Deg. F 0.1 Deg. F	PRT	SPRT	Calibration life depends on severity of use (1 to 5 years). One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.
	250 to 1000 Deg. F 1.0 Deg. F			Exposures to high temperatures reduce the useful life span and alter the calibration. May require frequent replacement of PRT or type "S" thermocouple with precalibrated elements (1year or less).
	>1000 Deg. F 5.0 Deg. F		Melting/freezing point standard	Available at several temperatures. Best accuracy. Life can be 10 years or more. Equipment needs further development for on-orbit use.
		Optical Radiometer	Black body/irradiance standard	Equipment needs further development to be practical for on-orbit use.
- Flow rate (liquid, gas)	TBD	Flow meter	Standard flow meter	When used on a limited basis calibration interval of standard could be up to 5 years. Some types of flow meters can be dimensionally verified. On-orbit primary flow standard needs to be developed.

Table 2.9 Task 2, Assessment of Calibration Techniques for On-Orbit Use System: Servicing System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
- Force (mass)	0-1000 lbs 1.0%	Load cell/strain gage	Standard load cell	Calibration interval for loads cells are 1 to 3 years. Primary standard for force calibration on-orbit needs development.
- Dimensional	Conventional ranges 0.0001 in.	Standard measurement equipment	Dimensional artifacts Laser interferometer(self calibrating)	Extreme care required for artifacts. Current dimensional equipment configuration not suitable for on-orbit use.
Optical				
- Spectral	UV, visible, IR TBD	Photometer/filter set	Standard sensor and spectral filter set	Spare sensor and filter set needed. Can be expendable or returned to earth for re-calibration (2 - 3 years). Susceptible to damage (scratches, contamination, over-exposure). Equipment needs further development for on-orbit use.
- Intensity	microwatt to watt/sq cm TBD	Photometer/filter set	Black body/irradiance standard	Equipment needs further development to be practical for on-orbit use.

Table 2.10 Task 2, Assessment of Calibration Techniques for On-Orbit Use

System: Guidance, Navigation & Control System

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Space station position with respect to earth				
- Latitude	-30 to +30 deg TBD	Ground/satellite tracking Star tracker	Stellar bodies	Conventional satellite technology
- Longitude	0 - 360 deg TBD	Ground/satellite tracking Star tracker	Stellar bodies	
- Altitude	300 - 500 km TBD	Ground tracking radar/laser	Timing of signal propagation	
- Attitude	Local vertical +/- 5 deg Yaw, pitch, roll, etc. 0.01 Deg.	Inertial system Star tracker Accelerometers	Star tracking (stellar bodies)	On-orbit calibration of inertial measurements needs further development. Fiber optic inertial sensors have been demonstrated.
- Distance	TBD	Ground tracking radar/laser	Time of signal propogation	Small errors are inherent due to atmospheric propogation.

Table 2.11 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Communications & Tracking System

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
RF/Microwave equipment performance				
- Frequency	10 MHz to 18 GHz 10 ppm	Crystal oscillators	Frequency counter	Calibration interval for quartz oscillators (in RF equipment) depends on accuracy required and drift rate. Can be 3 - 5 years. Continuous calibration can be accomplished by interconnection with on-board atomic frequency standard.
- Receiver sensitivity	› 0.1 microvolt 10.0%	Level detector	Signal source/attenuator	Test equipment and standards for On-orbit RF/microwave maintenance/calibration need to be developed. RF equipment may require recalibration or alignment every 3 to 5 years.
- Transmitter power	10 milliwatts to 20 watts 2 db	Standing Wave Ratio (SWR) bridge	Standard power sensor/attenuator	
Signal processing subsystems performance (S/S+N)	10 - 50 dB 2 db	System/design requirements	Noise source/analyzer	

Table 2.11 Task 2, Assessment of Calibration Techniques for On-Orbit Use System:Communications & Tracking System (Continued)

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Proximity determination				
- Range	0-20 miles in 3-D volume +/-(0.1%+0.5 cm)	Radar	Frequency counter	Calibration interval for quartz oscillators (in RF equipment) depends on accuracy required and drift rate can be 3 - 5 years. Continuous calibration can be accomplished by interconnection with on-board atomic frequency standard.
- Velocity	>1 cm/sec 1 cm/sec	Radar/laser (doppler)	Frequency counter	
- Angle	0-360 Deg 0.1 Deg.	Multi-axis ranging	Geometric verification (360 deg)	Standard measurement practice.

Table 2.12 Task 2, Assessment of Calibration Techniques for On-Orbit Use
System: Thermal Control System

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Heat flow rate (temperature)	0 - 10 kw 5.0% 0 to 200 deg F 5 Deg F	Thermistors	SPRT	Calibration life depends on severity of use (1 to 5 years). Shock can alter accuracy. One point recalibration of SPRT (e.g., ice point) can provide reasonable accuracy.
Liquid flow	0 - 160 lbs/ hr 5.0%	Differential pressure sensor	Standard pressure sensor	Standard sensor of better accuracy should be recalibrated periodically (2-3 years). Primary standard for on-orbit calibration needs to be developed.
Pressure	0 - 100 psi 2.0%	Pressure sensor	Standard pressure sensor	
Emissivity	0 - 100 % 3.0-5.0%	Optical pyrometer	Black body/irradiance standard	Optical temperature measurements have limited absolute accuracy, relative measurements to better than 0.1% are possible. Equipment needs further development to be practical for on-orbit use.

Table 2.13 Task 2, Assessment of Calibration Techniques for On-Orbit Use

System: Manned System

Measurement Requirements	Range/ Accuracy	Measurement Technique	Calibration Technique	On-Orbit Applicability
Leak rate	0 - 5 lbs/day max TBD	Acoustic emission	Standard leak	Needs further development for on-orbit application
Stress Strain Elongation Deflection	Design requirements TBD	Strain gages Optical fiber sensor Ultrasonics Holography	TBD	Needs further development for on-orbit application
Crack detection	Design requirements TBD	Acoustic emission (dynamic) Ultrasonic (static) X-ray Eddy current	NDE standards	Specific standards need to be developed for on orbit use.
Impact detection	TBD	Acoustic emission/ ultrasonic	TBD	Needs further development for on-orbit application.
Radiation monitoring	Electromagnetic range	Radiation sensor (semiconductor, film, Geiger counter)	Standard radiation source	Safety concerns with the standard source. 5 years life for semiconductor sensors. 90 days life for films. Film processing is a potential issue.
Maintenance work stations (test and diagnostic instruments)	Measurement requirements are similar to all items listed in Table 2.9, Servicing System, pages 69-74.			

2.C Task 3, Sensor Calibration Requirements

The results and discussion for this task are presented in Table 3. Data on specific types of sensors, their measurement applications, principles involved in calibrating these sensors, and comments concerning their advantages and limitations are included in the table. The specific sensors (for example, platinum resistance thermometer, quartz thermometer) included for each measurement category (for example, temperature) are candidate sensors that could be potentially used on-orbit (based on the specific application requirements). The information given in the comments column could be an aid in determining the applicability of a specific sensor for a particular application. Inputs were derived from the results of Task 1 and sensors used on earth and NSTS. Additional inputs were obtained from manufacturers' data books, metrology documents, etc.

There will be several hundreds of sensors aboard the Space Station with pressure, flow, and temperature sensors probably being used in the largest quantity. Resource and energy conservation will be a major concern aboard the Space Station with sensor data being used to determine usage rates and reserves. To allow detection of impending malfunctions, sensors must be as accurate as possible. Intercomparison of multiple sensors may be beneficial in evaluating the operation of various systems. However, the requirement for failure isolation of subsystem elements will limit the degree of correlation possible between data obtained from different sensory inputs.

Sensor drift is inevitable; therefore, some method must be provided to recalibrate the basic function of each sensor, which is to convert a measured condition into an useable output. Most sensors provide some form of analog electrical output, such as, proportional voltage, current, resistance, or frequency. This output may require additional conditioning before being converted into a digital format. Some sensor calibration methods simulate the function of the sensor electrically and determine the errors of only the output and conditioning circuitry. To accurately characterize the performance of a sensor a direct comparison to an appropriate reference condition or a standard sensor of better accuracy must be performed.

The sensor may be tested in-situ; however, calibration over the full range of the sensor may be possible only if the sensor is removed and operated in a separate calibration/test fixture. Sensor replacement with another calibrated sensor may be necessary when practical on-orbit calibration methods do not exist or to improve calibration efficiency.

Primary conclusions are:

- Most types of sensors investigated exhibit some undesirable properties, such as, sensitivity to electromagnetic interference, response to ambient environmental conditions, and accuracy deterioration due to aging. Compensations for these properties, whether performed at the sensor element with additional circuitry or in the form of software constants or algorithms, must be repeatedly determined.

- Effects of on-orbit natural environment on the accuracy of many types of sensors have not been completely understood.

Primary recommendations are:

- Long term stability should be considered as one of the primary selection criteria for on-orbit sensors.

- Calibration techniques for sensors must include verification of primary function (such as pressure to voltage conversion) as well as a determination of all major compensation constants (temperature and aging coefficients).

- Sensor applications must provide for necessary calibration access and interfaces.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Pressure				
- Semiconductor	0-300,000 psi (0-10,0-100,0-1000,etc.) 0.25% of Full Scale (0.1% with multipoint temperature and aging compensation)	Absolute (psia) Differential (psid) Gage (psig) Vacuum (mm Hg) (Both gas & liquid)	Sensitivity (input pressure to electrical output), linearity, offset, etc. Temperature effects must be considered if application differs from calibration temperature.	Temperature compensating components can be included on the substrate. Poor linearity requires multiple calibration constants. Drift (sensitivity, zero) can be as great as 1% per year in harsh environments.
- Piezoelectric	0-300,00 psi (0-10,0-100,0-1000,etc.) 0.25% of Full Scale (static) 2.0% (dynamic)	Absolute (psia) Differential (psid) Gage (psig) Vacuum (mm Hg) (Both gas & liquid) Best suited for very high speed measurements	Sensitivity (input pressure to electrical output), linearity, offset, etc. Temperature effects must be considered if application differs from calibration temperature.	Wide range, shock and vibration resistance, low mass. Has large temperature coefficient. Dynamic calibration is difficult.
- Foil strain gage	0-300,000 psi (0-10,0-100,0-1000,etc.) 0.25% of Full Scale	Absolute (psia) Differential (psid) Gage (psig) Vacuum (mm Hg) (Both gas & liquid)	Output sensitivity (mV/V/psi), linearity, zero offset, and hysterisis.	Poor zero stability but better linearity and full scale stability than semiconductor types. Requires less complicated compensation. Zero drift is greatest cause of error.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
- Electromechanical	0-20,000 psi 0.1% of Full Scale	Absolute (psia) Gage (psig) Vacuum (mm Hg) (Both gas & liquid) (can be enclosed in a ported chamber for differential (psid))	Full scale, linearity, and zero.	Bourdon tube mechanically linked to potentiometer. Sensitive to vibration and shock. Exhibits large hysterisis. Usually has a linear temperature coefficient.
- Quartz Crystal	0-11,000 psi 0.01% of Full Scale	Absolute (psia) (Both gas & liquid) High accuracy measurements	Linearity, zero, hysterisis and temperature coefficient.	Has high resolution, accuracy, long life. Recent developments allow use as secondary standard. Requires compensation for large temperature coefficient. Aging rate is less than 0.01% per year. Best suited for on-orbit use as transfer pressure standard.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy *	Sensor Uses	Calibration Principles	Comments
Temperature			Requires compensation for cold junction. Measuring instrument requires multiple calibration constants to compensate for non linear output.	Simple, economical measurement technique. Voltage is generated by temperature differential over entire length (not junction only). Accuracy depends on material homogeneity, subject to stress, corrosion, heat treating, and reactive atmospheres; involves low signal levels; sensitive to electromagnetic interference. Thermocouple applications should be thoroughly evaluated and alternative methods considered.
- Thermocouples				
--- "J" type	-210 to +760 deg C 1.1-2.9 deg C	Not recommended for low temperatures, high humidity		
--- "K" type	-270 to +1372 deg C 1.1-2.9 deg C	Not stable over 500 deg C		
--- "T" type	-270 to +400 deg C 0.8-2.9 deg C	High humidity, vacuum		
--- "E" type	-270 to +1000 deg C 1.7-4.4 deg C	Low temperatures, oxidizing atmospheres		
--- "S" type	-50 to +1768 deg C 1.4-3.8 deg C	High temperatures, short term high accuracy transfer standard over 700 deg C		

* NIST specified material range/accuracy.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
- Thermistors	-100 to +200 deg C 0.1 deg C (compensated)	Gas Fluids Solids	Linearity, self-heating coefficient, and zero offset.	Low mass of sensor gives fast response, good sensitivity. Has limited range, poor linearity, poor stability and fragile.
- PRT's	-200 to +850 deg C 0.001 deg C	Gas Fluids Solids	Linearity, self-heating, thermal EMF offset, and zero offset.	Long term stability (1-5 years). Best suited for use as on-orbit standard.
- Infrared	-60 to +2760 deg C 1.0% of reading	Steam Fluids Solids Moving targets	Spectral response, focal distance, thermal linearity, and distance/linearity and emissivity coefficients.	Non-contact, high temperature range, fast response, is sensitive to distance, emissivity, and spectral response of target.
- Quartz crystal	-100 to +250 deg C 0.04 deg C	Gas Fluids Solids	Sensitivity (temperature to frequency), crystal linearity, zero offset, and hysterisis.	Resolution (typically 0.0005C) is many times better than absolute accuracy.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Humidity				
- Semiconductor	0-100% RH 1.0% RH	Atmospheric humidity	Linearity, zero offset, and temperature and pressure coefficients.	Calibration interval is limited to 1 year or less. Recent application as trace moisture detector. Requires humidity standard for recalibration. Small size permits use as replaceable sensor.
- Psychrometer	10-100% RH 2.0% RH	Ventillation	Accuracy of thermometers	Simple temperature calibration (1-2 years)
- Optical dew Pointer	-80 to 60 deg C 0.1 deg C	Atmospheric humidity, trace moisture	Mirror cleanliness and linearity/accuracy of temperature sensors.	Requires more support circuitry and equipment than other methods. Does not require humidity standard for calibration.

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Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Flow				
- Vortex (Piezoelectric stress)	0.5-4000 GPM 3-30,000 SCFM 13-130,000 lb/hr 1.0% of Rate	Liquids Gases Steam	Linearity and the coefficients of viscosity and pressure loss.	Measurement media effects (viscosity, pressure, temperature) must be considered.
- Pitot tube	100-21,000 GPM 1.0% of Rate	Gases Steam	Linearity and the coefficients of viscosity, pressure loss, and temperature.	Pressure, temperature compensation required.
- Piston-spring	0-150 GPM 0-500 SCFM 5.0% of Full Scale	Fluid flow Gas flow	Linearity and the coefficients of temperature and pressure.	Measurement media effects (viscosity, pressure, temperature) must be considered. Limited temperature and pressure ranges.
- Heated sensor (Thermal anemometer)	5-10,000 FPM 0-500 SCCM 0-50 SLM 2.0% of Full Scale	Gas velocity Gas flow (mass)	Linearity.	No temperature or pressure compensation required.
- Rotating vane	40-8,000 FPM 0.5% of Reading	Gas velocity	Sensitivity, linearity.	Pressure, temperature compensation required. Subject to errors due to wear.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
- Heated tube	0-500 SLM 0-5000 SCCM 1.0% of Full Scale	Gas flow (mass)	Linearity	No temperature or pressure compensation required.
- Ultrasonic (Doppler)	0.5-20 FPS 5.0% of Full Scale	Liquid flow	Accuracy, sensitivity of frequency counter.	Requires suspended particles (>5 ppm) or bubbles (>30 microns).
- Turbine	0.5-650 US GPM 0.25% of Reading	Liquids	Frequency, pressure, temperature, and viscosity coefficients	Moving parts are subject to wear.
- Positive displacement	0.1-100 LPM 0.5% of Rate	Liquids	Volume per cycle	Can be used with liquid and semi-solid waste.
- Magnetic	0-5000 GPM 0.5% of Rate	Liquids	Linearity of voltage output and the electromagnetic excitation frequency.	Conductivity of liquid can affect output accuracy.
- Corolis (Vibration/ mass)	1-3,500 lb/min 0.5% of Reading	Liquids	Linearity of the input and the output voltage and electromagnetic excitation frequency. Determine the pressure loss coefficient.	Mass measuring instrument that does not depend on local gravity. Potential for on-orbit use is good,

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Rotation (RPM)				
- Photocell	5-500,000 RPM 1 RPM	RPM (speed)	Accuracy, sensitivity of frequency counter and the response of the photocell.	Can be non-contact measurement; measurement surface must have light/dark demarcations; can be very accurate. Light source required.
- Contact (mechanical)	0-50,000 RPM 0.5 RPM	RPM (speed)	Accuracy, sensitivity of frequency counter and mechanical transducer.	Mechanical connection (friction, etc.) to measurement object may be source of error.
- Magnetic	10-100,000 RPM 0.1%	RPM (speed)	Accuracy, sensitivity of frequency counter.	Non-contact measurement. Magnetic properties of rotating object must be known (number of gear teeth, keyway, etc.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Vibration				
- Piezoelectric	0-100,000G 0.5% of Reading	Acceleration Vibration Sound	Linearity, noise rejection, sensitivity, zero offset, and temperature coefficients.	Self excited, requires no power sources. Fast response applicable to impact detection. Signal levels for small amplitude vibrations require special circuitry (charge amplifier).
- Variable capacitance	0-30G 0.5% of Reading	Acceleration Vibration	Linearity, sensitivity, zero offset, and temperature coefficients.	Active self test and shunt calibration are possible. Has narrow range and large temperature coefficient.
- Piezoresistive	0-200,000G 0.5% of Reading	Acceleration Vibration Sound	Linearity, sensitivity, zero offset, and temperature coefficients.	Very wide bandwidth. Less signal distortion than above method.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Voltage				
- Bridge/Divider	1 microvolt-1000 V 0.001% of Reading VDC 0.01% of Reading VAC	AC/DC Voltage signal conditioning, ratio measurement	Terminal linearity and frequency response of the bridge/divider, zero offset and temperature coefficient.	Fixed ratio (10:1) or variable. Can be self calibrating.
- Inductive (Transformer)	0-1000 V (in circuit) 0-120,000 V (proximity) 0.1% of Reading (in circuit) 5.0% of Reading (proximity)	AC/DC Voltage	Ratio accuracy and frequency response.	Has long term stability. Limited frequency range. Accuracy affected by phase angle of AC or pulsed DC signals and loading.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Current				
- Shunt	1 microamp-10 amps 0.1% of Reading	DC Current	Resistance, power coefficient and temperature coefficient.	Long term stability.
- Inductive (Transformer)	0-1000 amps 0-10000 hertz 0.2% of Reading	AC/DC Current	Ratio accuracy and frequency response.	Long term stability. Limited frequency range. Accuracy affected by phase angle of AC or pulsed DC signals and loading.
- Magnetic	0-15 amps 3.0% of Reading	DC Current	Linearity, zero offset and temperature coefficient.	Non-contact method useful for troubleshooting and maintenance of electrical circuits.
- Hall effect	0-3000 amps 0-200000 hertz 0.5% of Reading	AC/DC Current	Linearity and frequency response, zero offset and temperature coefficient.	Recent developments show potential for use as accurate current sensor.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Magnetic flux - Gauss (Telsa)	100 mg-20 kg 20 mT-2 T 0.1% of Full Scale	Magnetic field measurements (flux density, directivity)	Sensitivity, linearity and zero offset. Should be calibrated with instrumentation.	Up to three axis measurement capability. Limited frequency range, probe must be periodically demagnetized.
Strain - Strain gages	10-50,000 Microstrain 1% of Full range	Compression Tension Bend Elongation Axial, shear, torsional loads Residual stress Displacement	Sensitivity (mV/V/input), linearity, zero offset, hysterisis, and temperature coefficient.	Used to sense pressure or force but must be calibrated after assembly or attachment.
Radiation - Geiger-Mueller	0-100 mR/Hr 0-50,000 cpm 5.0% of Reading	Ionizing radiation (all types)	Sensitivity and zero offset.	Not very selective (spectral).
Light - Photocell	0-50,000 LUX 1.0% of Reading	Optical intensity	Linearity, sensitivity, dark current, and spectral response.	Composition of sensor determines spectral response which can be altered with filters.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Leak				
- Acoustic	Sensitivity - 1 nbar (sound pressure)	Gas Fluids Vacuum Pressure Steam	Sensitivity, bandwidth.	Used for detection, calibrated only for minimum detectable leak.
Thickness				
- Ultrasonic	0.003-20 inches 0.1%	Thickness, corrosion detection, etc.	Sensitivity, linearity	Material coefficients (velocity) must be known.
- Electromagnetic	0-6 inch 0.1%	Coating thickness (magnetic or nonmagnetic materials)	Sensitivity, linearity and zero offset.	Must be recalibrated for each coating/substrate combination.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Gas detectors (Electrochemical)			Sensitivity, linearity and zero offset. Temperature, humidity, and pressure coefficients.	Short life span. Response to other gases may affect accuracy.
- Oxygen	0-100% O_2 0.5% of Reading	O_2 monitoring		
- Carbon monoxide	0-5000 ppm CO 1.0% of Reading	CO monitoring		
- Hydrogen sulphide	0-200 ppm H_2S 1.0% of Reading	Hydrogen sulfide (H_2S) monitoring		
- Chlorine	0-10 ppm CL_2 1.0% of Reading	Chlorine (Cl_2) monitoring		
- Combustible gases	0-100% 1.0% of Reading	Hydrogen, methane, etc.		

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Water analysis				
- pH	-2 to +20 ph 0.01 pH	Acidity/alkalinity	Sensitivity, linearity and zero offset, temperature and pressure coefficients.	Thermal and pressure effects, short life span, easily contaminated.
- Conductivity	10-5000 ppm 0-200,000 umhos 0-1,000,000 uS/cm 0.5% of Reading	Contamination (minerals, dissolved materials)		
- Ions (specific)	0.00001-100,000 counts 0.1% of Reading	Ionic contamination		Ion probes can be either a general ion measurement or specific ion selective.
- Oxygen (Dissolved)	0-200% 0-20 mg/L 0-20,000 ppm 1% of Reading	Contamination (Biological)		
- Solids (optical)	0-20 ppt 0-2000 ppm 0-200 counts 1.0% of Reading	Contamination (in suspension)	Calibration verified against test solution containing known quantity of particulates.	Chopped optical fibers are available as a SRM.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
RF Power				
- Power Sensor (Thermistor, thermocouple)	-40 to +20 dbm 0.5%	RF Power measurements	Effective efficiency and input SWR. Connector repeatability. Associated electronic circuitry can usually be calibrated with DC standards.	Very susceptible to damage from overload. Mismatch errors can be large at microwave frequencies. Power levels over 10 dbm require sensor/ attenuation combinations.
- Power Sensor (Semiconductor)	-60 to +20 dbm 2.0%	RF Power measurements (RF voltage)	Sensitivity and linearity in the linear and square law regions must be determined. RF voltage detector calibrated in terms of power with proper terminating impedance if not self contained.	When used at a single level or narrow power range, such as a detector for automatic level control of a RF gain stage, poor linearity may not be a problem.

Table 3 Task 3, Space Station Sensor Calibration Requirements

Type of Sensor	Range/ Accuracy	Sensor Uses	Calibration Principles	Comments
Optical Power				
- Photodiode (Silicon)	250-850 nm *	Precision Photometers	Electrical response of sensor to optical power. Broadband, weighted (usually filtered), or single line measurements depending on the application. Effective aperture and cosine response may also need to be measured. Some sensors require cryogenic cooling to provide desired response. Sensor dark current affected by temperature and other forms of electromagnetic radiation.	Measurement of optical radiance, irradiance, illumination, lumination, and spectral sensitivity differ in apparatus, techniques, and in units of measurement.
- Photodiode (Germanium)	800-1800 nm *	Near Infrared general purpose sensor		
- HgCdTe	5-16 um *	Far Infrared		
- PbS	1-3 um *	IR		
- Thermal detector	0.6-30 um *	Far Infrared		
- Photomultiplier Tube	200-800 um *	Low light levels		

* Accuracy of optical power levels are currently limited by primary standards maintained by NIST (0.5 to 5% from IR to UV)

2.D Task 4, Calibration Equipment Requirements

The Task 4 results pertaining to the assessment of available calibration equipment are presented in Table 4. The major measurement categories (temperature, pressure, etc.), description of pertinent available calibration equipment for each measurement category, and their on-orbit compatibility and deficiencies are included. Results of Tasks 1, 2, and 3 provided the inputs for this task. In addition, information obtained from equipment manufacturers' data books, metrology documents, discussions with equipment manufacturers, etc. was included in this assessment.

Most commercially available (on-ground) calibration equipment are not suitable for on-orbit use due to the minimal attention paid (during design and fabrication) to weight, size and power requirements. Some instruments, for example, a 100 ampere transconductance amplifier used for calibration of high current shunts and meters, are necessarily large and heavy. The volume efficiency (space utilized within the case) for many instruments is 40% or less. Common circuitry (such as, power supplies, displays, control panels, automation interfaces) of specialized, single purpose instruments usually account for up to 70% of the total weight.

Some examples of additional design deficiencies in currently available commercial equipment include the following. The internal thermal stability of many electronic instruments depends on thermal convection, which is absent in micro-g environment. This would severely impact the design of many high accuracy instruments which typically have a temperature specification of +/- 1 degree C. Further, transporting some delicate instruments may be difficult due to the sensitive mechanical components that may be present in these instruments. Many instruments are only moderately shielded against electromagnetic interference (EMI) and cannot be operated in close proximity to radiating equipment. A shielded enclosure or room (functioning as a Farraday cage) must be used to isolate some calibrations from outside interference. The shielding provided by the Space Station will perform the opposite by containing interference sources within the small interior volume of the modules.

Primary conclusions are:

- Vast majority of available calibration equipment cannot be used on-orbit without some redesigning and repackaging to reduce excess weight, size or volume.

- Redundant circuitry of individual equipment could be minimized or eliminated to achieve compactness, commonality, integration and weight savings by reducing the need for separate power supplies, displays, control panels, etc. for each equipment.

- Additional deficiencies (for example, instability, gravity dependence, sensitivity to natural environment) that are specific to a particular equipment were identified.

Primary recommendations are:

- Identify in detail the type of calibration equipment required for sustained operation.

- Develop an equipment commonality list to aid in the integration process.

- Investigate the innovative design features required for long term stability.

- Develop approaches for space qualification of calibration equipment.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
TEMPERATURE	Platinum Resistance Thermometer (PRT): Range -200 degrees C to +850 degrees C, accuracy 0.002 degrees C (includes instrumentation error). Consists of platinum resistance element and precision resistance measuring system.	Generally one of the most accurate temperature measuring devices in this range. Can be used below -200 degrees C with reduced accuracy. Exhibits long term stability, if isolated from shock and repeated exposure to temperatures above 200 degrees C. Encapsulation of PRT element is necessary for use in external environment to space station. Best suited for on-orbit calibration.
	Platinum/Platinum-Rhodium Thermometer: Recommended range +650 degrees C to +1,050 degrees C, accuracy 0.2 degrees C (limited use). Consists of Pt/Pt-Rh thermocouple probe and millivolt meter.	This device is the accepted transfer standard for this range. Generally thermocouples are sensitive to stress concentrations, reactive atmospheres, and produce relatively low EMF's. May be sensitive to electromagnetic interference. These require reference junction compensation for use. With proper care the type-S thermocouple can be useable from -50 to +1768 deg C with an accuracy of a few degrees.
	Quartz Thermometer: Range -100 degrees C to +250 degrees C, accuracy 0.04 degrees C. Consists of a quartz crystal probe which is a part of an oscillator/frequency counter. The resonance frequency of the quartz crystal is dependent on the temperature.	Provides exceptionally high resolution (0.0001 degrees C) for measuring temperature differences. It is extremely shock sensitive; does not exhibit long term stability and therefore requires frequent recalibration. Accuracy of quartz crystal may be affected by on-orbit magnetic and gravitational field variations.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
TEMPERATURE (cont.)	Thermistor Temperature Measurement System: Range -100 to +200C, accuracy 0.1 deg C (limited range accuracies to 0.05 deg C). Consists of a semi-conductor sensor with a nonlinear temperature to resistance response and a resistance measuring instrument.	Change in resistance per degree temperature is much greater than PRT. This allows the use of less sophisticated resistance measuring instrument. The thermistor is compatible with integrated circuit technology and can be included in hybrid electronic circuits. Materials used in making thermistors are not chemically stable and therefore have limited life requiring frequent recalibrations and/or sensor replacements. For on-orbit application, the simple electronics and small size of the sensors are an advantage. Can be a risk for imbedded applications because of their unstable nature. Can be utilized as economical throw-away sensors, when size and economy are critical.
	Radiation/Infrared Pyrometers: Range 1,000 to 5,000 degrees F, accuracy 1% of measurement. Other ranges are available but not accepted by NIST as a calibration method due to non-reproducible results. Consists of an optical or infrared sensor and a voltage, current or resistance measuring device.	Only method available for high temperature ranges. Has the advantage of being noncontact and can provide remote measuring capability. Method is sensitive to the nature of the temperature source and should be qualified/validated for each specific application. For calibration, a temperature source of known thermographic properties such as a black body is required. Stellar sources can potentially be used as standards but this may require further development and verification. Calibrations could be affected by background radiations. Technology could potentially be used on-orbit as-is.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
TEMPERATURE (cont.)	Melting/Freezing Point Temperature Reference Standards: Range - available at defined points over the entire International Practical Temperature Scale (IPTS), accuracy is the accepted international definition of temperature at that point. Practical devices are available to 0.0001 degrees C. Consists of means of heating or cooling a small quantity of a pure reference element to be maintained at the melting/freezing point. The sensor to be calibrated is placed in close thermal proximity to the reference material.	This is based on a physical constant of nature. Only those materials that exhibit long term stability are used. It can be packaged to limit the effects of impurities. Miniaturization and efficiency should be addressed for on-orbit use.
PRESSURE	Primary Calibration Standards: No primary standards for on-orbit use currently exists. Present designs of dead weight piston gages or liquid column pressure standards are not compatible with micro-g environment.	Recent development in quartz pressure sensors should be investigated for use as secondary pressure standard.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
PRESSURE (cont.)	Strain gage (Bonded or Semiconductor Substrate) Pressure Sensor: Specific ranges from 0-300,000 psi, accuracies from 0.1% to 1.0% of the full scale. Consists of a strain gage bridge and an electrical ratio measuring device.	This is a simple technology to use for most applications including dynamic and differential pressure measurements. Mechanical and electrical instability limit useful calibration life to one year or two years. Sensor response to temperature variations must be compensated for to achieve above stated accuracies. Generally sensitive to shocks and overpressure. Replacement of directly bonded sensors (Strain gages) will be difficult.
	Electro-Mechanical Pressure Devices: Specific ranges from 0 to 20,000 psi, best available accuracy 0.1% full scale. Consists of mechanical element (diaphragm or Bourdon tube) coupled to potentiometric resistance element and resistance measuring instrument.	Mechanical devices usually require disassembly for adjustments. Not suitable for rugged applications and extreme environmental conditions. Not recommended for on-orbit applications.
	Quartz Crystal Pressure Devices: Range 10 to 20,000 psi, accuracies up to 0.01%. Consists of a quartz crystal sensor and a suitable parametric measurement device dependent on the mode of operation (capacitive, resonant, charge).	Superior mechanical properties of quartz (especially capacitance type) can provide long term stability as compared to other devices. Appears to be best suited of available calibration technologies for on-orbit applications.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
PRESSURE (cont.)	Low Pressure Measurements Devices (Ion gage, etc.): Constant vacuum standard available outside the station.	On-orbit vacuum is not zero, therefore suitable for vacuum calibrations to 10^{-3} torr only. High vacuum standard needs to be developed.
HUMIDITY	Optical Dewpointer: Range -80 degrees C to +60 degrees C dewpoint (less than 1% RH to >99% RH), accuracy 0.1 degree C (1% RH). Consists of a chilled mirror optical sensor with an integral temperature sensor, a closed loop temperature controller, and temperature measuring device.	Calibration requires optimization of temperature control loop, mirror temperature, and ambient temperature sensors. This basically requires temperature calibration only, which is an advantage, since temperature calibration techniques are well established. Long term stability can be easily achieved by assuring the cleanliness of the chilled mirror. Also used for trace moisture measurement. Size, power and weight of the equipment could limit on-orbit applicability.
	Wet/dry Bulb Psychrometer: Range 10 to 90% RH, accuracy 2% RH. Consists of a wet and dry temperature sensor (thermistor, PRT, etc.) and a two channel temperature measuring instrument. Relative humidity values are calculated from temperature measurements using standard formulas.	Calibration depends on temperature measurements only. A step in the calibration process requires moisturing the wet bulb and this is commonly done manually but can be automated. Appears to be best suited for on-orbit monitoring of ducts, ventilations, etc. Comments: Semiconductor humidity sensors should be investigated for on-orbit use. Recent developments have resulted in accuracy and stability improvements. Sensors can be expendable (replaced with precalibrated spares).

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
FORCE	Strain Gage (Load Cell) Force Measuring System: Range from 1 gm to 1 million lbs, accuracy 0.25%. Consists of a bridge type load cell and a voltage or resistance ratio measuring device.	Can be used in many configurations to measure linear (tension or compression) and rotational (torque) forces either statically or dynamically. This is a most commonly used method for force calibrations. Load cells are sensitive to shock and over-ranging. In-situ force (load cell) calibration techniques need further development for on-orbit applications.
	Electromagnetic Balance: Range 0.001 gm to 20 kgm, accuracy 5 ppm. Consists of an electromagnet, current source/measuring instrument, and feedback loop to measure the applied force.	Commonly used for weighing and limited other force measuring applications. Provides much greater accuracy than load cell in this range. Stability and accuracy depends on the number of turns (fixed) of wire in the electromagnet (fixed) and stability of the current measuring instrument. Initial calibration must be against a known force while subsequent calibration of just the electronic portion of the system may be adequate for less accurate applications. Force calibration of this device using mass standards (dead weight) will require further development.
	Hydraulic Force Calibrator: Range 1 to 300,000 lbs, accuracy 0.25%. Consists of a hydraulic/pressure source, pressure sensor, and appropriate piston/cylinders with known effective areas.	Can be used to generate or measure force for calibrating other instruments. Since this device can generate forces, it can compensate for the low gravity in space. Calibration is relatively simple and is based on sound piston/cylinder design, leak checks and a calibrated pressure sensor. Hydraulic system may need regular maintenance. In general the best suited method for on-orbit force calibration. The design of this device could have a high degree of commonality with some already planned tooling.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
FORCE (cont.)	Load Ring/Proving Ring Force Calibrator: Range 10 lbs to 300,000 lbs, accuracy 0.07% of reading. Consists of generally a stainless steel ring and a displacement measuring device (micrometer, LVDT, capacitor, or potentially laser interferometer) to measure dimensional changes in the ring caused by an applied force.	Currently it is the most accurate practical transfer standard for force calibration. Exhibits better long term stability than load cell technology. To achieve maximum accuracy calibration against a dead weight on earth would be required. Best suited for on-orbit applications where most critical force measurements are required.
	Piezoelectric force sensor: Range 0.1 gm to 1,000 kgm, accuracy 2%. Consists of a piezoelectric force or acceleration sensor and electrical charge measuring device. It measures applied dynamic forces through the generated electrical charge and known acceleration or inertial relationship.	Exhibits fast response for measuring rapidly applied dynamic forces. The technique is usually applied with expendable sensors. Could be useful for the on-orbit calibration of impact detection systems. It may not be practical to calibrate this sensor on-orbit.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
OPTICAL INTENSITY/ SPECTRAL	Precision Photometer: Range 1 microwatts/sq. cm to 10 milliwatts/sq cm, accuracy 0.5%. Consists of a semiconductor sensor and a microamp measuring instrument.	It is the simplest optical calibration technique. Wide range of sensors are available for various applications (UV, IR, laser power and optical fibers) that can be used with common measuring instrument. Sensor output may be affected by ionizing radiations and can also cause permanent change in response. Recalibration of sensor needs to be done on-ground to provide traceability. Some of the natural optical sources could be used as standards for certain ranges.
	Spectro-photometer: Range 200 nanometers to 900 nanometers, accuracy 1%. Consists of an optical dispersing element (prism, slit or diffraction grating) and a sensor array.	It can be used for measuring the spectral content of the original light source and transmitted or reflected light. It can be easily miniaturized. Traceability can be provided through SRM's (filters, material samples, etc.). Best suited for general spectral calibrations on-orbit.
	Photometric Optical Bench: Range can be configured for the entire optical spectrum, accuracy can be 0.1% or better. Consists of a calibrated light source, wavelength interferometer and an integrating sphere with associated equipment.	This device can be used as a primary standard and has the best available accuracy. It is a very complicated calibration technique in addition to being bulky for on-orbit applications. Accuracy limited by National Standards.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
RF INTERFERENCE	EMI/RFI Receiver: Range 0 to -130db (frequency 10MHZ to 18GHZ), accuracy of 2db. Consists of calibrated antenna or RF probe and a RF spectrum analyzer or tunable receiver.	Measurement of radiated RF levels is the only method capable of determining continued performance of shielding and filters. Passive probe has long term stability. Can be used inside or outside to measure leakage of RF energy. Partial calibration of measuring instrument may be possible with telemetry. Instrument commonality with other RF equipment requirements is possible.
RADIATION	Radiation sensor: Range (x-ray, gamma ray, cosmic radiation, etc.), accuracy 2-5%. Consists of a semiconductor sensor, secondary emission sensor or ion chamber and an electric current measuring instrument. Can also include a radiation source for recalibration of sensor.	Low level source can provide long term calibration capabilities. Background radiation may serve as potential standard for portions of the electromagnetic spectrum. With proper controls, on-board source will present minimal hazard.
MAGNETICFLUX	Gauss meter: Range 0-20K Gauss, accuracy 0.5%. Consists of magnetic (coil) probe sensor, and impedance measuring instrument.	Long term stability of probe (must be demagnetized periodically) is offset by relatively complicated circuitry associated with impedance measurement. Requires frequent recalibration. Magnetic field variations on-orbit may affect calibration at low flux densities. This technique is suitable for on-orbit calibration in higher flux densities, and for electromagnetic and superconductivity research.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
MAGNETIC FLUX (cont.)	Hall-effect magnetic flux standard: Range and accuracy TBD. Consists of a semiconductor Hall sensor that exhibits predictable characteristics (electrical) in a weak magnetic field (potentially 1 to 10 gauss).	Development of this device is not complete. Could provide permanent traceability for calibration of magnetic flux measurements.
MICRO-G	Micro-g (and acceleration) calibration equipment for on-orbit use need to be developed.	Micro-g measurement techniques need to be evaluated and developed.
RPM	Rotational Speed (RPM): Range 1 RPM - 50,000 RPM, accuracy 0.001%.	Digital RPM measuring instruments (encoders, stroboscopes, optical tachometers) that require infrequent calibration of frequency counter circuits are generally available. Their accuracy can exceed the capabilities of current mechanical requirements.
DIMENSIONAL	Hand Tool Calibration Standards: Range 0 to 6 inches, accuracy 0.0001". Includes calipers, micrometers, etc.	Essential for verifying conformance of precision dimensional measurements. Calibration standards are stable and usually constructed of hard alloys or ceramics (gage blocks, templates, thread gages, etc.). The ceramic standards (low temperature coefficient) are best suited for on-orbit applicability. However, they must be handled with care.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
DIMENSIONAL (cont.)	Laser Interferometry: Range from 1 micro-inch to greater than 300 yards; accuracy 0.1 ppm. Consists of a dual frequency laser source, differential interferometer and other associated optical components.	Provides very high accuracy and can be adapted to most dimensional calibration applications. It also provides self traceability. It is suitable for use in the space environment outside the station as well as inside. Since it uses a low power laser the safety requirements are minimal. It is somewhat sensitive to vibrations during measurement. Though can be used for a large number of applications, some engineering modifications will be required.
STRESS/STRAIN	Strain Gage: Range micro-inches/inch; accuracy 1%. Consists of the strain gage element and a millivoltage ration measuring instrument.	The most commonly used strain/stress measuring method. It is generally used for measuring local strain/stress. They are very small in size and have negligible mass and can be incorporated onto the structure. However, it needs to be bonded to the structure and therefore repair is not possible increasing redundancy requirements. Recalibration of the on-orbit replacement strain gages is not feasible. There is substantial amount of wiring required for multiple strain gages.
	Optical Fiber Strain Gages: Range TBD; accuracy TBD. Consists of optical fiber and a optical reflectometer.	This is an emerging technology with potential for use as imbedded or bonded sensor for primarily composite structures (smart structures). The use as imbedded sensors for multiaxial strain/stress measurements require them to be incorporated in the manufacturing process. Calibration of optical fibers need to be developed.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
STRESS/STRAIN (cont.)	Laser Holography: Range 50 (2 millionths of an inch) nanometers to 10,000 nanometers (400 millionths of an inch). Accuracy 50 nanometers. Consists of holographic projection system and image analysis system for fringe interpretation.	This technique is in the final stages of development for practical applications. Holds potential for large area, relative or absolute, stress/strain measurements. It is noncontact technique. Technology appears to be potentially well suited for on-orbit application.
	Ultrasonic Stress Monitor: Range >5,000 psi; accuracy 1,000 psi. Consists of an ultrasonic transducer and a signal analyzer.	It is a more accurate method of measuring bolt tension than torque reading. It can also be used for measuring residual and applied stresses in structural members; but may need some additional development for practical applications. For on-orbit applications a suitable ultrasonic couplant needs to be developed.
MASS CALIBRATIONS	Mass Standards: Range 1 mgm to 10 kbms; accuracy 1 ppm. Consists of a series of reference artifacts in the above range.	It has long term (potentially for 30 years) stability when properly cared for. The standards may have to be configured (shape) for specific on-orbit applications.
	Mass Measurements: Mass measurement techniques for operational and research applications need further development.	Mass measuring equipment needs further evaluation.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
FLOW CALIBRATIONS	Standard Flow Meter: Range is dependent on application; standard flow meter should be selected to be more accurate than the measuring device. Consists of flow meter that is either substituted for or place in series with the measuring device to provide comparative calibration.	Interruption to flow may be necessary for flow calibration process. Flow meters that are dependent on gravity or thermal convection will not be suitable for on-orbit applications.
	Mass Flow Meter: Range 1 to 3,500 lbs/min; accuracy 0.5%. Consists of a dynamic mass measuring device (vibrating tube and phase detector).	This technique uses a constant cross section flow path with no associated restrictions and therefore has not parts that could wear or erode. Further development may be necessary for on-orbit applications.
	Volumetric Flow Calibrator: Range 1 SCCM to 1,000 SLM; accuracy: 0.1%. Consists of variable closed volume (piston/cylinder or bell prover), and a timer to determine time required for flow a specified volume (flow rate).	Definable primary standard for flow calibrations. Most accurate for direct flow calibrations, but not suitable for on-orbit use. For on-orbit applications the on-ground methods will have to be modified to compensate for the role of gravity.
		General comment: The on-orbit applications of flow measurements and calibrations need further development.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
CALIBRATIONS UTILIZING STANDARD REFERENCE MATERIALS (SRM's)	A variety of SRM's are available that provide direct traceability to recognized standards. Gas Composition (pure and mixture): Oxygen, CO, CO2, Nitrogen, water vapor, aliphatic and aromatic hydrocarbons, ammonia, outgassing species, H2S, halogenated hydrocarbons, hydrogen, trichloroethylene, etc. and mixtures thereof. Liquid and Solid Composition: Spectrometric solutions, ph indicator, clinical solutions, alloys, polymers, trace materials, particulates, fibers, ionic materials, etc. Radiation Standards: Radioactive sources, radioisotopes, X-ray sources, particle sources, gamma ray sources, photon sources, etc.	Stability of SRM's (on-orbit) must be evaluated on an individual basis. Comments: SRM's may not be available for specific applications and therefore may have to be tailored. Some SRM's have limited use or storage life requiring periodic resupply. The on-orbit environment may affect the stability of some SRM's and may also affect their chemical nature.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
CALIBRATIONS UTILIZING STANDARD REFERENCE MATERIALS (SRM's) (cont.)	Physical Standards: Viscosity, harness, molecular weight, conductivity, magnification standards, coating thickness standards, optical density, colorimetry standards, density, acoustic transducers, calorimetric standards, temperature references, standard leaks, etc.	See comments on previous page (113).
ELECTRICAL CALIBRATION	Zener Voltage Standard: Range 10.000000V, Accuracy 0.5 ppm (Initial). Consists of a Zener diode (6.2 volts) in a constant temperature enclosure to provide a source of accurate and stable DC Volts.	Recent development in electrical calibration technology. Appears to be more suitable for on-orbit calibration than saturated standard cells or present Josephson array designs. Exhibits predictable drift thus extending use for longer periods. Can be incorporated into equipment designs as an internal voltage reference. The Zener reference exhibits thermal and current hysterisis therefore requiring accurate temperature control and constant power. Accuracy may be affected by Ionizing radiation since current designs are not radiation hardened.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
ELECTRICAL CALIBRATION (cont.)	Analog voltage to digital converter: Range 0-10V, Accuracy 5 ppm + 1 uV. Consists of a high resolution (20 bit or greater) A-D converter, input signal conditioning, and data interface.	This device when used in conjunction with a Zener voltage reference provides a capability for calibrating sensor/transducer outputs. When used with input signal conditioning such as operational amplifiers or resistive dividers can measure voltages in the range of <1 uV to several thousand volts. This device is the basic data conversion element for most parametric measurements.
	Standard Resistors: Range 1 mOhm to 100MOhm, Accuracy 1 to 5 ppm. Consists of a sealed wire wound fixed resistor.	Standard Resistor must be constructed of a material that demonstrates highly stable resistance and a low thermal coefficient of resistivity. Present designs use pre-aged manganin alloys and are suitable for on-orbit applications. Resistors constructed using thick film semiconductor technology do not presently exhibit the long term stability of manganin resistors. Further development of this technology could provide miniaturation of these devices. Thermal shock or electrical overload can cause a permanent shift of resistance.
	Current Comparator: Range 1 nA to 1 mA, Accuracy 0.1 ppm. Consists of a toroidal-transformer and a detector bridge circuit.	Measurements are performed through a precise determination of ratio to a reference standard. Permanent accuracy is assured by the fixed turns ratio of the transformer. Shielding will be necessary to reduce susceptibility to varying magnetic fields for on-orbit use. In various configurations this instrument can be used for accurate measurements of AC current, DC current, resistance, resistance thermometry, and capacitance. Further development of this technology is necessary to provide extremely long term standards for on-orbit use.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
ELECTRICAL CALIBRATION (cont.)	Thermal Voltage Transfer Standard: Range 0.1 to 1,000 VAC (5 Hz to 1 MHz), Accuracy 50 ppm. Consists of a thermal element (thermocouple or hybrid semiconductor), low reactance range resistors, and a null detector.	The nearly equal response of the thermal element to the effective power of direct current and alternating current (RMS) allows the use of DC calibration standards for highly accurate AC measurements. Various thermal elements and shunts can be used to extend this technique to frequencies up to 1.2 GHz and to measure AC currents up to 200 amperes. These devices are well suited for on orbit applications.
	Impedance Measurement System: Range small values to big values, Accuracy 0.001%. Consists of an AC detector bridge, ratio transformer, null detector, AC voltage generator, and an internal standard capacitor.	Suitable for measuring complex impedances, capacitance, inductance, and dielectric properties. For on-orbit use this technique would require isolation from electromagnetic and electrostatic disturbances. This capability may be necessary for special on-orbit calibration and maintenance activities.
FREQUENCY AND TIME STANDARDS	Quartz Reference Oscillator: 10 MGz, 1 ppm. Consists of a quartz crystal resonator, temperature controlled chamber, digital frequency divider, and an output buffer amplifier.	A quartz oscillator provides short term frequency traceability. Phase lock loop circuitry can provide a wide range of frequency outputs (for example 123456 Hz). Aging effects and temperature coefficients limit this technology to short term on-orbit applications. Periodic calibrations (frequency adjustment) must be performed. Telemetry may be used to provide long term calibration traceability but accuracy is limited to 0.1 ppm due to radio propagational variations.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
FREQUENCY AND TIME STANDARDS (cont.)	Atomic Resonance Frequency Standard: 10 MHz, 0.1 ppb. Consists of a Cesium atomic beam oscillator, a voltage controlled quartz oscillator, and phase lock loop feedback circuitry.	This device is a true primary standard and requires no other reference for calibration traceability. Phase lock loop circuitry can also be used with this device to provide a wide range of frequency outputs (for example 123456.7890 Hz). Atomic frequency standards are presently being used in space.
	Frequency Counter: Range 0.001 Hz to 40 GHz, Accuracy depends on reference standard. Consists of input signal counter and time base divider to compare the ratio of the input signal to the reference frequency.	This technology is also currently in use in space.
	RF Power (Absolute and Relative) Measurement System: Range -120dbm to +50dbm, accuracy 0.1dB+0.1db/10db. Consists of coaxial thermistor rf power detector, a programmable precision attenuator, and associated circuitry to measure or control the heat generated in the detector by RF energy.	This system is used to calibrate several types of RF systems (transmitters, receivers, etc.) and test and measuring equipment such as power meters, spectrum analyzers, and other communication equipment. The power sensor and attenuator must be calibrated against a higher accuracy primary standard. Further development of this technology is necessary to provide long term traceability for on-orbit use.

TABLE 4 TASK 4, Assessment of Available Calibration Equipment (cont.)

TYPE OF MEASUREMENT	CALIBRATION EQUIPMENT AND DESCRIPTION	ON ORBIT COMPATIBILITY/ DEFICIENCIES
ADDITIONAL ELECTRONIC MEASUREMENT AND CALIBRATION EQUIPMENT	Generator: Audio, rf, and microwave frequency; precision signal level; pulse/function; and data word. Analyzers: Spectrum; waveform; modulation; data Meters: Digital multimeter; power; SWR; temperature Accessories: RF terminations; resistors; capacitors; waveguide and coaxial connectors; active probes; test cables	This equipment may require periodic calibration to the electrical standards listed in this section (pages 114-116) to assure the accuracy of measurements and calibrations performed on-orbit.

2.E Task 5, Traceability Requirements

Some of the inputs for this task were derived from the results of Tasks 1 through 4. Additional inputs were obtained from metrology literature, and discussions with metrologists in industry and government. Details of the results and discussion are included in the later paragraphs of this section. The primary conclusions and recommendations are presented first.

Primary conclusions are:

- Traceability for initial operation will be provided by the use of on-ground precalibrated instrumentation.

- Near term traceability for subsequent calibrations can be provided through the use of secondary transfer standards transported between the station and the earth.

- Long term traceability will require development of on-orbit primary standards to reduce the burden of repeatedly transporting the secondary standards into space.

- The in-space natural environment could potentially be better utilized to provide calibration standards.

Primary recommendations are:

- Develop detailed traceability approaches for near term operation.

- Determine feasibility and develop techniques for providing resident (on-board) primary reference standards.

- Research and develop methods for better utilizing the in-space natural environment as primary reference standards.

- Perform drift trending of appropriate data (with known uncertainties) to improve confidence in calibration.

Constancy of measurement accuracy over time is only possible through the use of highly stable reference standards, and a well defined and traceable path between the measured value and the value of the standard. Traceability of measurement data is necessary to assure that hardware specifications, operational performance and scientific experimentation meet design requirements. On Earth, traceability is accomplished through the direct comparison of measurement apparatus to standards of better accuracy and proven traceability to accepted national standards such as those maintained by the National Institute for Standards and Technology (NIST). Several levels of standards are used, with each level being compared to next higher level, since it is not practical to compare all measuring instruments directly to the national standards at NIST. Any discrepancies in accuracy detected during this process (calibration) are documented or eliminated (by adjustment). Accepted values of natural constants are also used to provide traceability (through definition) for some measurements. Examples of these include atomic resonance (unit of time-second), wavelength of light (the meter), and various properties of pure chemical substances. A transfer device is necessary when the use of a natural standard is not practical for a particular application.

Initial (first time) calibration of a measuring instrument does not provide long term traceability unless the tendency of the instrument to drift over time is determined and quantified. Since all measuring instruments can be expected to exhibit some degree of drift, confidence in measurement accuracy always deteriorates with time. Drift rates are seldom linear and must be recomputed periodically over the life of the measurement instrument. The initial calibration uncertainties (sum of all possible sources of error), the measured rate of drift, and the criticality of the measurement application (confidence requirements) limit the maximum interval between calibrations.

Measurement traceability for the Space Station will be an even greater challenge than it is on Earth. All traceability paths must be based on universally accepted standards. Although the International System (SI) of measurements will be used to define values of all primary standards, differences in techniques and apparatus for the practical realization of these standards may create small disagreements among the international partners. Discrepancies caused by misalignment of the respective standards of each international partner will be difficult to resolve in space. The remoteness of space, effects of the natural environment, and the constraints of weight, volume, and power placed on all payloads will make providing continuous traceability to the Space Station a substantial task.

Very few techniques exist that can provide accurate measurement capabilities (without periodic recalibration or replacement) for the thirty year life of the Space Station. Figure 2 shows the major measurement/calibration categories required for long term operation in space. The natural environment can satisfy (with current calibration technology) only a few of these requirements. Reference standards for some categories currently exhibit long term (greater than ten years) stability and would require infrequent renewal (with minor engineering or design adjustments for on-orbit application). These categories are shown as semi-permanent capabilities aboard the Space Station. Telemetry (Space Station to Earth) will be useful for the analysis of measurement data and detecting trends in operational performance which may indicate system malfunctions. With the exception of measurements based only on frequency (or time), telemetry cannot provide the necessary traceability for the measurement of physical parameters or the subsequent conversion of analog information into a digital format. These must be verified by comparison to appropriate reference conditions. Traceability for most categories, however, will require that calibration transfer standards be transported to the Space Station or that on board equipment be replaced (ORU's) and returned to earth at regular intervals. Approaches to providing traceability for each of the measurement categories identified in Figure 2 are described in the following paragraphs.

MASS

Mass artifact standards (weights) maintained on board the Space Station can be expected to remain stable for many years, if protected from exposure to environmental factors that could cause a loss of mass (corrosion) or a mass gain (contamination). Intercomparison of individual weights within a set or visual inspection for damage can be used to extend confidence in mass standards indefinitely for limited accuracy applications (for example, using a highly polished class "S" set for a class "F" application). Techniques and apparatus for mass measurement in space need to be developed and also the material, shape, and coating requirements for on-orbit mass standards needs to be

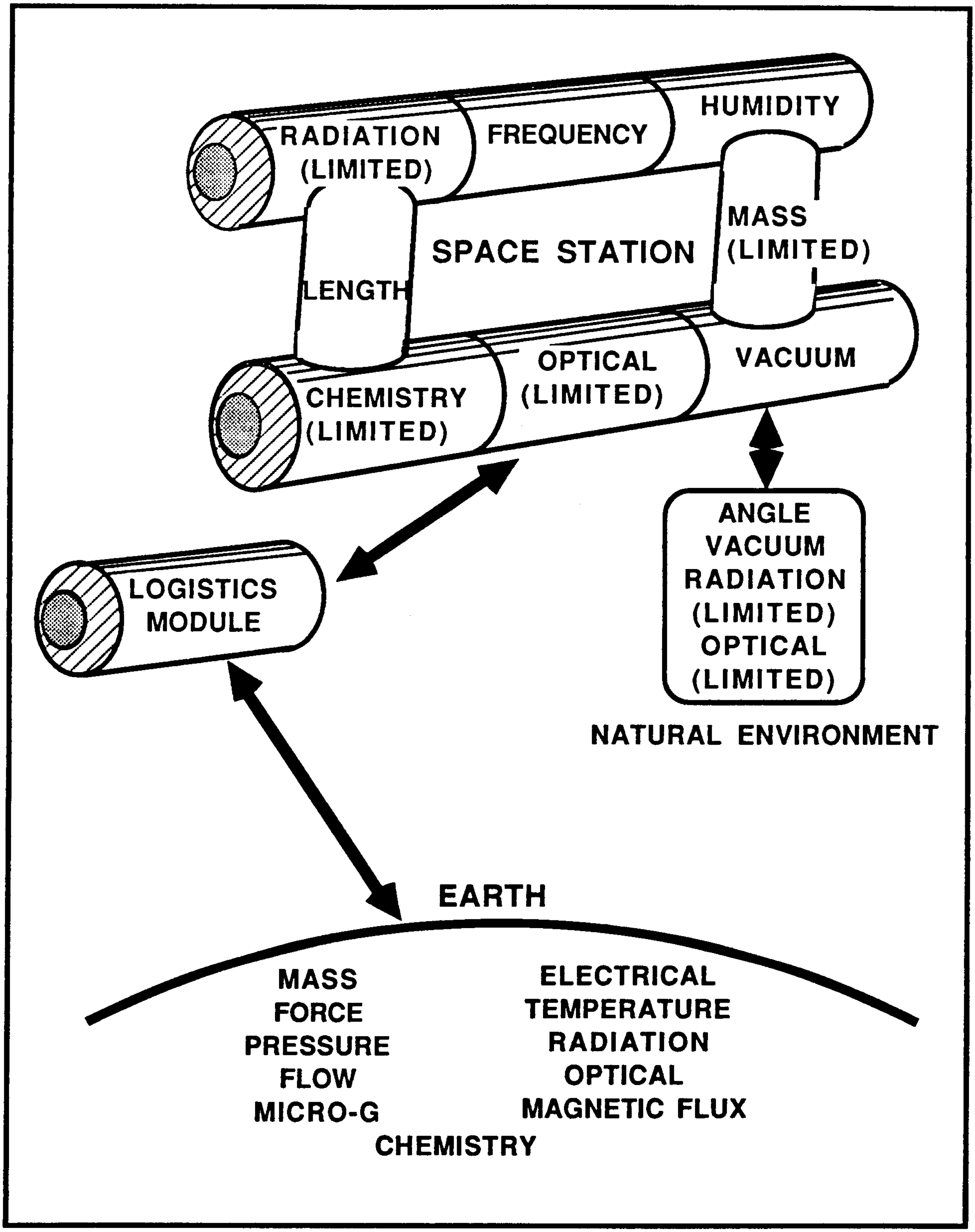

Figure 2. Short term traceability

developed. Ratio calibration techniques based on electrical (voltage) or physical (length) standards may be necessary for interpolation between fixed values to reduce the number of required standards. Mass standards can also be used to provide traceability for related measurements, such as, force, pressure, and quantity.

FORCE

Traceability for force measurement is derived from the unit of mass (kilogram). "Dead Weight" calibration techniques for force measuring instruments (load cells) are not practical for use aboard the Space Station. For most on-orbit calibrations a transfer standard load cell, initially calibrated on earth, should satisfy traceability requirements provided the accuracy of the transfer device exceeds the requirements of the measurement application. An alternative method could be the replacement of measurement load cells, within a reliable calibration interval, with spare load cells kept on-board or sent from the ground. Current designs (load cells) would allow calibration intervals of 1 to 2 years for frequent use, and 2 to 3 years for limited use (such as a transfer standard). Spares could be stored for 2 to 3 years before initial use.

PRESSURE

On Earth, traceability for pressure measurement is based on the kilogram. Small, light weight, and accurate pressure transducers are available that can serve as on-orbit transfer standards. Instability (long term) of these devices will require replacement (possibly every one to three years), but because of their small size they should not be a substantial burden to the logistics resupply plan. A transfer standard pressure sensor could be utilized for on-orbit calibration and for reducing the quantity of replacement sensors needed.

FLOW

Traceability for flow measurements (liquid and gas in terms of volume or mass per unit time) must be derived from multiple reference standards. Several compensation factors (pressure, temperature, density, etc.) must also be considered, since most gases and liquids exhibit less than ideal behavior. Flow calibration accuracies are thus limited by the accumulation of many sources of uncertainties. The use of transfer standards on-orbit (a 'standard' flow meter) will limit accuracy even further and may be useful only for lower accuracy calibrations. Suitable flow calibration equipment must be developed if accuracy requirements better than several tenths of a percent are anticipated. Calibration intervals will depend on accuracy requirement, type of flow meter selected, and the frequency of use. Continuous use applications may require recalibration as often as 1 to 2 years.

TEMPERATURE

Platinum resistance thermometers (PRTs) and fixed temperature points (melting/boiling points of elements such as gold, zinc, germanium, and oxygen) can easily provide traceability for most temperature measurements. Unless repeatedly subjected to high temperature, the PRT exhibits very good accuracy and stability, and is acceptable as a primary transfer standard for temperatures to greater than 600 degrees centigrade. Small replaceable PRT elements can be used for applications requiring extreme conditions. Quantities of these pre-calibrated standards can be stored for 5 to 10 years. Calibration requirements (resistance) for a PRT are within the expected capabilities for on-orbit electrical calibrations. The type "S" thermocouple can be substituted for the PRT in high temperature applications (but with less accuracy). Temperatures much above 1000 degrees centigrade must be calibrated using optical pyrometer/blackbody measurement techniques. This equipment may require some design/engineering modifications for practical use on the Space Station.

HUMIDITY (MOISTURE CONTENT)

The Optical Dewpointer (chilled mirror type) can be used for measurement/calibration of moisture (relative humidity and trace moisture) measurements from parts-per-million concentrations to nearly saturation levels in air and other gases through traceable temperature measurements. Saturated salt solutions can be used to generate very accurate humidity levels for the calibration of moisture sensors. Storage, preparation, and disposal of exhausted solutions may be an issue. The response time and sensitivity of this method may be affected by the lack of thermal convection in space. Semiconductor humidity sensors, because of their small size and weight could be used as a consumable transfer standard (replaced at 1 year intervals). Hermetically sealed sensors can be stored for up to a year before initial use.

MICRO-G (ACCELERATION)

The on-orbit calibration of sensitive instrumentation to measure very small gravitational, acceleration, and vibrational forces will require further development of techniques and equipment. Calibration of some instruments on earth in the presence of a one-g background may not be valid for use in space.

OPTICAL (POWER AND SPECTRUM)

Traceable optical power measurements are limited mainly by uncertainties of the equipment and techniques used to represent theoretical values. The resolution of relative power measurements can be many times the accuracy of absolute measurements; the latter can be a problem if long term trends must be established. Calibrated semiconductor sensors in conjunction with calibrated filters can be used as transfer standards and returned to earth for recalibration at one to two year intervals. Out-of-band radiation (such as short x-rays) may generate sensor currents and could result in errors. Several types of analytical instruments (chemistry) utilize spectrometric properties for material composition analysis. Standard Reference Materials (SRMs) with the desired optical properties must be available for the calibration of these instruments. Replenishment of these SRMs will be necessary due to shelf life limitations. The use of natural illumination for calibration purposes is limited but should be investigated for the future.

MAGNETIC FLUX

A source of magnetic flux (magnet) or a sensor (flux probe) are acceptable methods for calibrating magnetic field measuring instrumentation. Two standards will be required, one for weak fields and the other for strong fields. The magnetic and electrical variations that will be experienced on-orbit will generate errors in sensitive measurements and may (over long periods of exposure) cause changes in reference standards requiring replacement every 1 to 2 years. The Earth's magnetic field is sufficiently well known for calibrating some instruments on the ground, but cannot presently be used on-orbit as a calibration standard.

RADIATION

Radiation sensors (semiconductor, ion chamber, film, etc.) do not have sufficient long term stability to be used as calibration standards. Integrating sensors (such as a film badge) must be frequently resupplied (every 90 days) and will probably be returned to the ground for processing. Radiation sources are available as SRMs (from NIST) that are predictable over many years. Adequate shielding must be used to protect personnel. The background radiation in space is not presently useful in providing measurement traceability.

MATERIAL PHYSICAL PROPERTIES

Traceability for the measurement of material properties such as hardness and conductivity is provided through SRMs. Useful calibration intervals can be five to ten years if protected from environmental factors.

DIMENSIONAL MEASUREMENTS

Dimensional standards such as gauge blocks, internal and external diameter gauges, sine blocks and line standards can be designed for specific or generic calibration applications. Thermal coefficients of the standard can either be matched to the application or fixed at any practical value (nonmetallic standards can be made with very low coefficients). With proper care these standards can be expected to remain stable for several years (10 years or more). Laser interferometry can be used as a self-traceable calibration standard for manual and automated measurements from micro-meters to several hundred meters, and can also be configured for angular and velocity measurements. The predictable position of natural stellar bodies provide permanent traceability for the measurement of angles, angular rates, and attitude stability.

CHEMICAL PROPERTIES

The quantitative and qualitative analysis of resources, contaminants, and wastes will require many chemical Standard Reference Materials. These can be provided from approved sources (such as NIST) for many of the requirements. Some of these standards exhibit only short term stability and will need to be replenished frequently. Some may be highly corrosive, flammable, or even toxic. Solutions, liquid suspensions, and sediments may react differently in a low "g" environment than on Earth. Proportional mixing apparatus (to prepare gas and liquid mixtures of known concentrations) for calibration uses in space need to be developed.

ELECTRICAL

The traceability of almost every on-orbit measurement and calibration will be at least partially dependent on accurate electrical measurements. Conversion of several hundred channels of analog data into digital format for analysis, storage or transmission to Earth will be accomplished with electronic conditioning and conversion circuitry that must be periodically calibrated to assure the reliability of all data collected. Verification of sensor accuracy, stability of excitation sources, output amplifiers, interconnecting wiring, and analog to digital converter accuracy are usually based on the measurement of several electrical parameters which in turn are based on the value of the volt, the ohm, and the ampere. Traceability for electrical measurements will require on-board standards for these and other secondary parameters.

VOLTAGE, D.C.

The Zener Diode when operated properly is an acceptable transfer standard for voltage with an accuracy slightly better than one part per million per year. This device exhibits a hysteresis with changes in operating conditions such as junction temperature and current. A loss of power may cause a permanent shift in the operating point. Additional circuit components are necessary to compensate for large temperature and current coefficients (several parts per million). Zener drift (aging) is presently thought to be linear and can be predicted fairly accurately for a few years. Additional evaluation will be necessary before the long term (five years or longer) effects of aging can be reliably determined. Applications without rigid temperature controls, compensation, and backup power capability may require recalibration every two or three years.

The Josephson Array is a recent development in calibration technology that may prove useful in providing long term traceability (ten years or more) when it can be made more practical for on-orbit use.

To establish traceability for a large range of voltages (from microvolts to thousands of volts) requires the use of precise ratio requirement to allow comparison to a fixed reference voltage. The accuracy of the ratio device used will contribute to the total uncertainty at voltages different than the reference voltage. A ratio standard is also useful in extending measurement capabilities for resistance and current. The Current Comparator Bridge, another recent development, exhibits better long term stability than resistive type dividers. This should be compatible with on-orbit use with some minor engineering.

RESISTANCE

Special alloys with very low thermal coefficients and high stability are used in the construction of high precision wire wound standard resistors, which must be aged for several years before the final drift rate can be determined. Semiconductor (thick film) technology has improved to the point that resistors with thermal coefficients and aging rates almost as good as wire wound resistors can be made. Physical or electrical abuse can permanently change any precision resistor, with the semiconductor type being somewhat more sensitive. Soldering of attachment leads can often cause resistance variations that can be detected for years if proper techniques are not used to prevent excessive strain to the resistance element. With proper design and protection from damage, standard resistors can remain stable for many years, possibly up to thirty years.

A Quantum Hall Effect resistance standard has recently been developed that is based on a naturally occurring constant. This standard is not presently practical for on-orbit use due to the large amount of support apparatus presently required for operation. Further development is necessary even before this technology can be utilized in various calibration laboratories on Earth.

CURRENT

A current shunt (resistor) is the most common standard for DC current calibration. The accuracy of high current measurements (over 10 amps) is limited by the power and temperature coefficients of the shunt used. Accelerated aging can be caused by repeated electrical heating. Accuracy of 0.1% per year for a 100 amp shunt can be obtained, if high current use is limited to short durations.

A current transformer is used as a ratio device to divide a high AC current to a more easily measured value. Unless damaged, the current transformer can be used for many years without recalibration.

VOLTAGE, A.C.

The calibration of AC voltage (and current) is usually done using a thermal (RMS responding) converter with a known difference in response between a DC voltage and an equal AC voltage. Traceability is through this known difference and a DC voltage standard. The AC/DC difference of the thermal element is very stable but is extremely sensitive to abuse. Low reactance ranging resistors are required to cover a large measurement range. With proper care, the AC/DC transfer standard can be used for up to five years. Thermal converters are also available for RF voltage, current, and power measurement. Digital waveform sampling is a recent development that can also be used to provide traceability to DC voltage. This technique is better suited for automation than thermal methods.

FREQUENCY

The method used to provide traceability for frequency measurements depends on the accuracy desired. The highest possible accuracy will be obtained with an on-board Cesium (atomic) frequency standard; currently used in spacecrafts to provide a time and frequency reference accurate to better than one part in ten billion. Quartz oscillators can be used for less accurate requirements. Temperature and aging compensation can be used to provide accuracy to one or two parts per million per year. Telemetry can also be used but signal propagation variations will limit the accuracy. Cumulative errors are not a factor with telemetry as recalibration can be frequently performed.

The typical standards (using existing technology and practices) to provide basic traceability for on-orbit measurements have been presented in this section. Sending a reference standard for use in space does not guarantee that the performance of that standard will be the same as on earth. The effects of the natural environment, or the practicality of using these standards has not been fully addressed. Equipment will need to be developed that can transfer, ratio, and distribute the appropriate values to all measurement systems. Most calibration equipment was not designed with a need to keep weight, size, and power requirements at a minimum. Mechanical and thermal isolations are necessary to assure highly stable operating characteristics of most standards.

Potential methods to satisfy many of the traceability requirements of the Space Station may exist within the unique properties of the natural environment in space. Utilization of background fields, radiation levels, and spectra of various forms of energy as on-orbit calibration standards can greatly reduce the burden of furnishing traceability from the ground. The vast expanse of space and isolation from man induced factors may be an advantage in developing future standards that are presently limited by the environment on earth. A comparison of Figures 2 and 3 demonstrates this potential for self sustained on-orbit traceability. It is quite likely that calibrations performed in earth-bound laboratories will eventually look to on-orbit standards for traceability.

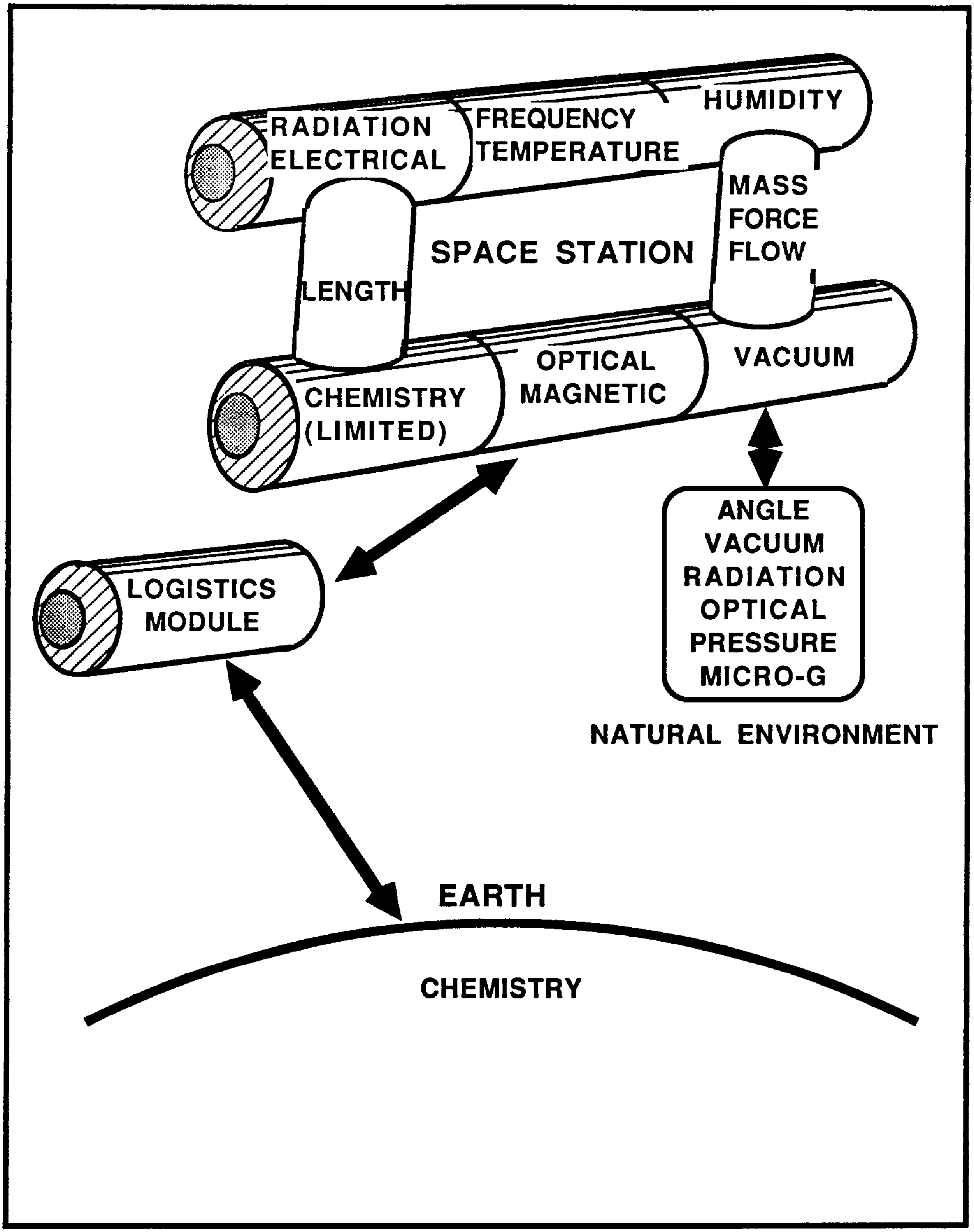

Figure 3. Long term (potential) traceability

2.F Task 6, Technology Development Plans

The calibration/measurement development areas for equipment, technology, methodologies, etc. are included in the results for this task. Technology Development Plans (TDPs) for some of the key items are presented. These items are: micro-g, mass, pressure/flow/force, electrical, optical/radiation, magnetic, contamination monitoring, gas sensors, temperature, and dimensional. Some of the minor areas, such as humidity, requiring very limited enhancements are not included. Each TDP consists of: Technology Item, Required Effort, Deficiencies, Technology Plan, Resource Requirements, Test Program, Schedule, Risk Assessment, and Benefits Assessment. The Required Effort for each plan is categorized as major, medium or minor, and this could allow prioritization of these TDPs. The results of Tasks 2 through 5 provided the inputs for the performance of this task.

The information presented here is intended for enhancements and long term reliability of Space Station operation. In a majority of the cases the initial safe operation of the station can be accomplished through the use of existing technologies.

Primary conclusions are:

- Micro-g, mass, and pressure/flow/force measurements could be major efforts.

- Electrical, magnetic, optical/radiation, and contamination measurements could be medium efforts.

- Gas sensors, temperature, and dimensional measurements could be minor efforts.

- Major technology gaps exist in gravity dependent measurement techniques and those that are sensitive to in-space natural environment conditions.

Primary recommendations are:

- Continue to focus efforts for developing appropriate technologies that are gravity independent.

- Develop more complete understanding of the effects of in-space natural environment.

TECHNOLOGY DEVELOPMENT PLAN #1

TECHNOLOGY ITEM: **MICRO-G (ACCELERATION) MEASUREMENTS**

REQUIRED EFFORT: Major
(Theoretical and experimental research, equipment development and validation)

DEFICIENCIES:

- Limitations in sensitive micro-g measurements
- Incompatibility of calibration techniques for on-orbit applications
- on-ground (1-g background) calibration may not be valid for on-orbit application

TECHNICAL PLAN:

- Need to develop on-orbit measurement and calibration methods
    - Methods for improved accuracy
    - Qualify methods for on-orbit use

RESOURCE REQUIREMENTS:

- Mechanical Engineer

TEST PROGRAM:

- On-ground
    - Experiment design and verification plan
    - Fabricate experimental systems
- Preliminary experiments (KC-135)
- Confirmation of results (Shuttle flight)

TECHNOLOGY DEVELOPMENT PLAN #1
(CONTINUED)

SCHEDULE:

- 3-5 years
  - On-ground testing of concepts
  - Preliminary validation of systems using KC-135 flights
  - Final verification of experiments using Shuttle flights

RISK ASSESSMENT:

- Lack of or less accurate micro-g measurement capabilities
- Long lead time for technique development

BENEFITS ASSESSMENT:

- Accurate micro-g measurements
- Aid in Space Station operation

TECHNOLOGY DEVELOPMENT PLAN #2

TECHNOLOGY ITEM: **MASS MEASUREMENTS**

REQUIRED EFFORT: Major
(Methods Development and Qualification)

DEFICIENCIES:

- Lack of accurate measurement methods
    - Measurement technique needs to be application-specific

TECHNICAL PLAN:

- Need to develop on-orbit measurement techniques
    - Non-rigid objects
    - Inhomogeneous materials
    - Complex, irregular shapes

RESOURCE REQUIREMENTS:

- Metrologist
- Mechanical Engineer

TEST PROGRAM:

- On-ground
    - Develop measurement concepts for various applications
    - Conduct preliminary experiments
- Perform final verification (KC-135)

TECHNOLOGY DEVELOPMENT PLAN #2 (CONTINUED)

SCHEDULE:

- 3-5 years
    - Verification of application-specific concepts (on-ground)
    - Final validation to confirm candidate techniques (KC-135)

RISK ASSESSMENT:

- Lack of optimum methodologies
- Lack of or less accurate measurements
- Precision Mass Measurements must be performed on ground

BENEFITS ASSESSMENT:

- Availability of precision on-orbit measurement capability

TECHNOLOGY DEVELOPMENT PLAN #3

TECHNOLOGY ITEM: **PRESSURE/FLOW/FORCE**
(these are derived measurements from the unit of mass)

REQUIRED EFFORT: Major
(primary standards development)

DEFICIENCIES:

- Current primary standards are gravity dependant
- Use of secondary standards limits accuracy and calibration intervals

TECHNICAL PLAN:

- Develop practical methods for on-orbit use

RESOURCE REQUIREMENTS:

- Mechanical Engineer
- Metrologist

TEST PROGRAM:

- On-ground
  - Develop and evaluate design
  - Assess gravity substitution methods
- Preliminary experiments (KC-135)
- Final validation of concepts (Shuttle)

SCHEDULE:

- 3-5 years
  - Develop concepts
  - Conduct experiments
  - Fabrication and testing of prototype

TECHNOLOGY DEVELOPMENT PLAN #3
(CONTINUED)

RISK ASSESSMENT:

- Accuracy and calibration life limitations
- Potential unsafe conditions
- Inefficient control of resources

BENEFITS ASSESSMENT:

- Optimization of systems performance
- Efficient use of resources
- Improved personnel and Space Station safety factors

TECHNOLOGY DEVELOPMENT PLAN #4

TECHNOLOGY ITEM: **ELECTRICAL MEASUREMENTS**

REQUIRED EFFORT: Medium
(Natural environment evaluation and equipment application engineering)

DEFICIENCIES:

- Effects of natural environment on accuracy of measurements are not fully understood
- Currently available equipment may not be compatible with mission requirements
- Multitude of electrical measurements widely distributed throughout the station; need access for calibration

TECHNICAL PLAN:

- Study the effects of space environment
- Develop approaches for automated measurements/ calibrations
- Develop appropriate long term standards
- Evaluate approaches for centralized and distributed calibration reference standards

RESOURCE REQUIREMENTS:

- Metrologist
- Electrical Engineer
- Physicist

TEST PROGRAM:

- On-ground
  - Research available data on the effects of space environment
  - Obtain and assess specific electrical requirements
  - Design and test multifunction electrical measurement/calibration system

TECHNOLOGY DEVELOPMENT PLAN #4
(CONTINUED)

SCHEDULE:

- 2-3 years
  - Define system design based on effects of natural environment
  - Qualify system design for use in space

RISK ASSESSMENT:

- Unknown measurement errors due to space environment
- Reduced reliability
- Frequent calibrations necessary for sustained reliability

BENEFITS ASSESSMENT:

- Enhanced reliability through reduced measurement errors
- Improved long term stability of equipment performance

TECHNOLOGY DEVELOPMENT PLAN #5

TECHNOLOGY ITEM: **OPTICAL/RADIATION MEASUREMENTS**

REQUIRED EFFORT: Medium
(Sensor and natural environment evaluation)

DEFICIENCIES:

- Measurement methods do not provide sufficient spectral information on radiation levels
- Out-of-band response of spectrally sensitive sensors generate errors
- Associated electronics may be affected by background radiation

TECHNICAL PLAN:

- Evaluation and selection of suitable sensors (including recent semiconductor technology)
- Further characterization of natural environment for use as reference standards

RESOURCE REQUIREMENTS:

- Physicist

TEST PROGRAM:

- On-ground
  - Perform spectral characterization of available sensors
  - Devise techniques for using natural environment (background radiation) as reference standards
- Verify results with on-orbit tests (Shuttle)

TECHNOLOGY DEVELOPMENT PLAN #5
(CONTINUED)

SCHEDULE:

- 1-2 years
  - Sensor evaluation
  - Natural environment evaluation

RISK ASSESSMENT:

- Less accurate spectral information
- Potential hazard to humans and animals

BENEFITS ASSESSMENT:

- Improved understanding of natural environment
- Enhanced exposure monitoring
- Potential for early warning of natural radiation events (solar activity)

TECHNOLOGY DEVELOPMENT PLAN #6

TECHNOLOGY ITEM: **MAGNETIC MEASUREMENTS**

REQUIRED EFFORT: Medium
(Probe and technique development, and validation)

DEFICIENCIES:

- Interference of varying background magnetic fields limits accuracy of magnetic flux measurements
- Electromagnetic interference (EMI) will affect instrumentation

TECHNICAL PLAN:

- Evaluate improvements in probe technology (including magnetic Hall effect sensors)
- Assess the long term (multiple orbit) stability of earth's magnetic field for use as an on-orbit reference standard

RESOURCE REQUIREMENTS:

- Physicist
- Electrical Engineer
- Metrologist

TEST PROGRAM:

- On-ground
  - Evaluate improved design for probes
  - Devise methods for beneficial use of natural magnetic fields

TECHNOLOGY DEVELOPMENT PLAN #6
(CONTINUED)

SCHEDULE:

- 2-3 years
  - Design and test probes
  - Validate design concepts (Shuttle)

RISK ASSESSMENT:

- Less accurate magnetic measurements

BENEFITS ASSESSMENT:

- Improved accuracy of scientific experiments and earth science research

TECHNOLOGY DEVELOPMENT PLAN #7

TECHNOLOGY ITEM: **CONTAMINATION MONITORING** (trace quantities)

REQUIRED EFFORT: Medium (sensor development and methodologies)

DEFICIENCIES:

- Sensor specificity and sensitivity limitations
- Limited definition of species and detectability requirements
- Instability and lack of appropriate standards

TECHNICAL PLAN:

- Identification of species and measurement requirements
- Selection and/or evaluation of sensors
- Development of stable standards

RESOURCE REQUIREMENTS:

- Chemist
- Electrical Engineer

TEST PROGRAM:

- On-ground
  - Evaluation of sensors
  - Development of measurement methodologies
  - Verification and qualification of methods

SCHEDULE:

- 2-3 years
  - Evaluation of available equipment
  - Development of new methods
  - Validation of methods

TECHNOLOGY DEVELOPMENT PLAN #7
(CONTINUED)

RISK ASSESSMENT:

- Insufficient monitoring of environment
- Potentially unsafe conditions for personnel

BENEFITS ASSESSMENT:

- Safer environmental conditions

TECHNOLOGY DEVELOPMENT PLAN #8

TECHNOLOGY ITEM: **GAS SENSORS**
(For major constituents such as oxygen, carbon dioxide, nitrogen, etc. in a sample medium)

REQUIRED EFFORT: Minor
(Sensor material selection and application testing)

DEFICIENCIES:

- Short calibration life
- Short operating and shelf life
- Interference from nonrelevant gases present in the medium
- Contamination of sensors
- Instability of Standard Reference Materials (SRMs) for specific gases (for example, carbon monoxide)

TECHNICAL PLAN:

- Identify essential gases that need to be detected and quantified
- Investigate materials/chemistry for long life sensors
- Conduct experiments to establish long life sensor characteristics
- Develop and test prototype sensors

RESOURCE REQUIREMENTS:

- Analytical chemist
- Material scientist
- Instrumentation engineer
- Prototyping facility

TECHNOLOGY DEVELOPMENT PLAN #8
(CONTINUED)

TEST PROGRAM:

- On-ground
  - Selection of appropriate gases and atmospheres
  - Statistical validation

SCHEDULE:

- 1-2 years
  - Sensor material selection
  - Evaluation of chemical responses
  - Laboratory testing
  - Evaluation of prototype

RISK ASSESSMENT:

- Premature sensor failures
- Excessive replacement/recalibration
- Potential unsafe atmospheric conditions

BENEFITS ASSESSMENT:

- Sensors with longer life
- Reduced operating costs
- Increased reliability
- Improved safety

TECHNOLOGY DEVELOPMENT PLAN #9

TECHNOLOGY ITEM: **TEMPERATURE MEASUREMENTS**

REQUIRED EFFORT: Minor
(Equipment application engineering)

DEFICIENCIES:

- Calibration accuracy of optical pyrometers
- Multitude of contact type sensors distributed throughout the station may not be accessible

TECHNICAL PLAN:

- Improved calibration of optical pyrometers
- Miniaturization/packaging of contact type temperature measurement system

RESOURCE REQUIREMENTS:

- Physicist
- Electrical Engineer
- Metrologist

TEST PROGRAM:

- On-ground
  - Validation of optical pyrometry standards
  - Designing and testing of temperature measurement system

SCHEDULE:

- 1 year
  - Optical pyrometry standards development/ validation
  - Prototyping/testing of temperature measurement system

TECHNOLOGY DEVELOPMENT PLAN #9
(CONTINUED)

RISK ASSESSMENT:

- Less efficient use of resources (electrical, thermal, power)
- Less accurate temperature measurements
- Space and weight penalties (equipment)

BENEFITS ASSESSMENT:

- Thermal control system optimization
- Energy conservation
- Reduced calibration effort

TECHNOLOGY DEVELOPMENT PLAN #10

TECHNOLOGY ITEM: **DIMENSIONAL MEASUREMENTS**

REQUIRED EFFORT: Minor
(Equipment application engineering)

DEFICIENCIES:

- Majority of measurements are manual
- Inaccuracies of extremely large and small dimensional measurements
- Wide variety of measurement requirements

TECHNICAL PLAN:

- Investigate methods for measurement automation
  - Laser interferometry
  - Optical measurement
  - Image recognition

RESOURCE REQUIREMENTS:

- Physicist (optics)
- Computer Scientist

TEST PROGRAM:

- On-ground
  - Modify existing equipment designs
  - Develop and test prototype equipment

SCHEDULE:

- 1-2 years
  - Equipment redesign
  - Prototype fabrication and testing

TECHNOLOGY DEVELOPMENT PLAN #10
(CONTINUED)

RISK ASSESSMENT:

- Limited measurement accuracies
- Equipment space and weight penalties

BENEFITS ASSESSMENT:

- Self-traceable dimensional measurements
- Universal (automated) dimensional measurement system

3. CONCLUSIONS

Primary conclusions for individual tasks were presented in Subsections 2.A through 2.F, respectively. These conclusions are given below in a consolidated form.

Task 1, Literature Review

- Maximum calibration activities appear to be in ECLSS, EVA, and EPS.
- Some similar calibration needs (for example, voltage) are widely distributed across the station.
- ECLSS information on submarines could be valuable for the station.
- Information on Soviet work that is available in the open literature provided no definitive data.

Task 2, On-Orbit Calibration Techniques

- Several calibration techniques are currently available (though not fully optimized) for on-orbit use.
- Calibration techniques for mass and micro-g are not currently suitable and may have to be developed.

Task 3, Sensor Calibration Requirements

- Majority of the sensors exhibit some undesirable properties (for example, sensitivity to electromagnetic interference).
- Effects of in-space natural environment on sensor measurements are not completely understood.

Task 4, Calibration Equipment Requirements

- Most equipment will require some redesigning and/or repackaging to reduce weight and size.
- Redundancies (for example, separate power supplies for each equipment) in various instruments could be minimized by redesign
- Some equipment could be influenced by micro-g and other in-space natural ambient conditions.

Task 5, Traceability Requirements

- Use of precalibrated instruments could provide traceability for initial operation.
- Transporting of secondary standards could provide traceability for near term operation.
- On-board, long term, primary standards need to be developed.
- In-space natural environment could be better utilized to provide some of the primary standards.

Task 6, Technology Development Plans

- Major efforts may be required in the areas of mass, micro-g, and pressure/flow/force measurements.
- Medium efforts may be required in the areas of electrical, magnetic, optical/radiation, and contamination measurements.
- Minor efforts are anticipated in the areas of gas sensors, temperature, and dimensional measurements.
- Conduct select experiments in simulated in-space environments (KC-135) and also on the Shuttle.

4. RECOMMENDATIONS

The primary recommendations given below are a consolidation of those that were presented in Subsections 2.A through 2.F, respectively, for the individual tasks. In addition, some general recommendations (near term and long term) are also presented.

Task 1, Literature Review

- Develop definitive measurement requirements for all systems as more design details become available.
- Generate integrated measurement requirements incorporating all the work packages to aid in assessing the commonality needs.
- Conduct a detailed analysis of submarine ECLSS information for potential use in Space Station.
- Assess the information on Soviet work that is available in the classified literature.

Task 2, On-Orbit Calibration Techniques

- Conduct a detailed evaluation of state-of-the-art and emerging calibration techniques for potential on-orbit use.
- Develop improved techniques to increase accuracy and extend calibration life.
- Define and develop solutions for voids in calibration techniques (for example, mass).

Task 3, Sensor Calibration Requirements

- Include long term stability of sensors as an important selection criterion.
- Assure that sensor calibration techniques verify its primary function as well as compensation factors.
- Insure that calibration access and interfaces are incorporated in the design.

Task 4, Calibration Equipment Requirements

- Identify calibration equipment required for sustained operation.

- Develop an equipment commonality list.
- Consider innovative and inventive approaches in equipment design for long term stability.
- Prepare space qualification procedures for calibration equipment.

Task 5, Traceability Requirements

- Develop traceability approaches for near term operation.
- Develop on-board, long term primary standards.
- Evaluate methods for better utilizing the in-space natural environment as primary standards.
- Apply procedures for drift trending of appropriate data to improve confidence in calibration.

Task 6, Technology Development Plans

- Evaluate appropriate methods for developing gravity independent techniques.
- Develop a complete understanding of the effects of in-space natural environment.

General short term recommendations are:

- Prepare an on-orbit metrology design guide as an aid to instrumentation and other design engineers. The guide should include as a minimum: design considerations, effect of space environment, potential calibration techniques and procedures, reliability considerations (uncertainties), traceability, and design checklist.

- Generate detailed technology development plans which shall include, but not be limited to, the following: detailed analysis of technology gaps and their impacts, potential solutions, trade studies and prioritization, selection and optimization of concepts, and detailed approaches for technology development.

General long term recommendations are:

- Conduct preliminary design study for an on-orbit metrology system. Study results should yield an integrated system design, method of operation, logistics and maintenance requirements, and life cycle costs.

- Develop final design and fabricate the on-orbit metrology system. This effort shall also include test and checkout of the system. Provisions shall be implemented for the logistics, maintenance, operating procedures and manpower required for routine operation of the system in Space Station environment.

5. BIBLIOGRAPHY

This section contains a complete listing of all documents, publications, and technical papers used in the performance of this study. Those that were considered to be significant and important are indicated by an asterisk (*) adjacent to the document number. NASA documents, such as, Space Station RFP Work Packages 1 through 4, Architectural Control Documents, Configuration Control Documents, and Operation and Maintenance Plans were used to determine the on-orbit measurement requirements (Task 1), from which the results of all successive tasks (2 through 6) were developed. In cases where specific requirements were expressed as TBD, related technical reports, papers, workshop/conference proceedings, etc were utilized to derive the best estimate requirements.

Several papers dealing with environmental and contamination monitoring systems for submarines provided important information because of the similarity of its mission (remote, self-sustained operation) to that of the Space Station. The Space Station Environmental Control and Life Support System (ECLSS) will be expected to perform many of the same functions as a submarine ECLSS. Detection of trace contaminants and rapid recovery from out-of-tolerance conditions are critical for both space and sub-oceanic life support. Long term operation in space as opposed to the average 90 day mission of a submarine does not allow operating contingencies such as surfacing, in-port repair and maintenance or practically unlimited logistic support.

A limited amount of Soviet space program information available in the open literature was obtained and reviewed. Several of their problems and experiences were noted in this review, however, technical details were generally omitted. It appeared that system reliability has been a major concern for the Soviets. Further, it appeared that only very limited capabilities existed for measuring and monitoring the system functions. This could have permitted the system malfunctions to proceed to nearly total failure. These conditions at least in part could be attributable to deficiencies in on-orbit measurement and calibration capabilities. Some of the pertinent findings are: a) Repeated (undetected) contamination of the station's internal atmosphere and the lack of appropriate on-board analytical instrumentation capabilities; b) Frequent failures of electronic equipment; c) Excessive use of manual operations and lack of automation; d) Deterioration of optical equipment due to the cumulative effects of radiation; and e) Repair or maintenance of some equipment could not be performed using on-board capabilities.

The primary conclusions and recommendations based on the general review of all the listed documents are given below.

Primary conclusions are:

- Detailed specifications in some areas of the station were not completely identifiable.
- Data on submarine ECLSS could be valuable for Space Station.
- Information on Russian work available in the open literature provided very limited amount of definitive data, and it appeared that their use of advanced technology (for example, automation) was minimal.

Primary recommendations are:

- Conduct detailed evaluation of submarine ECLSS technology for use in Space Station.
- Research information on Russian work that may be available in the classified (non-public) domain.

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