IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Interferometric Fiber Optic Gyros

Sponsor

Gyro and Accelerometer Panel
of the
IEEE Aerospace and Electronic Systems Society

Reaffirmed 10 December 2008
Approved 16 September 1997

IEEE-SA Standards Board

Abstract: Specification and test requirements for a single-axis interferometric fiber optic gyro (IFOG) for use as a sensor in attitude control systems, angular displacement measuring systems, and angular rate measuring systems are defined. A standard specification format guide for the preparation of a single-axis IFOG is provided. A compilation of recommended procedures for testing a fiber optic gyro, derived from those presently used in the industry, is also provided.
Keywords: fiber gyro, fiber optic gyro, gyro, gyroscope, IFOG, inertial instrument, inertial sensor, interferometric fiber optic gyro, optical gyro, Sagnac effect, Sagnac gyro

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th, New York, NY 10017-2394, USA

ISBN 1-55937-961-8

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE that have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

Note: Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

Introduction

(This introduction is not a part of IEEE Std 952-1997, IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Interferometric Fiber Optic Gyros.)

This standard was prepared by the Gyro and Accelerometer Panel of the IEEE Aerospace and Electronic Systems Society and consists of two parts.

Part I is a specification format guide for the preparation of a single-axis interferometric fiber optic gyro (IFOG) specification. It provides a common meeting ground of terminology and practice for manufacturers and users. The user is cautioned not to over specify; only those parameters that are required to guarantee proper instrument performance in the specific application should be controlled. In general, the specification should contain only those requirements that can be verified by test or inspection. Parameters in addition to those given in this standard are not precluded.

Part II is a compilation of recommended procedures for testing a single-axis IFOG. These procedures, including test conditions to be considered, are derived from those currently in use. For a specific application, the test procedure should reflect the requirements of the specifications; therefore, not all tests outlined in this standard need to be included, nor are additional tests precluded. In some cases, alternative methods for measuring performance characteristics have been included or indicated.

The intent is for the specification writer to extract the applicable test conditions and equipment requirements from Clause 11 for inclusion in the appropriate subclauses listed under 6.5. Similarly, it is intended that the writer extract the applicable test procedures from Clause 12 for inclusion in the appropriate subclauses listed under 6.6. Part II can also be used as a guide in the preparation of a separate gyro test specification with appropriate clause numbering. In general, the intent is for the Part II test procedure to refer to Part I requirements for performance, mechanical, electrical, environmental, reliability, and quality assurance. To that end, a test should not be listed in Part II unless a related requirement exists in Part I.

Blank spaces in the text of this standard permit the specification writer to insert specific information such as parameter values and their tolerances, clause numbers, etc. Brackets are to be used to enclose alternative choices of dimensional units, signs, axes, etc. Boxed statements are included for information only and are not part of the specification or test procedures. The terminology used conforms to IEEE Std 100-1996 and IEEE Std 528-1994. The units used conform to ANSI 268-1992. The abbreviation of units conforms to IEEE Std 260.1-1993. The graphic symbols used conform to IEEE Std 315-1975.

This standard defines the requirements and test procedures for an IFOG in terms unique to that gyro. The requirements contained in this standard cover application where the gyro is used as an angular motion sensor in navigation and control systems.

The term “interferometric fiber optic gyro” is accepted to include the electronics necessary to operate the gyro and to condition the output signal.

Annex A lists various gyro design features for which this format is applicable. The table therein is not intended to make any suggestions regarding the selection of particular design features that might restrict the free choice of manufacturers.

Annex B is an overview of dynamic and stochastic modeling.

Annex C is an overview of noise process variance analysis as a method for determination of the drift rate coefficients and the quantization coefficient.

This standard represents a large scale, group effort. More than 116 individuals attended over 40 meetings of the Gyro and Accelerometer Panel during preparation of this standard. The following persons were on the Gyro and Accelerometer Panel:

S. Bennett, *Chair*

D. Anderson	T. Fuhrman	R. Morrow
M. Ash	F. Garcia	G. Murray*
C. Barker	B. Katz	J. Neugroschi
J. Beri	J. Kieffer	R. Peters*
S. Bongiovanni	M. Koning	L. Richardson
P. Bouniol	L. Kumar	G. Shaw
J. Brewer	K. Lantz	P. Simpson
H. Califano	T. Lear*	T. Stanley
A. Campbell*	D. Lynch	C. Swanson
J. D'Angelo	R. Marquess	L. Thielman
G. Erickson	H. Morris	L. Trozpek
J. Ficalora	G. Morrison*	B. Wimber*
S. Finken		B. Youmans

*Former Chair

The following persons were on the balloting committee:

D. Anderson	S. Finken	G. Neugebauer
W. Armstrong	T. Fuhrman	P. Palmer
M. Ash	K. Homb	R. Peters
C. Barker	B. Katz	F. Petri
S. Bennett	J. Kieffer	G. Shaw
S. Bongiovanni	L. Kumar	C. Swanson
P. Bouniol	J. Mackintosh	M. Tehrani
J. Brewer	E. Mettler	L. Thielman
H. Califano	H. Morris	C. Trainor
A. Campbell	G. Morrison	B. Wimber
J. D'Angelo	R. Morrow	D. Winkel
G. Erickson		B. Youmans

When the IEEE Standards Board approved this standard on 16 September 1997, it had the following membership:

Donald C. Loughry, *Chair* **Richard J. Holleman,** *Vice Chair*
Andrew G. Salem, *Secretary*

Clyde R. Camp	Lowell Johnson	Louis-François Pau
Stephen L. Diamond	Robert Kennelly	Gerald H. Peterson
Harold E. Epstein	E. G. "Al" Kiener	John W. Pope
Donald C. Fleckenstein	Joseph L. Koepfinger*	Jose R. Ramos
Jay Forster*	Stephen R. Lambert	Ronald H. Reimer
Thomas F. Garrity	Lawrence V. McCall	Ingo Rüsch
Donald N. Heirman	L. Bruce McClung	John S. Ryan
Jim Isaak	Marco W. Migliaro	Chee Kiow Tan
Ben C. Johnson		Howard L. Wolfman

*Member Emeritus

Also included are the following nonvoting IEEE Standards Board liaisons:

Satish K. Aggarwal
Alan H. Cookson

Kim Breitfelder
IEEE Standards Project Editor

Contents

IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Interferometric Fiber Optic Gyros

1. Overview

1.1 Scope

This standard defines requirements for a single-axis interferometric fiber optic gyro (IFOG), including any necessary electronics, to be used in [an attitude control system, an angular displacement measuring system, an angular rate measuring system, __________].

2. References

This standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

ANSI 260.1-1993 American National Standard Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units, and Certain Other Units).[1]

IEEE/ASTM SI 10-1997, Standard for Use if the International System of Units (SI): The Modern Metric System.[2]

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.

IEEE Std 280-1985 (Reaff 1996) IEEE Standard Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering (ANSI/DoD).

[1]ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std 315-1975 (Reaff 1993), IEEE Graphic Symbols for Electrical and Electronics Diagrams (ANSI/DoD).

IEEE Std 315A-1986 (Reaff 1993), IEEE Supplement to Graphic Symbols for Electrical and Electronics Diagrams (ANSI/DoD).

IEEE Std 528-1994, IEEE Standard for Inertial Sensor Terminology (ANSI).

IEEE Std 812-1984, IEEE Standard Definitions of Terms Relating to Fiber Optics.[3]

Part I—Specification format

3. Definitions

Except for the term defined below, IEEE Std 100-1996, IEEE Std 528-1994, and the model equation of 8.3 define terminology used in this standard.

3.1 Shupe effect: A time-variant non-reciprocity due to temperature changes along the length of the fiber.

4. Applicable documents

The following documents form a part of the specification to the extent specified in this specification. In the event of any conflict between the requirements of this specification and the listed documents, the requirements of this specification shall govern.

Give identification number, title, date of issue, and revision letter of each listed document.

4.1 Specifications

4.1.1 Government

MIL-P116J Methods of Preservation 1 October 1991.

4.1.2 Industry/Technical

4.1.3 Company

[3]IEEE Std 812-1984 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

4.2 Standards

4.2.1 Government

MIL-STD-105E Sampling Procedure and Tables for Inspection by Attributes 1 February 1995.

MIL-STD-461D Electromagnetic Interference Characteristics, Emission and Susceptibility January 1993 Requirements for the Control of Electromagnetic Interference.

MIL-STD-462D+ Electromagnetic Interference Characteristics, Measurements of 1 April 1995.

MIL-STD-704E Aircraft Electric Power Characteristics January 1991.

MIL-STD-740B Airborne and Structure borne Noise Measurements and Acceptance 1 June 1965 Criteria of Shipboard Equipment.

MIL-STD-781D Reliability Design Qualification and Production Acceptance Tests: October 1986 Exponential Distribution.

MIL-STD-785B Reliability Program for Systems and Equipment Development and Notice 2 Production 2 August 1988.

MIL-STD-810E Environmental Test Methods and Engineering Guidelines 2 September 1993.

4.2.2 Industry/Technical

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.

IEEE Std 528-1994, IEEE Standard for Inertial Sensor Terminology.

4.2.3 Company

4.3 Drawings

4.3.1 Government

4.3.2 Industry/Technical

4.3.3 Company

4.4 Bulletins

4.4.1 Government

4.4.2 Industry/Technical

4.4.3 Company

4.5 Other publications

Other applicable documents should be listed under the appropriate subclause.

5. Requirements

5.1 Description

The design features of the gyro described in this specification are an enclosure and mounting means, a __________ light source, a sensing coil of __________, a photosensitive readout device, and the following additional optical and electronic components: __________. The gyro is intended for use as an angular [rate, displacement] sensor.

To fill in the blanks, refer to Annex A for examples.

5.2 General requirements

5.2.1 Precedence

In the event of conflict among the purchase agreement, this specification, and other documents referred to in this specification, the order of precedence shall be as follows:

a) Purchase agreement.
b) This specification and its applicable drawings (see 5.4.2 and 5.5.1).
c) Other applicable documents (see Clause 4).

5.3 Performance

Performance characteristics shall be as specified in this subclause. The tolerances include a summation of manufacturing and test errors, and environmental effects. Any exception due to environmental effects shall be listed in 5.6.3.1.

When required by the application, the sensitivity of a gyro characteristic to variations in voltage, frequency, temperature, or other variables should be included in the subclause specifying that characteristic.

5.3.1 Input rate limits

5.3.1.1 Maximum

The input rate limits about the gyro input axis (IA) shall be ±__________ [°/s, rad/s].

The positive and negative input rate limits need not be equal. Multiple rate limits may be specified.

5.3.1.2 Minimum (dead band)

The gyro dead band shall not exceed __________ [°/s, rad/s].

5.3.2 Gyro scale factor, S

__________ ["/p, μrad/p, _____] + __________ %.

In the angular rate sensing mode, the scale factor is normally specified in (°/h)/V, (°/h)/Hz. In the angular displacement sensing mode, the scale factor is normally specified in "/p. Different values and tolerances may be specified for different input ranges. The scale factor range includes the manufacturing tolerance. The test procedure will result in a nominal scale factor that is defined in the model equation in 8.3.

5.3.2.1 Gyro scale factor errors

a) Linearity Error. __________ [ppm, %] of full scale and/or __________ [ppm, %] of output, [maximum 1σ, _____].

Scale factor linearity error may have a component periodic in rate due to optical feedback to the source.

b) Asymmetry. The difference between the scale factor measured with positive input rates and negative input rates shall not exceed __________ [ppm, %] of half the sum of the magnitudes of the scale factor determined for positive and negative inputs.

c) Repeatability. [ppm, %], [maximum spread, 1σ, _____].

Repeatability involves changes in scale factor that occur between periods of operation. Thermal cycles and other environmental exposures, shutdowns, time between runs, remounting, and additional factors pertinent to the particular application should be specified.

d) Stability. __________ [ppm, %], [maximum spread, 1σ, _____] for __________ [hours, days, _____].

5.3.2.2 Gyro scale factor sensitivities

a) Temperature. The change in gyro scale factor resulting from a change in steady-state operating temperature shall not exceed __________ ppm from that measured at __________°C over the range __________°C to __________°C.

b) Other sensitivities.

Additional sensitivities may be specified such as those due to variations in supply voltage, rate of temperature change, temperature gradient, orientation, acceleration, vibration, magnetic field, radiation, and other environments pertinent to the particular application.

5.3.3 Drift rate, D, E

5.3.3.1 Bias and random, D

5.3.3.1.1 Bias, D_F

__________ ± __________ °/h.

Repeatability. __________ °/h [maximum spread, 1σ, _____].

Thermal cycles and other environmental exposures, shutdowns, time between runs, remounting, and additional factors pertinent to the particular application should be specified.

5.3.3.1.2 Random, D_R

Random drift rate is usually defined in terms of the Allan variance components. These components should be specified. See D_R terms under 8.3 and Annex C.

a) Angle random walk (rate white noise) coefficient, N. _____°/h$^{1/2}$ maximum.
b) Bias instability coefficient, B. _____°/h maximum.
c) Rate random walk coefficient, K. _____(°/h)/h$^{1/2}$ maximum.
d) Ramp coefficient, R. _____(°/h)/h maximum.

For some applications it may be sufficient to define random drift as the standard deviation of the output. The time interval and integration time should be specified.

5.3.3.1.3 Measurement noise, D_Q

Quantization noise coefficient, Q _____ [", μrad] maximum.

Measurement noise is usually defined as the Allan variance component Q. See 8.3 and Annex C.

5.3.3.2 Environmentally sensitive, E

5.3.3.2.1 Thermal

a) Temperature. The change in gyro bias resulting from a change in steady-state operating temperature shall not exceed __________ °/h from that measure at __________ °C over the range __________ °C to __________ °C.
b) Temperature ramp. The change in gyro bias resulting from a temperature ramp of __________ °C/min shall not exceed __________ °/h.

The characteristics of the ramp should be representative of the intended application.

c) Time-dependent temperature gradient. The maximum change in gyro bias resulting from a change in temperature ramp of __________ °C/min shall not exceed __________ °/h.

The magnitude of the temperature ramp should be representative of the intended application. This is intended to specify the bias error associated with the Shupe effect, which arises from the time-dependent temperature gradient with respect to the center of the fiber length. The magnitude of the effect is dependent on gyro design, including coil-winding techniques and thermal packaging, and exhibits differences depending on the direction of thermal input. The mounting arrangements and method of thermal input should be specified if required by the installation design.

5.3.3.2.2 Magnetic

The change in gyro bias resulting from a change in steady-state flux density shall not exceed _________°/h over the range __________ to __________ [mT, G, _____].

Gyro axis and characteristics of the field should be defined. If exposure to a varying field is required, the nature of the variation should be described. Demagnetization may be necessary following exposure.

5.3.3.2.3 Other sensitivities

Additional sensitivities may be specified such as those due to variations in supply voltage, rate of temperature change, orientation, acceleration, vibration, radiation, and other environments pertinent to the particular application.

5.3.4 IA alignment characteristics

5.3.4.1 IA misalignment

__________ [', mrad], maximum with respect to the input reference axis (IRA).

The specific direction of IA misalignment may be important in some applications and should be specified with respect to XRA and YRA gyro case reference axes. Note that these axes are defined in 5.4.3.

5.3.4.2 IA alignment repeatability

__________ [", μrad], [maximum spread, 1σ, _____].

Thermal cycles and other environmental exposures, shutdowns, time between runs, remounting, and additional factors pertinent to the particular application should be specified.

5.3.4.3 IA alignment sensitivities

IA alignment sensitivities may be specified, such as those due to temperature, thermal gradients, rate of temperature change, acceleration, vibration, and additional environments pertinent to the particular application.

5.3.5 Operating temperature

__________ ± __________ °C.

The operating temperature above applies only to temperature-controlled gyros. For gyros intended to operate without temperature control, see 5.6.4.4.

5.3.6 Warm-up time

__________ [s, _____], maximum.

The limits of gyro performance during that portion of warm-up time following the turn-on time should be specified for certain applications. These limits could be fixed bounds or functions of time. More than one function may be specified for different temperatures at the time of turn-on, or different functions may be specified for each performance parameter (i.e., scale factor, bias, etc.).

5.3.7 Turn-on time

The gyro output rate shall be within __________ [°/h] of the input rate within __________ [s, _____] after the application of power.

5.3.8 Polarities

5.3.8.1 Input axis (IA)

The positive IA shall conform to [drawing number __________, Figure __________].

5.3.8.2 Output signals

The output signals representing gyro rotation shall conform to [drawing number __________, Figure __________].

5.3.9 Reference constants

These constants are for reference only. They are not specified independently, because they may vary within the framework of the specification, or because they are difficult or impossible to measure independently in a complete gyro. Nominal values are listed.

5.3.9.1 Light source wavelength

__________ [nm, _____].

5.3.9.2 Number of turns

__________.

5.3.9.3 Effective area per turn

__________ [m^2, _____].

5.3.9.4 Physical pathlength

__________ [m, _____].

5.4 Mechanical requirements

Mechanical characteristics shall be as specified hereinafter.

5.4.1 Exterior surface

Additional requirements controlling surface finish, workmanship, processing, etc., may be specified.

5.4.2 Outline and mounting dimensions

Outline and mounting dimensions, and accuracy requirements of mounting surface shall conform to [drawing number _____, Figure _____].

Specify center of gravity if required.

5.4.3 Gyro axes

The X gyro case reference axis (XRA) and Y gyro case reference axis (YRA) are mutually perpendicular and are located by means of the gyro mounting surface and the reference index on the gyro case [notch, pin, scribe line, _____]. The IRA, XRA, and YRA are reference axes defined with respect to the mounting provisions. These axes are nominally parallel to IA, XA, and YA respectively, and define a right-handed coordinate system. The IRA is perpendicular to the gyro mounting surface and shall conform to [drawing number __________, Figure __________] (see Figure 1).

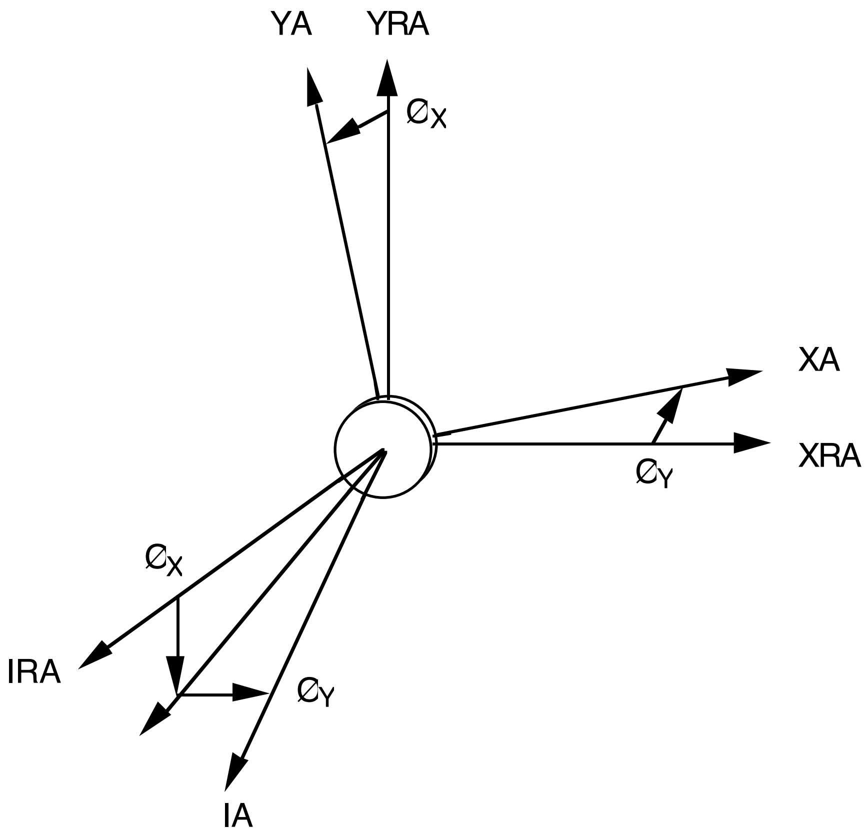


Figure 1—Gyro axes and misalignment angles

5.4.4 Weight

__________ + __________ [g, _____].

Specify those components such as cables, connectors, and electronics that are to be included in the weight.

5.4.5 Seal

The gyro shall be sealed such that the equivalent helium leak rate is less than __________ [cm^3/s, _____] when subjected to a pressure of __________ ± __________ Pa and gyro temperature of __________ ±__________ °C for a minimum of __________ minutes.

5.4.6 Identification of product

The gyro shall be identified on the surface and in the manner indicated in drawing number __________. Identification shall include the following:

a) Fiber optic gyro or IFOG
b) Specification number
c) Unit serial number
d) Axis identification marking as shown in [drawing number __________, Figure __________]
e) Manufacturer's name or symbol

> The purchase agreement may require additional identification such as date of manufacture and safety warnings.

5.4.7 Acoustic noise

The acoustic noise emissions shall conform to _________.

5.5 Electrical requirements

Electrical characteristics shall be as specified in this subclause.

5.5.1 Schematic

The electrical circuits shall be connected as shown in [drawing number __________, Figure __________].

> The schematic may include preamplifiers, temperature sensing circuits, heater circuits, trim components, test points, etc.

5.5.2 Impedances

The gyro impedances shall be __________ Ω.

> Load impedances and impedances of excitation, monitoring, temperature sensing, and test circuits should be specified.

5.5.3 Input power

The input power shall not exceed __________ W.

> Requirements such as power factor for each circuit, frequency, voltage, ripple, starting, and operating current should be specified. Transient conditions may need to be specified.
>
> Gyros with environmental controls may exhibit substantial changes in input power requirements over the operation temperature range.

5.5.4 Test points

Test points required for monitoring and testing of the gyro should be specified. These may include excitation voltages, other control signals, or temperature sensor(s). Any special buffering or scaling requirements should be specified.

5.5.5 Grounding

Electrical grounding design requirements (for example, requirements for isolation between input, output power returns and the grounding requirements for shields, chassis and critical components) should be specified.

5.5.6 Output signals

The type and characteristics of output signal(s) required, such as analog voltage or current, parallel or serial digital, or incremental angle pulses should be specified. For example: Type: Pulses indicating positive angular increments on one signal line and pulses indicating negative angular increments on a second line. Characteristics: Source impedance Load impedance Wave shape (see Figure 2) Maximum pulse rate

5.5.7 Temperature sensors

The output of the temperature sensor(s) shall be __________ ± __________ [Ω, V, _____] in the operating temperature range specified in 5.6.4.4 of this standard. The temperature rise of the sensor due to self-heating shall not exceed __________ °C at __________ mA. The scale factor of the temperature sensor(s) shall be [±] __________ ± __________ [V/°C, _____].

Thermistors, thermocouples, or other temperature sensors may be specified. Temperature sensors may be built into the gyro for use in characterizing its temperature sensitivity. If sensors are required, specify quantity, locations, and characteristics. The temperature range over which the scale factor should be specified is given by 5.3.5 for temperature-controlled gyros and 5.6.4.4 for all other gyros.

5.5.8 Insulation resistance

The insulation resistance between isolated interface circuits and between the case(s) and circuits isolated from the case(s) shall not be less than __________ MΩ measured at __________ ±__________ V dc, applied for __________ ± __________ s.

Different voltages may be specified for different circuits.

5.5.9 Dielectric strength

The leakage current shall not exceed __________ nA when __________ ± __________ V RMS, at __________ Hz, are applied between isolated interface circuits, and between the case(s) and circuits isolated from the case(s) for __________ ± __________ s.

Different voltages may be specified for different circuits. In some instances, lower voltages may be specified for subsequent tests.

5.5.10 Electromagnetic interference

The electromagnetic emissions and susceptibilities shall conform to __________.

Describe the requirements. In the United States, a common standard is MIL-STD-461.

5.5.11 Electromagnetic compatibility

Describe the requirements. In the United States, a common standard is MIL-STD-461.

5.6 Environmental requirements

This subclause contains environmental requirements only. Test procedures that are to be used, including required combinations of environments, are covered in 6.6 of this standard.

5.6.1 Storage

The gyro shall conform to all requirements of this specification after exposure to the following environments or specified combinations thereof, while packaged as specified in Clause 7.

The procuring organization should list the applicable environments from 5.6.4 of this standard and specify the limits for each based on the storage conditions expected.

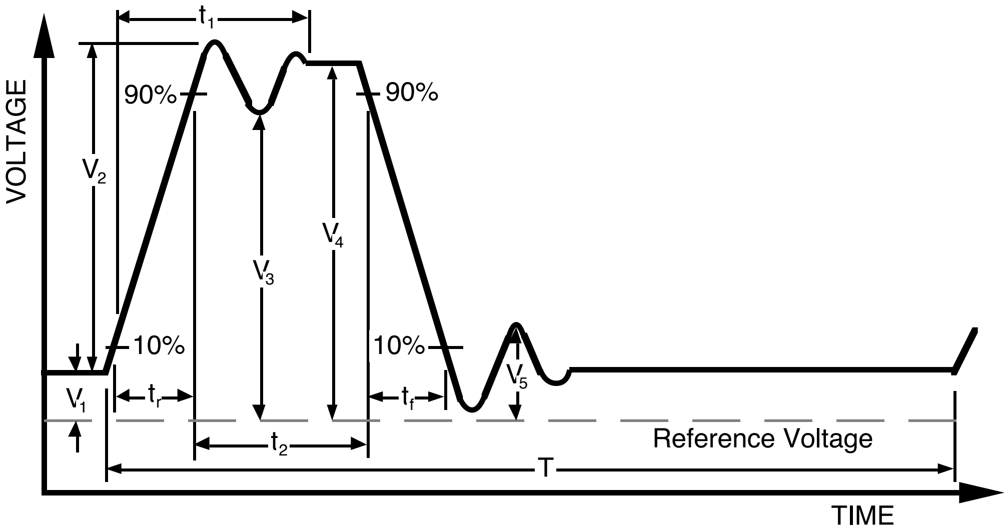
5.6.2 Transport

The gyro shall conform to all requirements of this specification after exposure to the following environments or specified combinations thereof, while packaged as specified in Clause 7.

The procuring organization should list the applicable environments from 5.6.4 of this standard and specify the limits for each based on the transportation conditions expected.

5.6.3 Operation

In order to properly specify the environmental requirements for a gyro, three different sets of environments or environmental limits, or both, as defined in 5.6.3.1, 5.6.3.2, and 5.6.3.3 of this standard may need to be described.



	UNITS	MAXIMUM	MINIMUM	REMARKS
V_1	volts	_______	_______	Steady-state low voltage
V_2	volts	_______	N/A	Overshoot voltage
V_3	volts	N/A	_______	Undershoot voltage
V_4	volts	_______	_______	Steady-state high voltage
V_5	volts	_______	N/A	Maximum low voltage transient
t_r	seconds	_______	_______	Rise time
t_f	seconds	_______	_______	Fall time
t_1	seconds	_______	_______	Turn-on transient time
t_2	seconds	_______	_______	High voltage on time
t_1/t_2	_______	_______	N/A	Ratio of turn-on transient to required on time
T	seconds	_______	_______	Waveform period
t_2/T	_______	_______	_______	Duty cycle

Figure 2—Wave shape requirements for direct coupled pulse-type signals

5.6.3.1 Operating environment

The gyro shall conform to all requirements of this specification during exposure to the following environments or specified combinations thereof (except during exposure to __________ where the deviations of this specification are given in the following clauses).

> Where degraded performance is to be allowed, include the parenthetical phrase in 5.6.3.1 of this standard and list in the blank space those environments for which degraded performance is allowed. The procuring organization should list the applicable environments from 5.6.4 of this standard and specify the limits for each based on the conditions expected when the gyro is in use. For those environments where degraded performance is allowed, specify the performance deviation in the clause that specifies the environment.

5.6.3.2 Survival environment, operating

The gyro shall conform to all requirements of this specification after the operating gyro has been exposed to the following environments or specified combinations thereof.

> The procuring organization should list the applicable environments from 5.6.4 of this standard and specify the limits for each based on the conditions expected when the gyro is operating, but not in use.

5.6.3.3 Survival environment, nonoperating

The gyro shall conform to all requirements of this specification after the nonoperating gyro has been exposed to the following environments or specified combinations thereof.

> The procuring organization should list the applicable environments from 5.6.4 of this standard and specify the limits for each based on the conditions expected when the gyro is not operating. Such conditions are expected to occur when the gyro is mounted in the system and the system is stored or transported in severe environments.

5.6.4 Environments

Environmental characteristics shall be as specified in this subclause.

> This list is intended as an aid to the selection of the applicable environments under 5.6.1, 5.6.2, and 5.6.3 of this standard. 5.6.4 in this form would not be included in a final specification.

5.6.4.1 Vibration

> Axes should be defined.
>
> When available, supply the specific vibration characteristics including dwell frequencies, frequency spectrum, time duration, etc.
>
> If exposure to random vibration is required, power spectral density (PSD), bandwidth, peak acceleration level, and duration should be specified.

5.6.4.1.1 Linear

Sinusoidal: __________ [cm, inches] DA (double amplitude) __________ to __________ Hz; __________ [m/s^2, g] peak, __________ to __________ Hz. Sweep rate: __________ min/octave (continuous). Exposure time: __________ [min, _____] per axis.

5.6.4.1.2 Angular

Sinusoidal: __________ [$°/s^2$, rad/s^2] __________ to __________ Hz. Sweep rate shall be __________ min/octave (continuous). Exposure time: __________ [min, ___] per axis.

5.6.4.2 Mechanical shock

__________ [m/s^2, g, _____] peak, __________ wave shape, __________ ms, __________ shock(s) per axis.

> Gyro axes and direction of shock should be defined. A figure may be included to describe more complex waveforms. A shock spectrum may be specified.

5.6.4.3 Acceleration

Gyro axes and direction of acceleration should be defined.

5.6.4.3.1 Linear acceleration

__________ [m/s^2, g], exposure time __________ [min, _____].

5.6.4.3.2 Angular acceleration

__________ [°/s^2, rad/s^2], exposure time __________ [min, _____].

5.6.4.4 Temperature

__________ °C to __________ °C.

5.6.4.5 Thermal shock

__________ °C to __________ °C within __________ [s, _____].

If exposure to cyclic conditions is required, temperature limits for each level, dwell times, and sequence should be specified. A figure may be included to describe more complex profiles.

5.6.4.6 Time-dependent temperature gradient

__________ °C between specified gyro surfaces to __________ °C within __________ [s, _____].

5.6.4.7 Thermal radiation

__________ W/cm^2 of radiation of wavelength from __________ to __________ meters; exposure time: __________ [min, _____].

5.6.4.8 Ambient air pressure

__________ to __________ [Pa, _____].

If exposure to cyclic conditions is required, pressure limits for each level, dwell times and sequence should be specified. A figure may be included to describe more complex profiles.

5.6.4.9 Acoustic noise

__________ dB referenced to $2 \cdot 10^{-5}$ Pa, __________ to __________ Hz; exposure time: __________ [s, _____].

When available, the specific sound pressure versus frequency for the application should be specified. Sweep rate may be specified as __________ min/octave (continuous), if applying sinusoidal acoustic noise.

5.6.4.10 Humidity

__________ % relative humidity for __________ h obtained from steam or distilled water having a pH value of __________ + __________.

5.6.4.11 Air currents

__________ [m/s, ft/s].

Gyro axes and direction of air flow should be defined.

5.6.4.12 Fungus

Fungi organisms, length of exposure, temperature, and humidity conditions during exposure should be specified.

5.6.4.13 Salt spray

__________ % salt solution; exposure time: __________ [s, _____].

5.6.4.14 Nuclear radiation

__________ [J/kg, rad(Si)] with an exposure of __________ [(J/kg)/s, rad(Si)/s] and/or combinations of __________ particles at a fluence of __________ /cm^2 with energy greater than __________ MeV.

Radiation field characteristics and direction with respect to gyro axes should be defined. If exposure to varying fields is required, the nature of the variation should be described.

5.6.4.15 Magnetic fields

__________ [mT, G]; exposure time: __________ [s, _____].

Gyro axes and direction of field should be defined. If exposure to varying fields is required, the nature of the variation should be described.

5.6.4.16 Electromagnetic fields

Electromagnetic fields shall conform with __________.

In the United States, a common standard is MIL-STD-461.

5.6.4.17 Sand and dust

__________ [Kg/m^3, _____] at a velocity of __________ + __________ [m/s, _____]; exposure time: __________ [s, _____].

Particle size, shape, and chemical composition should be specified.

Authorized licensed use limited to: IEEE Standards Staff. Downloaded on January 27, 2009 at 15:00 from IEEE Xplore. Restrictions apply.

5.6.4.18 Solar radiation

__________ + __________ [W/m^2, W/ft^2] of wavelength __________ to __________ meters; exposure time: __________ [min, ___].

Distribution of power density versus wavelength should be specified.

5.6.4.19 Rain

__________ + __________ [mm/h, _____] consisting of droplets having a minimum diameter of __________ mm; exposure time: __________ [s, _____].

5.6.4.20 Excitation variation

The variations of excitation voltage and frequency shall conform with __________.

In the United States, a common standard is MIL-STD-704.

5.6.4.21 Life

5.6.4.21.1 Storage

__________ [years, _____].

5.6.4.21.2 Operating

__________ [h, _____].

5.6.4.21.3 Start cycles

__________ minimum.

Life may need to be specified under varying environmental conditions.

5.7 Reliability

5.7.1 Reliability program

The reliability program required shall conform with __________.

In the United States, a common standard is MIL-STD-785.

5.7.2 Mean time between failure (MTBF)

The MTBF shall be __________ h minimum.

Conditions, methods of analysis, and failure criteria should be specified.

6. Quality assurance provisions

6.1 Classification of tests

Inspection and testing shall be classified as follows:

a) Acceptance tests. Acceptance tests are those tests performed on gyros submitted for acceptance under contract.
b) Qualification tests. Qualification tests are those tests performed on gyros submitted for qualification as a satisfactory product.
c) Reliability tests. Reliability tests are those tests performed to demonstrate the reliability specified in 5.7 of this standard.

6.2 Acceptance tests

6.2.1 Individual tests

Each gyro shall be subjected to the following tests as described in 6.6.

> The list and sequence of individual tests should be specified by the procuring organization based on individual requirements. Those tests that are usually specified are listed below. A burn-in period under specified conditions may be required before beginning individual tests.
>
> | | |
> |---|---|
> | 6.6.1 | Examination of product (mechanical) |
> | 6.6.2.1 | Insulation resistances |
> | 6.6.2.2 | Impedances |
> | 6.6.4 | Input power and circuit excitations |
> | 6.6.5 | Turn-on time |
> | 6.6.6 | Warm-up time |
> | 6.6.7 | Polarity |
> | 6.6.9.1 | Gyro scale factor |
> | 6.6.9.2 | Gyro scale factor errors |
> | 6.6.10 | Input rate test series |
> | 6.6.11.1 | Bias repeatability |
> | 6.6.11.1 | Bias sensitivities |
> | 6.6.11.3 | Random drift |
> | 6.6.12.1 | IA misalignment (nominal) |
>
> There are other individual tests that are not generally specified but that may be included under individual tests based on specific application. In some cases the gyros are subjected to specific environmental tests.

6.2.2 Sampling plans and tests

6.2.2.1 Sampling plans

> This subclause is intended to designate a sampling plan if required. Sampling plans are up to the discretion of the procuring organization based upon usage, size of contract, individual requirements, etc.

Gyros selected shall be subject to the tests specified in 6.2.2.2, which are described in 6.6.

> In the United States, selection according to MIL-STD-105 is common.

6.2.2.2 Sampling tests

> In addition to the individual tests listed in 6.2.1 of this standard, the procuring organization should specify from 6.6 those tests that should be performed on gyros selected by 6.2.2.1. Sampling plan units may be used for delivery unless the procuring agency specifies life tests or other destructive type tests under the sampling plan.

6.2.2.3 Rejection and retest

When one item selected from a production run fails to meet the specification, the procuring organization shall be immediately notified of the failure, and at the discretion of the procuring organization no items still on hand or later produced shall be accepted until the extent and cause of failure are determined. After corrections have been made, all necessary tests shall be repeated. For operational and production reasons, individual tests may be continued pending the investigation of a sampling plan failure.

> Other requirements suitable to an individual contract may be substituted for this subclause.

6.2.2.4 Defects in items already accepted

The investigation of a test failure could indicate that defects may exist in items already accepted. If so, the manufacturer shall fully advise the procuring organization of defects likely to be found and of methods for correcting them.

6.3 Qualification tests

6.3.1 Qualification test samples

A sample of __________ gyros manufactured in accordance with the requirements of this clause shall be subjected to qualification tests specified in this specification at an activity designated by the procuring organization.

If the gyro is later modified in any way, the modified gyro shall be subjected to and pass those qualification tests designated by the procuring organization.

The qualification test samples shall be identified with the manufacturer's part number and/or any other information required by the procuring organization.

6.3.2 Qualification tests

> The procuring organization should specify from 6.6, those tests, or combinations of tests, that should be performed on gyros submitted for qualification.

6.4 Reliability tests

> The reliability tests may be performed at the gyro or higher assembly level, or both.

6.4.1 Burn-in

Each gyro shall be subjected to a__________ h burn-in period under the following conditions.

Environment and operating conditions should be specified. Consideration should be given to not compromising the useful operating life by excessive test time during burn-in.

6.4.2 Demonstration testing

The MTBF requirements of 5.7.2 shall be demonstrated by testing __________ units for a minimum of __________ h each, for a combined total of __________ h minimum.

In the United States, testing in accordance with MIL-STD-781 is common. Other methods of demonstration testing may be selected. A demonstration test plan should be prepared to define test conditions, stress levels, failures, types of tests, etc.

6.5 Test conditions and equipment

The procuring organization should specify from Part II, Clause 11, the nominal test conditions and test equipment required. The conditions should apply to all tests unless otherwise specified. When a test condition is specified, the complete test condition should be detailed in this specification. The test equipment required should also be listed by name and model, part number, or performance requirement.

6.6 Test methods

Instructions for performing specified tests in this clause are detailed in Part II, Clause 12. When a test is specified, the complete test method should be detailed in this specification, including requirements to be met to determine satisfactory performance. A test method should not be listed in 6.6 unless a requirement exists in Clause 5 of this specification. The corresponding test methods are shown in Annex D for each requirement.

6.6.1 Examination of product (mechanical)

6.6.2 Examination of product (electrical)

6.6.2.1 Insulation resistances

6.6.2.2 Impedances

6.6.2.3 Dielectric strength

6.6.3 Leak test

6.6.4 Input power

6.6.5 Turn-on time

6.6.6 Warm-up time

6.6.7 Polarity

Authorized licensed use limited to: IEEE Standards Staff. Downloaded on January 27, 2009 at 15:00 from IEEE Xplore. Restrictions apply.

6.6.8 Operating temperature test series

6.6.8.1 Temperature sensor characteristics

6.6.8.2 Operating temperature

6.6.9 Gyro scale factor test series

6.6.9.1 Gyro scale factor

6.6.9.2 Gyro scale factor errors

6.6.9.3 Gyro scale factor sensitivities

6.6.10 Input rate test series

6.6.10.1 Maximum input rate

6.6.10.2 Minimum input rate

6.6.11 Drift rate test series

6.6.11.1 Bias

6.6.11.2 Measurement noise

6.6.11.3 Random drift

6.6.11.3.1 Angle random walk

6.6.11.3.2 Bias instability

6.6.11.3.3 Rate Random walk

6.6.11.3.4 Ramp

6.6.12 IA alignment test series

6.6.12.1 Misalignment (nominal)

6.6.12.2 Alignment repeatability

6.6.12.3 Alignment sensitivities

6.6.13 Generated fields

6.6.13.1 Electromagnetic interference

6.6.13.2 Acoustic noise

6.6.14 Environmental test series

6.6.14.1 Temperature

6.6.14.2 Excitation variation

6.6.14.3 Mechanical shock

6.6.14.4 Thermal shock

6.6.14.5 Vibration

6.6.14.5.1 Linear

6.6.14.5.2 Angular

6.6.14.6 Acceleration

6.6.14.6.1 Linear acceleration

6.6.14.6.2 Angular acceleration

6.6.14.7 Life

6.6.14.7.1 Storage

6.6.14.7.2 Operating

6.6.14.7.3 Start cycles

6.6.14.8 Fungus

6.6.14.9 Humidity

6.6.14.10 Salt spray

6.6.14.11 Acoustic noise

6.6.14.12 Thermal radiation

6.6.14.13 Air currents

6.6.14.14 Nuclear radiation

6.6.14.15 Pressure

6.6.14.16 Magnetic fields

6.6.14.17 Electromagnetic fields

6.6.14.18 Sand and dust

6.6.14.19 Solar radiation

6.6.14.20 Rain

6.6.14.21 Other

Specific applications may require combined environmental tests, such as:

a) Thermal vacuum (6.6.14.1, 6.6.14.12, and 6.6.14.14)
b) Margin tests (6.6.14.1, 6.6.14.2, and 6.6.14.14)
c) Thermal shock/vacuum (6.6.14.1 and 6.6.14.14)

7. Preparation for delivery

Detailed procedures should be provided for:

a) Preservation and packaging
b) Packing
c) Marking of shipping containers

A common United States specification covering preservation and packaging is MIL-P-116.

8. Notes

8.1 Intended use

Description of application if it is considered necessary or helpful.

8.2 Ordering data

Procuring documents should specify the following:

a) Title, number, and date of this specification
b) Level of packaging and packing desired
c) Mode of shipment required
d) Whether sampling plan tests are to be conducted
e) Number of preproduction samples to be submitted for qualification testing
f) Data package

8.3 Model equation

The model equation for a single-axis ifog expresses the relationship between the input rotation rate and the gyro output in terms of parameters whose coefficients are necessary to specify the performance of the gyro.

The use of the coefficients defined in this subclause to simulate gyro performance is discussed in Annex B.

$$S_0(\Delta N / \Delta t) = [I + E + D][1 + 10^{-6}\varepsilon_K]^{-1}$$

where

S_0 is nominal scale factor ("/p)
$(\Delta N/\Delta T)$ is output pulse rate (p/s)

In the analog rate sensing mode S_0V is $[\mathrm{I} + E + D]\,[1 + 10^{-6}\ \varepsilon_K]^{-1}$ S_0 is nominal scale factor [(°/h)/V] V is analog output (volts)

I is inertial input terms (°/h)

E is environmentally sensitive terms (°/h)

D is drift terms (°/h)

ε_K is scale factor error terms (ppm)

I is $\omega_{IRA} + \omega_{XRA}\sin\Theta_Y - \omega_{YRA}\sin\Theta_X$

E is $D_T\Delta T + D_{\dot{T}}(dT/dt) + \bar{D}_{\nabla\dot{T}} \bullet \frac{d\nabla\bar{T}}{dt}$

D is $D_F + D_R + D_Q$

where

D_R is $D_{RN} + D_{RB} + D_{RK} + D_{RR}$

ε_K is $\varepsilon_T\Delta T + f(I)$

ω_{IRA}, ω_{XRA},
ω_{YRA} are components of the inertial input rate resolved into the gyro reference coordinate frame

Θ_X is misalignment of the IA about the XRA

Θ_Y is misalignment of the IA about the YRA

D_F is bias

$D_T\Delta T$ is drift rate attributable to a change in temperature, ΔT, where D_T is the drift rate temperature sensitivity coefficient

$\varepsilon_T\Delta T$ is scale factor error attributable to a change in temperature, ΔT, where ε_T is the scale factor temperature sensitivity coefficient

$D_{\dot{T}}(dT/dt)$ is drfit rate attributable to a temperature ramp, dT/dt, where $D_{\dot{T}}$ is the coefficient of the temperature-ramp drift-rate sensitivity

$\bar{D}_{\nabla\dot{T}} \cdot \frac{d\nabla\bar{T}}{dt}$ is drift rate attributable to a time-varying temperature-gradient, $\frac{d\nabla\bar{T}}{dt}$, where $\bar{D}_{\nabla\dot{T}}$ is the coefficient vector of the time-varying temperature-gradient drift-rate sensitivity

$f(I)$ is cale factor errors dependent on input rate

D_{RN} is random drift rate attributable to angle random walk, where N is the coefficient

D_{RB} is random drift rate attributable to bias instability, where B is the coefficient

D_{RK} is random drift rate attributable to rate random walk, where K is the coefficient

$\mathrm{D_{RR}}$ is random drift rate attributable to ramp, where R is the coefficient

D_Q is equivalent random drift rate attributable to angle quantization, where Q is the coefficient

Other sensitivities may be added to the model equation, such as those due to variations in supply voltage, orientation, acceleration, vibration, and other environments pertinent to the particular application.

Part II—Test procedures

9. Test procedure overview

This test procedure describes the test requirements for __________ [model number, part number, change letter (if any), other identification], gyro specification number __________, manufactured by __________.

10. Description

The gyro considered in this standard is a single-axis IFOG that senses angular rate utilizing the Sagnac effect. The gyro output may be either angular rate or angular displacement. The characteristics of the gyro are expressed by the model equation given in 8.3.

11. Test conditions and test equipment

11.1 Standard test conditions

Unless otherwise stated, the conditions in 11.1.1.1 through 11.1.1.4 apply.

11.1.1 Ambient environment

11.1.1.1 Atmospheric conditions

a) Pressure: __________ + __________ [Pa, in Hg]
b) Ambient temperature: __________ + __________ °C
c) Relative humidity: __________ to __________ %

11.1.1.2 Magnetic field

a) Horizontal component: __________ [mT, G] maximum
b) Vertical component: __________ [mT, G] maximum

11.1.1.3 Radiation

List type of radiation and application intensity limits.

11.1.1.4 Seismic conditions

11.1.1.4.1 Tilt

Stable within __________ [", μrad] with respect to the local vertical.

11.1.1.4.2 Linear vibration

a) Acceleration: __________ g maximum
b) Frequency range: __________ to __________ Hz

The preceding limits apply to each of the three axes of a coordinate system.

11.1.1.4.3 Angular vibration

a) Oscillations: __________ [°/s^2, rad/s^2] maximum
b) Frequency range: __________ to __________ Hz

The preceding limits apply to rotation about each of the three axes of a coordinate system.

11.1.2 Installation conditions

> In designing the mounting fixture, consideration should be given to the installation conditions of the application. Reference to a specific mounting block thermal and mechanical design, etc., may be necessary if deemed important to meet performance requirements. If temperature control is required, the following should be specified:
>
> a) The unit operating temperature
> b) The means of temperature determination
> c) The criteria for establishing thermal equilibrium
>
> Where necessary, the test installation should provide means to measure and/or control the temperature gradients.

11.1.2.1 Thermal conditions

All tests requiring stable temperatures shall be performed with the gyro at thermal equilibrium as evidenced by __________. The gyro operating temperature shall be __________ ± __________ °C.

> The method of determining the temperature should be specified if required.

11.1.2.2 Mechanical conditions

The gyro shall be mounted in such a way that the alignment of the IRA with respect to the test fixture is maintained within __________ [', mrad] under all specified test conditions.

11.1.3 Electrical excitation and load conditions

Excitation and load conditions shall be as specified hereinafter.

11.1.3.1 Input power

> The gyro may require more than one input voltage. For each circuit, the source impedance, voltage, frequency, ripple, warm-up, and operating current should be specified.

11.1.3.2 Output signals

> Typical output signals are either analog signals proportional to angular rate or digital signals proportional to angular displacement. The output load or the type of logic devices and the number of unit loads to be driven should be specified.

11.1.3.3 Electrical connections and phasing

Electrical connections and phasing shall be specified on schematic diagram __________.

Grounding, shielding, test points, load requirements, etc., should be specified as needed.

11.1.4 Turn-on procedure

The sequence of operations required to bring the gyro to operating condition shall be __________.

11.1.5 Turn-off procedure

The sequence of operations required to turn off the gyro shall be __________.

11.2 Standard operating and test equipment

11.2.1 General requirements

The accuracy and response characteristics of the test equipment should be compatible with the requirements of the gyro performance specification. Provisions should be made for adequate stabilization of the test equipment. Adequate limitations should be placed on the test equipment to prevent the gyro from excessive inputs and loads, such as electrical, mechanical, thermal, etc.

11.2.2 Standard operating equipment

Standard operating equipment is the equipment used to provide standard gyro operation and should be listed here by name, manufacturer, model, part number, or by performance requirements.

11.2.3 Test equipment

Test equipment is the equipment used to provide a stimulus or measurement capability and should be listed here by name, manufacturer, model, part number, or by performance requirements.

12. Test procedures

12.1 Examination of product—Mechanical

The gyro shall be inspected visually and dimensionally for proper identification, surface finish, and for defects in workmanship to determine that it conforms to the requirements of subclause __________.

12.2 Examination of product—Electrical

The gyro shall be inspected electrically according to the following subclauses to measure insulation resistances, impedances and dielectric strength.

For gyros where preamplifiers or other sensitive devices are included within the gyro case, care should be taken to avoid the application of voltages that could damage those devices.

12.2.1 Insulation resistance

12.2.1.1 Purpose of insulation resistance test

The purpose of this test is to measure the insulation resistance between the isolated circuits and between the gyro case and the circuits isolated from the gyro case.

12.2.1.2 Insulation resistance test—Equipment

> In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:
>
> a) Megohmmeter

12.2.1.3 Insulation resistance test—Setup and procedure

Apply __________ ± __________ V dc for a period of __________ ± __________ s between the indicated circuits and between the circuits and the gyro case. Record the resistance reading.

12.2.1.4 Insulation resistance test—Results

The results shall conform to the requirements of subclause __________.

12.2.2 Impedance

12.2.2.1 Purpose of impedance test

The purpose of this test is to measure the impedance of the specified gyro circuits.

12.2.2.2 Impedance test—Equipment

> In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:
>
> a) Impedance bridge with frequency generator adjustable to the specified frequency
> b) DC resistance bridge or other suitable resistance measuring system

12.2.2.3 Impedance test—Setup and procedure

The gyro shall be allowed to reach thermal equilibrium at the temperature specified in clause __________ in order that the final value will not be affected by changing temperature.

Measure all gyro impedances specified in subclause __________. To protect the gyro, the test current through the circuit shall be as small as practical considering the sensitivity of the measuring instruments.

The test current shall be uninterrupted for __________ ± __________ s.

12.2.2.4 Impedance test—Results

The impedance measured shall be recorded and shall conform to the requirements of subclause __________.

12.2.3 Dielectric strength

12.2.3.1 Purpose of dielectric strength test

The purpose of this test is to ascertain that a circuit element or component part of the gyro can operate safely at its rated voltage and withstand momentary overvoltage due to switching, surges, etc., between isolated circuits and between the gyro case and the circuits isolated from the gyro case.

12.2.3.2 Dielectric strength test—Equipment

In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:

a) AC high-voltage source equipped with voltage and current-measuring devices.

12.2.3.3 Dielectric strength test—Setup and procedure

Apply __________ ± __________ V RMS at __________ Hz between the insulated portion and the case ground. The test voltage shall be raised from zero to the specified value as uniformly as possible, at a rate of approximately 500 V RMS/s. The specified value of the test voltage shall be maintained for a period of __________ s. The voltage shall then be gradually reduced to avoid surges. During each test, the leakage current shall be measured.

12.2.3.4 Dielectric strength—Test results

The results shall conform to the requirements of subclause __________.

12.3 Leak test

12.3.1 Purpose of leak test

The purpose of this test is to determine if leakage through the gyro case is occurring.

12.3.2 Leak test—Equipment

In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:

a) Helium leak detector
b) Vacuum enclosure

12.3.3 Leak test—Setup and procedure

The gyro shall be cleaned of all dirt and grease and placed in a vacuum enclosure at __________ ± __________ [Pa, _____] and stabilized at __________ ± __________ °C gyro temperature. External gas leakage shall then be measured using a helium leak detector.

12.3.4 Leak test—Results

The measured gas leakage rate shall conform to the requirements of subclause _________.

12.4 Input power

12.4.1 Purpose of input power test

The purpose of this test is to measure the input power (current) required from each source.

12.4.2 Input power test—Equipment

In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:

a) Power (current) measuring equipment

12.4.3 Input power test—Setup and Procedure

Connect the power (current) measuring devices and apply power as specified in subclause __________. Record the input power (current) from each source.

12.4.4 Input power test—Results

The results shall conform to the requirements of subclause __________.

12.5 Turn-on time

12.5.1 Purpose of turn-on time test

The purpose of this test is to determine the time interval between the application of power and the presence of a usable output of the gyro.

12.5.2 Turn-on time test—Equipment

In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:

a) Rate table with angle or rate output, depending on gyro output data format
b) Gyro output measuring and recording equipment
c) Timing device

12.5.3 Turn-on time test—Setup and procedure

Mount the gyro in the fixture on the rate table so that the IRA is parallel to the table rotational axis within __________ [', mrad]. Connect the gyro to the output measuring equipment. Turn the rate table on and set the rate at __________ [°/s, rad/s]. Apply power to the gyro and record elapsed time and the gyro output.

12.5.4 Turn-on time test—Results

From the recorded data, determine the time interval from the application of power until the indicated rate from the gyro is within __________ [°/s, rad/s] of the table rate after correcting for earth rate and bias. This time shall conform to the requirements of subclause __________.

12.6 Warm-up time

12.6.1 Purpose of warm-up time test

The purpose of this test is to determine the time interval required for the gyro to reach specified performance from the instant it is energized under specified operating conditions.

12.6.2 Warm-up time test—Equipment

In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:

a) Rate table
b) Gyro output measuring and recording equipment
c) Timing device

12.6.3 Warm-up time test—Setup and procedure

Operate the gyro in accordance with the standard test conditions of 11.1, except that the starting conditions shall be __________ and the starting sequence shall be __________.

Energize the gyro and record the specified performance characteristics as a function of time for __________ [s, _____]

12.6.4 Warm-up time test—Results

The time for the gyro to meet the specified performance characteristics shall conform to the requirements of subclause __________.

12.7 Polarity

12.7.1 Purpose of polarity test

The purpose of the polarity test is to determine the gyro output polarity with reference to the axis defined in clause __________ of this specification.

12.7.2 Polarity test—Equipment

In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:

a) Rate table
b) Means of measuring the gyro output

12.7.3 Polarity test—Setup and procedure

Mount the gyro on the rate table with the gyro IRA nominally parallel to the table axis. Connect the gyro to the output measuring equipment. Prepare the gyro for test in accordance with the standard test conditions of 11.1. Accelerate the table to __________ [°/s, rad/s] with the input vector in the same direction as the positive IRA and record the gyro output polarity. Rotate the table in a similar manner in the opposite direction and again record the gyro output polarity.

12.7.4 Polarity test — Results

The results obtained shall conform to the requirements of subclause __________.

12.8 Operating temperature test series

12.8.1 Temperature sensor characteristics

This test applies only when the gyro has externally available terminals for temperature sensor readout.

12.8.1.1 Purpose of temperature sensor characteristics test

The purpose of this test is to determine the output of the temperature sensor and its variation with temperature.

12.8.1.2 Temperature sensor characteristics test — Equipment

> In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:
>
> a) Temperature control chamber
> b) Temperature sensor output measuring equipment

12.8.1.3 Temperature sensor characteristics test—Setup and procedure

Mount the gyro in a temperature-controlled chamber in accordance with the standard test conditions of 11.1. Stabilize the gyro temperature for __________ [h, ___] at __________ ± __________ °C (operating temperature). Measure and record the temperature sensor output. Repeat these measurements at the following temperatures: __________ and __________ ± __________ °C.

> For temperature-controlled gyros, one of the temperatures should be above and one below the operating temperature.

During this test, the power to the sensor shall not exceed __________ W. Record chamber temperature and sensor output.

12.8.1.4 Temperature sensor characteristics test—Results

The output of the sensor within the specified temperature range shall conform to the requirements of subclause _______.

From the data recorded in 12.8.1.3, compute the temperature sensor scale factor. The results shall conform to the requirements of subclause _______.

12.8.2 Operating temperature

> This test applies only to temperature-controlled gyros.

12.8.2.1 Purpose of operating temperature test

The purpose of this test is to ensure that the gyro operating temperature is within the operating temperature range as indicated by the temperature sensor output.

12.8.2.2 Operating temperature test—Equipment

In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this clause:

a) Temperature measuring equipment
b) Temperature chambers (if required)
c) Temperature sensor output measuring equipment

12.8.2.3 Operating temperature test—Setup and procedure

Operate the gyro in accordance with the standard test conditions of 11.1. The gyro shall be at thermal equilibrium for __________ [h, ___] before the temperature measurement is made. Measure and record the temperature sensor output.

12.8.2.4 Operating temperature test—Results

The gyro operating temperature shall be within the operating temperature range specified in subclause __________.

12.9 Gyro scale factor test series

12.9.1 Purpose of gyro scale factor test series

The purpose of this test series is to measure gyro scale factor, gyro scale factor errors, and gyro scale factor sensitivities.

12.9.2 Gyro scale factor test series—Equipment

In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:

a) Rate table with angle or rate output, depending on gyro output data format
b) Gyro output measuring and recording equipment
c) Gyro electronics and power supplies
d) Timing device
e) Environmental temperature control equipment

12.9.3 Gyro scale factor test series—Setup and procedure

12.9.3.1 Gyro scale factor and gyro scale factor errors

Align the rate table rotation axis to within __________ [', mrad] of vertical. Mount the gyro in the fixture on the table so that the IRA is parallel to the table rotational axis within __________ [', mrad]. Connect the gyro to the output measuring equipment. Set the instrumentation to record the elapsed time and gyro output. With the table rotating, operate the gyro in accordance with the standard test conditions of 11.1. The tests shall be performed and the output data recorded in accordance with the following tabulation.

Nominal input rate	Direction: positive, negative	Total number of revolutions	Number of measurements at each input rate	Output data
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
⋮	⋮	⋮	⋮	⋮
—	—	—	—	—

The output is the sum of data outputs for angle output gyros and the average data output for rate output gyros.

A warm-up test should be performed first. The warm-up test duration should be long enough to determine the warm-up effects on scale factor. The number of table revolutions per measurement for the warm-up test is a compromise between a large number of revolutions (so as to reduce noise due to table angle resolution, gyro output quantization and gyro output noise) and a small number of revolutions (to increase time resolution).

Sufficient measurements should be specified to provide for determination of the scale factor and scale factor errors. A zero table-rate measurement at one or more table positions is required to remove the effects of earth's rate and uncompensated drift rate from the scale factor data. In selecting the zero table-rate test time and the number of table revolutions consideration should be given to the error contributions of the table angle uncertainty, gyro output quantization, IA misalignment and gyro output noise. For scale factor measurements at extremely low input rates, a procedure of orienting the gyro to measure various components of earth's rate, instead of table rotation may be necessary.

12.9.3.2 Gyro scale factor sensitivities

12.9.3.2.1 Temperature

Using the environmental temperature control equipment, repeat 12.9.3.1 at temperatures __________ ± __________°C, after a minimum of __________ [h, _____] dwell at the specified temperatures.

Measurements need not be taken at all of the rates of 12.9.3.1.

12.9.3.2.2 Other sensitivities

12.9.4 Gyro scale factor test series—Results

12.9.4.1 Gyro scale factor

From the test data taken in 12.9.3.1, compute the nominal gyro scale factor by computing he slope of the straight line that can be fitted by the method of least squares to the input-output data, after correction for the zero table rate. The gyro scale factor shall conform to the requirements of subclause ________.

Alternatively, the gyro scale factor can be determined as the value obtained at a specified rate, may be the mean value over several rates, or an algorithm may be used.

12.9.4.2 Gyro scale factor errors

12.9.4.2.1 Linearity Error

From the test data taken in 12.9.3.1, compute the deviation of the output data at each input (rate, angle) from the least squares fit of the data calculated in 12.9.4.1. The linearity error shall conform to the requirements of subclause __________.

Alternate methods include weighting, calculation over a limited range, and computing linearity error after compensation.

12.9.4.2.2 Asymmetry

Compute the asymmetry at specified rates as the ratio of the difference in magnitudes of scale factor measured for positive and negative inputs to one-half the sum of the magnitudes. Asymmetry shall conform to the requirements of subclause __________.

12.9.4.2.3 Repeatability

Compute changes in the scale factor [ppm, _____], [maximum spread, 1σ, _____] that occur between specified periods of operation. The results of the gyro scale factor repeatability shall conform to the requirements of subclause __________.

12.9.4.2.4 Stability

The variation in scale factor obtained from the test series of 12.9.3.1 shall conform to the requirements of subclause __________.

12.9.4.3 Gyro scale factor sensitivities

12.9.4.3.1 Temperature

From the test data taken in 12.9.3.2.1, compute the temperature sensitivity as the maximum scale factor change over the specified temperature range, divided by the temperature range. The temperature sensitivity of the gyro scale factor shall conform to the requirements of subclause __________.

12.9.4.3.2 Other sensitivities

12.10 Input rate limits

12.10.1 Purpose of input rate limits test

The purpose of this test is to measure the input rate limits.

12.10.2 Input rate limits test—Equipment

In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:

a) Rate table with angle or rate output, depending on gyro output data format
b) Gyro mounting fixture
c) Gyro output measuring and recording equipment
d) Timing device

12.10.3 Input rate limits test — Setup and procedure

Install and operate the gyro in accordance with the procedure of 12.9.3. The data points selected shall include the input rate limits of subclause ____.

> When a dead band test is required, perform the test using either rate table or earth rate input, with rate intervals (near zero rate) of 25% (or less) of the dead band specified in 5.3.1.2.

12.10.4 Input rate limits test—Results

12.10.4.1 Maximum rate limit

From the test data taken in 12.10.3, compute the linearity error of the gyro scale factor with the maximum input rate of clause _____ included in the set of data, using the same method described in 12.9.4.1 and 12.9.4.2.1. The gyro scale factor linearity error shall conform to the requirements of subclause _____.

12.10.4.2 Minimum rate limit (dead band)

Using the data from 12.10.3, determine the dead band as the input range (near zero) over which the output is less than 10% of the input. The dead band shall conform to the requirements of subclause _____.

> The data averaging time should be long enough to reduce the gyro noise to less than 25% of the dead band. Prior to analyzing data, any bias should be removed.

12.11 Drift rate test series

12.11.1 Purpose of drift rate test series

The purpose of this test series is to measure the bias, random drift rate, measurement noise, environmentally sensitive terms, their repeatabilities, and sensitivities.

12.11.2 Drift rate test series—Equipment

> In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:
>
> a) Precision positioning means
> b) Gyro output measuring and recording equipment
> c) Timing device
> d) Environmental temperature control equipment
> e) Magnetic field generating equipment
>
> If the gyro output is analog, the test equipment should have provision for digitizing the output.

12.11.3 Drift rate test series t—Setup and procedure

12.11.3.1 Bias, random, and measurement noise

Mount the gyro so that the [IRA, XRA, YRA] is [vertical, horizontal, polar, __________] within __________ [', mrad]. Connect the gyro to the output measuring equipment and energize the gyro in accordance with the standard test conditions of 11.1. Record the gyro output for a period of __________ [h, __________] with data accumulated over __________ [s, __________] sample intervals.

In general, the data record length (test duration) should be sufficient to determine performance characteristics at desired confidence levels. The data sample rate should be at least twice the highest frequency of interest. If prefiltering of the raw data is required to minimize the effect of quantization the test results will be different than if prefiltering is not used. PSDs are useful to isolate and identify specific frequency components that may be present in the gyro output. In 12.11.4, the appropriate data reduction procedure should be used. See Annex C for a discussion of data reduction techniques.

Care should be taken in mounting the gyro so that the effects of the earth's rotation rate and the ambient magnetic field may be taken into account.

12.11.3.2 Repeatability

Repeat the procedure of 12.11.3.1 __________ times.

12.11.3.3 Environmentally sensitive drift

12.11.3.3.1 Temperature

Using the environmental temperature control equipment, stabilize the gyro at __________ ± __________ °C. Perform the procedure of 12.11.3.1. Repeat the procedure at additional temperature(s) of __________ ± __________ °C.

12.11.3.3.2 Temperature ramp and time-dependent temperature gradient

Mount the gyro in a temperature-controlled chamber in accordance with the standard test conditions of 11.1. Stabilize the gyro temperature for __________ minutes at __________ ± __________ °C. Measure and record the gyro output as specified in 12.11.3.1 and the gyro temperature sensor output. Continue these measurements as the environmental chamber is ramped to __________ °C at a rate of __________ °C per minute.

The duration of the temperature ramp should be sufficient to permit the transient bias change associated with the Shupe effect to die out. The location of the sensor for the temperature to be measured and the temperature to be controlled should be specified. The temperature profile may also include several periods of stabilization followed by ramping, with a period of stabilization following the last ramp.

12.11.3.3.3 Magnetic

Using the magnetic field generating equipment, repeat 12.11.3.1 at steady-state flux densities of ± __________[mT, G] directed along the IRA. The test shall also be performed with the magnetic field directed along the __________ [XRA, YRA].

12.11.3.3.4 Other sensitivities

12.11.4 Drift rate test series—Results

The data processing applied to the drift rate test series data from 12.11.3 includes least squares estimation and Allan variance computation methods for the purpose of determining bias and random drift coefficients.

Annex B presents an overview of dynamic modeling methods including the Allan variance method.

Agreement between the supplier and the user concerning the modeling method and the data reduction and analysis process is recommended.

12.11.4.1 Bias, random and measurement noise

12.11.4.1.1 Bias, D_F

From the test data taken in 12.11.3.1 after warm-up, compute the bias, D_F, for each sample interval by dividing the accumulated number of pulses in each sample interval by the corresponding sample time, multiplying by the gyro scale factor and removing the component of earth rate along the IA.

Compute D_F by obtaining the average of all the D_F data. The results shall conform to the requirements of subclause __________.

12.11.4.1.2 Random, D_R and measurement noise, D_Q

From the test data taken in 12.11.3.1 after warm-up compute the random drift coefficients *R, K, B, N,* and *Q* by forming the Allan variance estimates

$$\sigma_\Omega^2(nT_0) = \frac{1}{2(M-2n)} \sum_{m=1}^{M-2n} (\Omega_{m+2n} - 2\Omega_{m+n} + \Omega_m)^2$$

for $n = 1, 2, 3, ..., n_{max} \leq (M-1)/2$ and fitting the results to the polynomials

$$\sigma_\Omega^2(nT_0) = \frac{R^2 n^2 T_0^2}{2} + \frac{K^2 n T_0}{3} + B^2\left[\frac{2}{\pi}\right]\ln(2) + \frac{N^2}{nT_0} + \frac{3Q^2}{n^2 T_0^2}$$

in the least squares sense,

where

Ω_m	is gyro rate output calculated in the manner described in 12.11.4.1.1
$1/T_0$	is data sample rate
MT_0	is data record length

The results shall conform to the requirements of subclauses ________ and ________.

Annex C presents a detailed explanation of the random drift coefficients and their relationship to the Allan variance method.

12.11.4.2 Repeatability

From the test data in 12.11.3.2, repeat the analysis procedure of 12.11.4.1.1 __________ times to compute the changes in bias that occur between specified periods of operation. The results of the bias repeatability (°/h, _____) (maximum spread, 1σ, _____) shall conform to the requirements of subclause __________.

12.11.4.3 Environmentally sensitive drift

12.11.4.3.1 Temperature

From the test data taken in 12.11.3.3.1 after warm-up, calculate the gyro bias as in 12.11.4.1.1. Compute the bias temperature sensitivity as the slope of a least squares fit of bias over the test temperature range. The bias temperature sensitivity shall conform to the requirements of subclause __________.

> It is assumed that the data from gyros with a supplied bias thermal model are compensated with that model prior to the above analysis.

12.11.4.3.2 Temperature ramp

From the data taken in 12.11.3.2 after warm-up, calculate the maximum change in gyro bias and divide this by the temperature ramp rate. The temperature ramp drift rate shall conform to the requirements of subclause _____.

> The initial transient bias change associated with the Shupe effect should be excluded from the data analysis.

12.11.4.3.3 Time-dependent temperature gradient

From the test data taken in 12.11.3.3.3 after warm-up, calculate the gyro bias as in 12.11.4.1.1. Compute the time-dependent temperature gradient drift rate as the maximum bias change. The time-dependent temperature gradient drift rate shall conform to the requirements of subclause __________.

12.11.4.3.4 Magnetic

From the test data taken in 12.11.3.3.4 compute the magnetic sensitivity as the maximum bias change over the specified field range. The magnetic sensitivity of the gyro bias shall conform to the requirements of subclause __________ for each axis specified.

12.11.4.3.5 Other sensitivities

12.12 IA alignment

12.12.1 Purpose of IA alignment test

The purpose of this test is to measure the misalignment of the IA to the IRA.

12.12.2 IA alignment test—Equipment

> In addition to the standard operating equipment from 11.2.2, the following test equipment from 11.2.3 is required for this test and should be listed in this subclause:
>
> a) Rate table with angular readout
> b) Gyro output measuring equipment
> c) Gyro output recording equipment
> d) Right angle test fixture

12.12.3 IA alignment test—Setup and procedure

12.12.3.1 IA alignment

Mount the gyro in the fixture on the rate table so that the IRA is perpendicular to the rate table rotational axis within __________ [', mrad]. Operate the gyro in accordance with the standard test conditions of 11.1. Apply a positive table rate of __________ ± __________ [°/s, rad/s] and record the gyro output over __________ revolutions. Repeat the test with a negative input rate whose magnitude is within ± __________ [°/s, rad/s] of the positive rate. Rotate the gyro +90° about the IRA and repeat the test for positive and negative table rates.

> If the direction of the IA misalignment is important, the XRA should be aligned parallel to the rate table rotational axis for the initial mounting position. For the second mounting position the YRA should be aligned to the table rotational axis.
>
> If it is desirable to eliminate the test fixture error, rotate the gyro 180° about the IRA with respect to the fixture and repeat the test.

12.12.3.2 Repeatability

Repeat the procedure of 12.12.3.1 __________ times for the condition specified in subclause __________.

12.12.4 IA alignment test—Results

12.12.4.1 Alignment of the IA to the IRA

The misalignment, α, is calculated from the data obtained in 12.12.3.1 using the gyro scale factor obtained from 12.9.3 as follows:

$$\delta_{1,2} = \frac{\left(\begin{matrix}\text{gyro output from} \\ \text{positive rotation}\end{matrix} - \begin{matrix}\text{gyro output from} \\ \text{negative rotation}\end{matrix}\right) * \text{ gyro scale factor}}{2 * \text{ table rotation}}$$

$$\alpha = \sin^{-1}(\delta_1^2 + \delta_2^2)^{1/2}$$

δ_1 is misalignment in initial gyro orientation in fixture
δ_2 is misalignment in 90° gyro orientation in fixture

The misalignment shall conform to the requirements of subclause __________.

> When the XRA and YRA are used in performing the procedure of 12.12.3.1, δ_1 and δ_2 correspond to $-\Theta_y$ and $-\Theta_x$ respectively in the model equation in 8.3.

12.12.4.2 Repeatability

Repeat the test result calculations of 12.12.4.1 using the data from 12.12.3.2. The misalignment angles shall agree with those obtained in 12.12.4.1 within the requirements of subclause __________.

Authorized licensed use limited to: IEEE Standards Staff. Downloaded on January 27, 2009 at 13:00 from IEEE Xplore. Restrictions apply.

12.13 Generated fields

12.13.1 Electromagnetic interference

The purpose of these tests is to measure the electromagnetic emissions of the gyro.

MIL-STD-462 is a reference commonly used in the United States to describe test procedures and equipment required for this test.

These tests should be outlined in the following manner to conform to the format used in the rest of this standard:

12.13.1.1 Purpose
12.13.1.2 Test equipment
12.13.1.3 Test setup and procedure
12.13.1.4 Test results

12.13.2 Acoustic noise

The purpose of this test is to measure the acoustic noise generated by the gyro.

MIL-STD-740 is a reference commonly used in the U.S. to describe test procedures and equipment required for this test.

The test should be outlined in the following manner to conform to the format used in the rest of this standard:

12.13.2.1 Purpose
12.13.2.2 Test equipment
12.13.2.3 Test setup and procedures
12.13.2.4 Test results

12.14 Environment test series

These tests are to verify that the gyro performs as specified during or after subjection to environments outside of the standard operation conditions, or both, but within the specified environmental limits.

Procedures for most environmental tests are covered by existing industry, government, and military documents, an example of which is MIL-STD-810. Selection criteria should include the following:

a) Importance of the stability and sensitivity of the parameter in a given environment
b) Practicability of running the test with existing equipment. Testing should be limited to that required by the application

The tests should be outlined in the following manner to conform to the format used in the rest of this standard:

1 Name of test
1.1 Purpose
1.2 Test equipment
1.3 Test setup and procedure
1.4 Test results

Annex A

(informative)

Design features of IFOGs

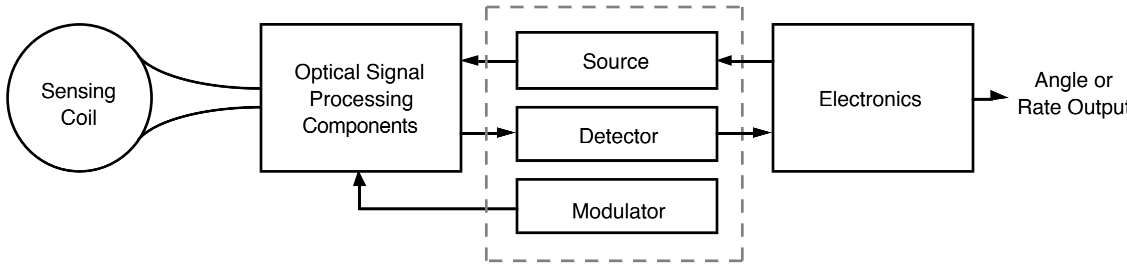


Figure A.1—Configuration of an IFOG

a) Sensing coil
   1) Multi-mode fiber
   2) Polarization maintaining fiber
   3) Single mode fiber

b) Optical signal processing components
   1) Directional coupler
   2) Depolarizer
   3) Isolator
   4) Polarization controller
   5) Polarizer
   6) Y-junction
   7) Mode filter
   8) Mode scrambler
   9) Optical dump

c) Opto-electric interface
   1) Sources
      —Laser diode
      —Light emitting diode/edge light emitting diode
      —Super luminescent diode
      —Pumped rare earth doped fiber
   2) Detector
   3) Modulator
      —Phase modulator
      —Piezo-electric
      —Electro-optical
      —Frequency modulator

d) Electronics
   1) Signal processing
   2) Power conditioning
   3) Environmental control

NOTE—A number of components such as y-junction, polarizers, and electro-optical modulators, can be fabricated as part of an integrated optic circuit (IOC). The IOC is typically based on a lithium niobate substrate.

Annex B[4]

(informative)

Dynamic and stochastic modeling overview

B.1 Introduction

This annex introduces dynamic and stochastic modeling, as applied to gyro modeling and performance evaluation. This is intended to be a tutorial overview [B41].[5]

The general form of the model consists of the following:

— A mathematical statement of the physical plant equations
— An error model consisting of a perturbation model and environmental sensitivities
— A stochastic model describing random drift behavior
— A measurement model consisting of a linear combination of the output and additive measurement noise

These are related in a generic form of a gyro model equation, consisting of the response to inertial inputs, environmental sensitivities, drift rate and scale factor error contributors.

Methods of determining input/output characteristics (dynamic modeling, system identification) are discussed. Stochastic modeling via time series analysis is introduced, including frequency domain methods. Emphasis is placed on application of the Allan variance and PSD. An approach to test and analysis is presented. Data acquisition, data reduction, processing, and evaluation of results are discussed.

The general non-linear problem was posed by Norbert Wiener during the early 1940s [B2]: given the yet to be analyzed system, which he defined as a black box, identify and characterize the system in terms of bodies of known structures, or what he called white boxes.

The solution to the linear problem uses various time and frequency domain techniques to find an operational equivalent of the black box, which may then be constructed by combining certain canonical forms of these white boxes. Although the model structure may be different from the true structure, the input-output properties are to be equivalent.

B.1.1 Historical review

The foundation of modeling dates back to approximately 1800, with Gauss's method of least-squares estimation [B20]. Current methods of determining the steady-state input-output characteristics of a variety of devices are based on this approach.

By 1905, Albert Einstein and Willard Gibbs had independently conceived methods of statistical physics. By 1910, Fisher applied the use of the probability density function to maximum likelihood estimation [B20]. In 1930, Wiener [B2] made the first significant use of frequency domain analysis and in 1940 established the beginnings of modern optimization theory [B20]. During WWII, game theory [B1] and operations research [B7] were conceived. These involved some of the earliest applications of modern modeling techniques.

During the 1950s stochastic process theory and differential game theory were developing. By 1960, Kalman conceived a time domain approach to optimal recursive filter design [B3], [B11], [B12], [B17], [B20]. By

[4]This annex is adapted from Annex B in IEEE Std 647-1995, IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Laser Gyros.

[5]The numbers in brackets preceded by the letter B correspond to those of the bibliography in B.6.

1963 Signal Identification [B20] and frequency domain Time Series Analysis (TSA) [B4], [B5], [B9], [B12], [B20] methods were developed. In 1965 Tukey and Cooley published their famous paper on the fast Fourier transform (FFT) [B20]. In 1966 David Allan proposed a simple variance analysis method for the study of oscillator stability [B8], [B16], [B18], [B21], [B23], [B29], [B30], [B38], [B40]. The method has since been applied to gyro drift analysis [B24], [B26], [B34], [B35], [B39]. Parameter Identification methods were known by 1968 [B19] and [B20].

During the decade that followed, time domain and frequency domain characterization of sensors gained importance. By 1970, the Box-Jenkins method of time series analysis was developed [B14], [B20], [B33] together with System Identification and Adaptive Kalman Filter techniques [B20]. During the 1980s non-linear multiple input, multiple-output stochastic optimal control/estimation gained interest. For the 1990s, artificial intelligence and expert systems ideas are finding application to modeling.

B.1.2 Unit model

The term unit refers to an operational entity that performs a well defined unique function. It can be a sensor, system, or other device. The unit model may be broken down into several other parts, as illustrated in Figure B.1. One part, the plant, or physical model, is described by either differential or algebraic equations that express the physics of its operation. This is the deterministic part of the plant that we are trying to address with dynamic modeling techniques. The second part, the error model, consists of a perturbational model, which includes the sensitivity to the variation of parameters in the plant equations, and an environmental model, which includes the sensitivities to environmental disturbances. The third part is the stochastic model, which includes the random drift observed under otherwise benign operating conditions. The measurement model consists of a linear combination of the system states and additive output noise.

The idea is that if the unit under test could be so modeled, optimal use of the model to evaluate or possibly improve performance at some higher level could be achieved. That is through optimal filtering, system error could be reduced to the limit of minimum residual white noise. The model also can be used for performance prediction and evaluation relative to a specification [B10], [B11], [B17], [B20].

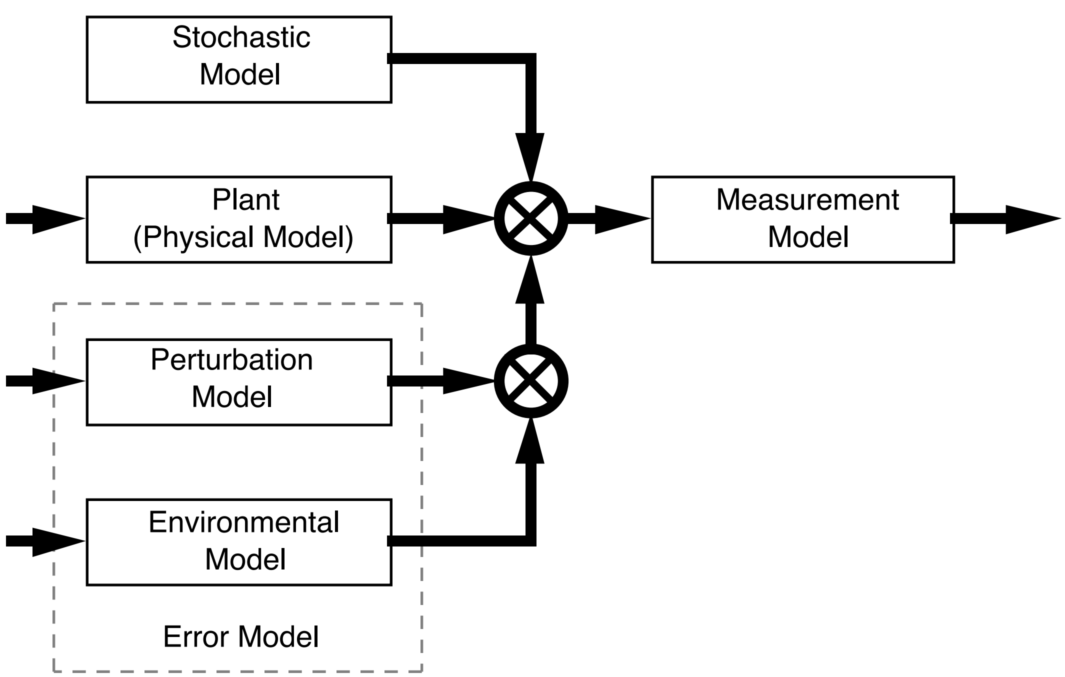
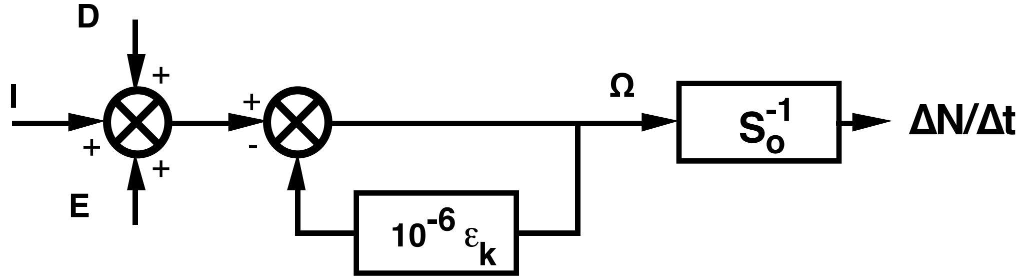


Figure B.1—System model

B.1.3 Gyro model equation

A generic model equation [B13] and [B15] that applies to many types of inertial sensors is shown in Figure B.2. It consists of inertial (including misalignment), environmental, and random (including quantization) contributors.

This approach to compartmentalizing gyro model equations is introduced to better organize the various model components.



$S_0(\Delta N/\Delta t)$	is $[I + E + D](1 + 10^{-6}\varepsilon_k)^{-1}$
S_0	is nominal scale factor
$\Delta N/\Delta t$	is output pulse rate
I	is inertial input terms
E	is environmentally sensitive terms
D	is drift terms
ε_k	is scale factor error terms (ppm)
Ω	is equivalent gyro rate output

Figure B.2—Generic model equation

B.2 Modeling

Some of the important applications of modeling occur in simulation studies, performance evaluation, and Kalman filter design [B15]. The basic difference between dynamic and stochastic modeling is as follows: in dynamic modeling, given one or more inputs, (input vector), and one or more outputs (output vector) it is desired to determine the input/output relationships from both time series. Applications include those where random noise is summing at the output.

In stochastic modeling, on the other hand, there may be no direct access to an input. A model is hypothesized which, as though excited by white noise, has the same output characteristics as the unit under test. Such models are not generally unique, so certain canonical forms are chosen. For example, David Allan of the National Institute of Standards and Technology (NIST) used a power series for the PSD and the corresponding Variance analysis in the time domain for the analysis of oscillator stability [B8]. This type of variance analysis is discussed in Annex C. The idea is that one or more white noise sources of strength N_i^2 drive the canonical transfer function(s), resulting in the same statistical and spectral properties as the actual device (black box model). This is also the objective of the gyro drift analysis.

B.2.1 Dynamic modeling

Exclusive of environmental sensitivities, dynamic modeling of an optical gyro involves only scale factor, bias, and misalignment. This model is determined using regression methods, with the gyro being forced with deterministic inputs.

Spinning wheel gyroscopes such as the two-degree-of-freedom gyro, or single-degree-of-freedom gyros that exhibit very high two-degree-of-freedom effects [B14], [B16], are far more interesting subjects for dynamic modeling. The latter are gyros that have significant finite spring constants on the cross axis, or large angular momentum relative to the spring constant. There is then a large interaction from the angular momentum on the response of the gyro. The result is a two-degree-of-freedom model, which is similar to the model equation for the dynamically tuned gyro. The dynamics have a fourth order characteristic response. The four eigenvalues are dependent on the angular momentum of the gyro. The resulting frequency-dependent transfer function may be analyzed by methods described below.

Many methods of estimating transfer functions are presented in Sinha and Kuszta [B33]. Of the classical approaches, for example, the frequency response method is one of the earlier methods used [B9]. Prior to development of the FFT, the input signal was stepped through discrete frequencies while measuring the relative amplitude and phase from input to output. With current methods, white noise is inserted at a rate proportional summing point. The open and closed loop transfer functions are computed using digital processing. This method allows for estimation in the presence of uncorrelated additive noise.

Time response methods are another classical means (using step and impulse response) to estimate the transfer function. One method, called deconvolution [B33], determines the impulse response from the input and output by using the convolution integral (discrete form) in terms of the sampled data. A matrix equation describes the output at each point of time as a function of the input. The solution to the equation is the impulse response of the black box unit under test.

Another approach to using the impulse (or step) response method models the discrete form of the transfer function (Z-transform) as the ratio of two power series [B33]. Two matrix equations are derived that express the coefficients in terms of the output impulse response. The denominator coefficients may be solved in terms of the impulse response data, and the numerator coefficients may be solved in terms of the denominator coefficients and the output data.

Several approaches model the output in terms of a difference equation corresponding to the discrete time transfer function [B33]. The output is expressed parametrically in terms of its past values (the autoregressive part) together with present and past values of the input (the moving average part). A matrix equation relates the parameter vector, which comprises the transfer coefficients, to a concatenated set of the input, output data (expressed in a matrix) and output vector comprising another set of the sequential output data. The problem has been variously formulated for noisy data using least-squares or maximum likelihood estimation methods. Recursive forms have been derived for on-line estimation.

Another technique is to introduce a white noise input and analyze the output relative to the input. This time-domain method is called the correlation method [B9], [B33]. The cross correlation between the input and the output is computed, from which the impulse response is deduced. This method is limited to stationary time series from linear time invariant systems. The main problem with this approach is that as the model becomes more complicated, it becomes more difficult to identify the cross correlation function. The contributors are particularly difficult to decompose into constituent parts when they cover a large dynamic range or overlap in frequency content. If the form of the model is unknown, identification is a difficult job. This is one of the problems with Box-Jenkins time domain method of time series analysis, and most of the above methods of dynamic modeling.

Frequency domain approaches (also referred to as spectral decomposition) [B12] are usually a better tool for model investigation. The Fourier transform of the correlation function is the PSD. Means of calculating the

PSD from the raw data using the FFT are more commonly used. Real-time processing with ensemble averaging has considerably improved the ability to analyze transfer functions.

With the frequency domain approach, the transfer function may be estimated from the cross-PSD of the output with the input, divided by the PSD of the input [B9]. This gives both the amplitude and phase of the transfer function.

B.2.2 Stochastic modeling

The idea of applying white noise and constructing the transfer function in this manner is important to stochastic modeling. The reason for that is, if the input is white noise, you can estimate the transfer function of a linear, minimum phase, time invariant system simply from the power spectrum of the output. Instead of getting the cross PSD between input and output, the transfer function can be estimated from the power spectrum of the output alone. The phase information is uniquely determined from the magnitude response.

Thus, for a linear time-invariant system, by having knowledge of the output only, and assuming white noise inputs, it is possible to characterize the unknown model. Many of the methods are very similar to some of the dynamic modeling methods except that the input is unobservable. The frequency domain approach of using the PSD to estimate transfer functions is straight forward. Even certain pathological cases, such as bias instability [B8], [B25], [B26], [B34], [B35], which looks like a 1/f process [B32], (flicker rate noise), and angle quantization noise (characteristically different from continuous white angle noise) [B6], [B31], [B35] can be discerned with careful analysis technique.

As in the case of dynamic modeling, several time domain methods have been devised for stochastic modeling. The correlation function approach [B5], [B6], [B9], [B33] is the dual of the PSD approach, being related as Fourier transform pairs. Similar to the corresponding dynamic modeling method, the equivalent impulse response may be deduced from the autocovariance sequence computed from the output data. One approach models the covariance function as sums of exponentials and damped sinusoids, using least squares estimation to obtain model parameters. This is analogous to expressing the frequency response function in terms of partial fraction expansion.

Another correlation method relates the autocovariance sequence to coefficients of a difference equation, expressed as an autoregressive moving average (ARMA) process. This method was expounded by Box and Jenkins [B14], [B20], [B33]. Correlation methods are very model sensitive and not well suited to dealing with odd power law processes, higher order processes or wide dynamic range. They work best with a priori knowledge based on a model of few terms.

Yet another class of time domain methods, several variance techniques have been devised. They are basically very similar, and primarily differ in that various signal processing, by way of weighting functions, window functions, etc., are incorporated into the analysis algorithms in order to achieve a particular desired result of improving the model characterizations. Many of these are discussed in Rutman [B25]. The two simplest are the Allan variance, and Modified Allan variance [B29], [B40], which, in addition to the PSD, are discussed in B.3.

The adaptive Kalman filter is another means of system identification [B20]. The noise covariance and dynamics may be estimated if the form of the model is known. This may be combined with a model adjustment or learning model approach for more flexibility.

B.2.3 Gyro random drift model

Noise contributors in typical gyro models [B11], [B20], [B24], [B26], [B27], [B34], [B35] include white angle noise, quantization noise [B6], [B20] white rate noise, correlated (Markov) random drift, bias instability (1/f or flicker rate), rate random walk, flicker angular acceleration (ramp instability), and random rate ramp. Correlated (Markov) drift rate has been recently reported in optical rotation sensors, but is more common in spinning wheel gyros. White angle noise has also been observed in dithered laser gyros at both the gyro and system level. Bias instability (flicker rate) and ramp instability (flicker angular acceleration, flicker acceleration) behave like evolutionary (non-stationary) processes.

Normally, the PSD of a random process is expected to exhibit even order log-log slopes of –2, 0, +2 and so on, indicating even powers of frequency (+2 slope corresponds to +6 dB per octave). However, the 1/f flicker process has a –1 slope PSD (–3 dB per octave). It occurs in certain types of distributed parameter type models; for example, a hypothetical resistive-capacitance (R-C) transmission line excited with white noise current will exhibit a 1/f noise voltage at the input [B32]. Because flicker noise is not readily expressed in terms of ordinary state equations, it is sometimes approximated by a Markov model or a multiple stage ARMA model. Rate random walk is a long term, very low-frequency phenomenon. Even lower in frequency is flicker angular acceleration, which can be thought of as instability in the slope of rate ramp, and is equivalent to the integral of 1/f noise.

Other model contributors include deterministic ramp (different from flicker angular acceleration), usually removed together with the bias prior to processing, and periodic signals that ought to be removed through filtering, better selection of oscillator frequencies, electromagnetic interference (EMI) reduction, etc.

B.3 Preferred means of analysis

Of the less restrictive methods of analysis, the PSD and Allan variance methods have more general application to investigation of stochastic models. Thus, they have been adopted as preferred means of analysis in the inertial systems community.

B.3.1 Power spectral density (PSD)

The PSD is the most commonly used representation of the spectral decomposition of a time series. It is a powerful tool for analyzing or characterizing data, and stochastic modeling. The PSD, or spectrum analysis, is also better suited to analyzing periodic or aperiodic signals than other methods.

To summarize the basic relationship for stationary processes, the two-sided PSD, $S(\omega)$ and covariance, $K(\tau)$ are Fourier transform pairs, related by:

$$S(\omega) = \int_{-\infty}^{\infty} e^{-j\omega\tau} K(\tau) d\tau$$

Unless specifically stated, the term PSD in Annex B refers to the two-sided PSD. Graphical representations frequently use the one-sided PSD, whose amplitude is twice the two-sided PSD. See Figure B.6.

$$K(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{j\omega\tau} S(\omega) d\omega$$

$$K_{xy}(\tau) = \langle x(t) y(t+\tau) \rangle$$

It can be shown [B6] that for nonstationary processes, the average covariance $K(\tau)$ and average power spectrum $S(\omega)$ are related in the same way.

The transfer function form of the stochastic model may be estimated directly from the PSD of the output data (on the assumption of an equivalent white noise driving function). Similar to curve-fitting a Bode plot, the transfer function may be estimated using the pole-zero form, partial fraction expansion, power series, ARMA model spectral estimation, etc.

B.3.1.1 Useful properties

For linear systems, the output PSD is the product of the input PSD and the magnitude squared of the system transfer function. If state space methods are used, the PSD matrices of the input and output are related to the system transfer function matrix by:

$$S_{yy}(\omega) = H(j\omega)S_{xx}(\omega)H^{*T}(j\omega)$$

where

H^{*T} is the complex conjugate transpose of H

Thus, for the special case of white noise input, the output PSD directly gives the system transfer function.

The Fourier transform representation of the PSD is directly related to the bilateral Laplace transform derived from the transfer function of the corresponding stochastic model. The corresponding Allan variance of a stochastic process may be uniquely derived from its PSD; however, there is no general inversion formula. The same is true of the relationship between a process probability density function and its PSD.

The white noise covariances of process and measurement noise pertaining to the (continuous) Kalman Filter theory are identical to the corresponding two-sided PSD's white noise strengths expressed in units squared per Hertz.

For a process to have finite power, its PSD must eventually terminate in a negative slope at high frequencies. This property must be produced to satisfy the Nyquist sampling criterion for sampled data. This is discussed further in B.4.2. Likewise, a PSD cannot continue to rise (without limit) toward zero frequency (over a finite time interval). In practice, this is limited by the finite length of the time series.

Certain processes, such as periodic, narrow band, or quantization noise are better described by their energy spectrum or an integrated PSD, since their PSD amplitudes are dependent on the resolution bandwidth, a function of sampling rate. This property is used to distinguish, for example, quantization noise from white angle noise. Both have a +2 slope rate PSD, but whereas the amplitude of the white angle noise PSD is independent of the sample rate (resolution bandwidth), the amplitude of the quantization noise PSD is directly proportional (approximately) to the sample period.

The time average PSD of a nonstationary process has the properties of a PSD of a stationary process [B6]. With present real-time PSD analysis, evolutionary spectra can be represented as either two-dimensional or time varying PSDs. For nonstationary processes, the covariance function is a function of two time variables (e.g., the age variable and the running time variable). In the frequency domain, a two dimensional PSD is defined as the double Fourier transform of the covariance function and is a function of two frequency variables.

For reference, the alternate representations are:

$$K_{xy}(t_1, t_2) = \overline{x(t_1)y(t_2)}$$

and

$$K_{xy}(t_1, t_2) = \langle x(t_1)y(t_2)\rangle$$

The two-sided, two dimensional PSD $\Gamma(\omega_1, \omega_2)$ and the general covariance function $K(t_1, t_2)$ are double Fourier transform pairs related by:

$$\Gamma(\omega_1, \omega_2) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} K(t_1, t_2) e^{-j(\omega_1 t_1 - \omega_2 t_2)} dt_1 dt_2$$

$$K(t_1, t_2) = \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Gamma(\omega_1, \omega_2) e^{+j(\omega_1 t_1 - \omega_2 t_2)} d\omega_1 d\omega_2$$

For further discussion on non-stationary processes, see Papoulis [B6].

For certain types of spectra, where wide dynamic range is required, such as when periodic content is present, application of a window function as part of the FFT processing can improve resolution. Windows such as the Hamming and Von Hann (Hanning) windows reduce the impact of Gibb's phenomenon resulting from truncation of a time series. Thus, for example, two adjacent spectral peaks of significantly different amplitudes may be separated at the expense of somewhat broadening them. These issues are discussed further in B.3.2 and in [B9], [B22], [B25]. PSD properties of the various contributors are given in Figure B.4 and Table B.1.

B.3.2 Allan variance

The two-sided (first difference) Allan variance was developed in the mid 1960s and adopted by the time and frequency standards community for the characterization of phase and frequency instability of precision oscillators. Because of the close analogies to inertial sensors, the method has been adapted to random drift characterization of a variety of devices. Annex C treats this subject in more detail than the discussion below.

The old method of specifying drift in terms of a single RMS number, even when associated with a correlation time, was inadequate for predicting system performance, leading to some very conservative means of specification. Later, frequency domain methods proved superior for evaluating performance, but difficult for non-system analysts to understand.

The Allan variance is a reasonable compromise. Simply put, it is a method of representing RMS random drift error as a function of averaging time. It is simple to compute, much better than having a single RMS drift number to apply to a system error analysis, relatively simple to interpret and understand. It is not well suited to rigorous analysis, but a reasonable second step in the modeling process (after the quick look, discussed in B.4.3). Its most useful application is in the specification and estimation of random drift coefficients in a previously formulated model equation.

The basic Allan variance relations are summarized as follows:

$$\theta(t) = \int^{t} \Omega(t')dt'$$

$$\bar{\Omega}_k(\tau) = \frac{\theta(t_k + \tau) - \theta(t_k)}{\tau}$$

Then the Allan variance[6] is defined by:

$$\sigma_{\Omega}^2(\tau) = \frac{1}{2}\overline{(\Omega_{k+1} - \Omega_k)^2} = \frac{1}{2}\langle(\bar{\Omega}_{k+1} - \bar{\Omega}_k)^2\rangle$$

and is related to the two-sided PSD, $S_{\Omega}(f)$ by:

[6]Frequently the term Allan variance is also used to refer to its square root, $\sigma(\tau)$.

$$\sigma_{\Omega}^{2}(\tau) = 4\int_{0}^{\infty} S_{\Omega}(f)\,\frac{\sin^{4}(\pi f\tau)}{(\pi f\tau)^{2}}\,df$$

There is no inversion formula.

One of the most notable deficiencies of the standard Allan variance is the non-unique characterization of white angle, flicker angle, and quantization noise at the high frequency end, and random rate ramp vs. flicker angular acceleration at the low-frequency end. These, however, may be sorted out by using the Modified Allan variance and/or prewhitening methods discussed in B.4.3. Other approaches include applying a prefilter to the time series (such as a triangular filter), or alternatively incorporating it into the Allan variance computation, or applying it as a window. The theory and use of windows is discussed by Hamming [B22]. This approach is equivalent to some of the other variance methods discussed by Rutman [B25].

If the standard Allan variance is viewed as an application of a variable rectangular window to the time series, then the Modified Allan variance may be viewed as the application of a variable triangular window to the time series. Maximum efficiency is obtained by using an algorithm that uses maximum overlap. Some of these issues are discussed in Stovall [B39], where a triangular prefilter with maximum overlap is suggested. The more obvious advantage of the higher order filtering is in dealing with these high pass processes (those with positive PSD slopes) by terminating the filtered process in a controlled low pass characteristic, insuring a finite variance.

Allan variance properties of the various contributors is given in Table B.1.

Table B.1—Properties of noise and drift processes

Stochastic model contributor				Asymptotic properties PSD $S(f)$		
Nomenclature	Equivalent white noise input: Generic	Equivalent white noise input: This Std	Other name	θ	Ω	$S_\Omega(f)$
White angle	$N_\theta{}^2$	Φ^2	Angle measurement noise	0	+2	$(2\pi f)^2\phi^2$
Angle quantization	—	Q^2	White angle energy spectrum	0	+2	$\frac{4Q^2}{\tau}\sin^2\pi f\tau$
Flicker angle	$N^2{}_{F\theta}$	—	Pink angle noise	–1	+1	$2\pi f N^2_{F\theta}$
Angle random walk, white rate noise	$N_\Omega{}^2$	N^2	Reg angle noise	–2	0	N^2
Rate quantization	—	—	Discrete white rate noise or white rate energy spectral density	–2	0	—
Bias instability	$N_{F\Omega}{}^2$	B^2	Pink rate noise	–3	–1	$\frac{B^2}{2\pi f}$
Markov rate	$N_{c\Omega}{}^2$	q^2	Correlated drift rate	–2, –4	0, –2	$\frac{(q_c\tau_c)^2}{1+(2\pi f\tau_c)^2}$
Rate random walk	$N^2_{\dot{\Omega}}$	K^2	Red rate noise	–4	–2	$\frac{K^2}{(2\pi f)^2}$
Ramp instability	$N^2_{F\dot{\Omega}}$	R^2	Pink angular acceleration noise	–5	–3	$\frac{R^2}{(2\pi f)^3}$
Random bias	$\Omega(0)$	$B_0{}^2$	Bias or fixed draft	See Note 2	See Note 2	$B_0^2\delta(f)$
Random ramp	$\dot{\Omega}(0)$	$R_0{}^2$	Rate ramp	See Note 2	See Note 2	—
Periodic rate	Ω_0	—	Harmonic	Discrete spectra	Discrete spectra	$\frac{1}{2}\Omega_0^2\delta(f-f_0)$

NOTES
1—Mod σ—Modified Allan variance
2—Remove by regression or by filtering

in frequency and tau domain

Asymptotic properties Allan variance σ(t)		
θ	Ω	$\sigma_{\Omega}^{2}(\tau)$
−1/2	−1, (−3/2) See Note 1	$\frac{3\Phi^2}{\tau^2} f_n$
0	−1	$\frac{3Q^2}{\tau^2}$
0	−1	$\frac{N_{F\theta}^2}{2\pi\tau^2}[3(2+\ln 2\pi f_n\tau)-\ln 2]$
+1/2	−1/2	$\frac{N^2}{\tau}$
+1	0	—
+1	0	$\frac{2B^2\ln 2}{\pi}$
+1 1/2, +1/2	+1/2, −1/2	$\frac{(q_cT_c)^2}{\tau}\left[1-\frac{T_c}{2\tau}\left(3-4e^{-\frac{\tau}{T_c}}+e^{-\frac{2\tau}{T_c}}\right)\right]$
+1 1/2	+1/2	$\frac{K^2\tau}{3}$
+2	+1	—
See Note 2	See Note 2	—
See Note 2	See Note 2	$\frac{R_0^2\tau^2}{2}$
See Note 2	See Note 2	$\Omega_0^2\left[\frac{\sin^2\pi f_0\tau}{\pi f_0\tau}\right]$

NOTES
1—Mod σ—Modified Allan variance
2—Remove by regression or by filtering

B.4 Test, data processing, and analysis considerations

This clause discusses methods of test, data acquisition, and data processing. Several suggestions are made to improve the efficiency of these operations and the subsequent analysis.

B.4.1 Approach

General test conditions and equipment are discussed in Clause 11. Test procedures are discussed in 12.11. It is important to control the influence of external environments on the test. External sources of error should be removed or compensated for in an appropriate pre-filter. Differential techniques (such as back-to-back sensor test) are also effective. Error detection/correction is also an important step of the data acquisition process.

Sample rates, anti-aliasing filtering, and record lengths are to be chosen with regard to various system considerations [B9]. The longer term effects of random drift on performance with regard to the mission profile should be separated out using signal processing techniques prior to data acquisition, and the higher frequency data should be analyzed separately.

B.4.2 Data acquisition

In terms of economy, efficiency is achieved by combining data reduction methods into the data acquisition process [B36] and [B37], thus transforming data into a more usable form. Generally, the sample rate is selected to be at least twice the sample bandwidth (limited by filtering to the highest frequency of interest), however, Papoulis [B6] shows that six samples per bandwidth cycle are required to characterize a signal from its past values only. The record length should be at least several times the required performance interval, as dictated by the mission profile. Coverage of too large a temporal dynamic range, however, is uneconomical, impractical, and unnecessary; collecting 0.1 ms data for 1000 h yields a large, unwieldy number of data points.

The recommended approach is to limit the time/frequency domain dynamic range (of record length to sample period) to about 3 orders of magnitude. This is done by dividing the total range into overlapping intervals of geometrically increasing lengths. Thus, the high frequency data is acquired for a short period of time. Lower frequency data is filtered (integrated) and acquired for a longer period (e.g., 0.1ms data collected for 0.1 s, 0.01 s data for 10 s, 1 s data for 1000 s and 100 s data for 10^5 s). Signal processing is used to remove the undesired effects outside the bandwidth of interest. It is noted that frequency domain (PSD) analysis is particularly appropriate to investigating high frequency phenomena as well as long term random drift, whereas time domain analysis should be confined to the low-frequency phenomena where it is often simpler to use.

The appropriate sampling rates/record lengths should be chosen to overlap about one decade of frequency (time), consideration being given to the particular characterization of the process. Prior characterization of the process is necessary for proper determination of data acquisition parameters. One approach is to choose geometric means of the record length and sample period to correspond to the geometric mean of the corresponding frequency or time domain range of the dominant characteristic of interest. For example, if bias instability (flicker) is to be observed in the interval 10^4 s to 10^6 s (1.0–100 mHz) the geometric mean is 10^5 s (10 mHz); the corresponding sample period and record length would be $\sim 10^3\sqrt{10}$ s and $\sim 10^6\sqrt{10}$ s respectively. However, if the mission profile provided for a fix (or calibration) at 10^5 s a record length of $10^5\sqrt{10}$ s might be satisfactory, thus requiring only two decades of time (or frequency). Another aspect of this idea relates to prewhitening, which is usually done as part of a post-processing operation after the data is usually collected but prior to detailed analysis.

Quantization noise, as discussed in Britting, et al., [B31] and equivalently random binary transmission, as discussed in Papoulis [B6], can limit the ability to estimate model coefficients efficiently. It can also have a deleterious effect on short-term performance. Since quantization is often dictated by sensor design considerations, such as laser gyro scale factor, or otherwise constrained to unsatisfactory levels, its effect must be handled externally by signal processing. This can be done as part of the data acquisition/reduction process, or in post processing. It usually entails processing through a second or higher order digital filter, with calculations scaled to higher precision.

B.4.3 Post-Processing

Post-processing of the acquired data includes the quick look data editing, trend removal, digital filtering of other deterministic signal (i.e., periodic) and other pre-whitening signal processing.

The quick-look is a cursory visualization of each record of the data in the form of graphical time series. Bad data is edited out and replaced by interpolated or simulated data. Trends are observed for removal and separate analysis by least squares estimation techniques. Possible periodic content is observed for removal by other filtering techniques. Such removal is a first step in the prewhitening processing.

Best estimates of the model are achieved when the estimation error (residuals, innovations) is a white noise process. Some analysis techniques, such as an adaptive Kalman filter can be designed to do this. Another approach requires a priori knowledge of the stochastic model [B36] and [B37].

In this approach, an inverse filter is mechanized in the signal processing to pre-whiten the data (example Figure B.3). This may simply entail applying either an integration operation (as with angle white noise) or a differencing operation (as with rate random walk). As a practical matter, additional high frequency poles must be added to band limit the resulting dynamic range required for subsequent analysis.

$$S_\Omega(\omega) = N_\Omega^2 + \frac{N_{\dot{\Omega}}^2}{\omega^2}$$

$$H(s) = \frac{\frac{1}{\hat{N}_\Omega}}{1 + \frac{\hat{N}_{\dot{\Omega}}}{s}\frac{1}{\hat{N}_\Omega}} = \frac{1}{\hat{N}_\Omega + \frac{\hat{N}_{\dot{\Omega}}}{s}}$$

$$S_R(\omega) = H_{R\Omega}(j\omega)S_\Omega(\omega)H_{R\Omega}^{*T}(j\omega) = \left|H_{R\Omega}(j\omega)\right|^2 S_\Omega(\omega)$$

$$= \left[\frac{1}{\hat{N}_\Omega^2 + \frac{\hat{N}_{\dot{\Omega}}^2}{\omega^2}}\right]\left[N_\Omega^2 + \frac{N_{\dot{\Omega}}^2}{\omega^2}\right]$$

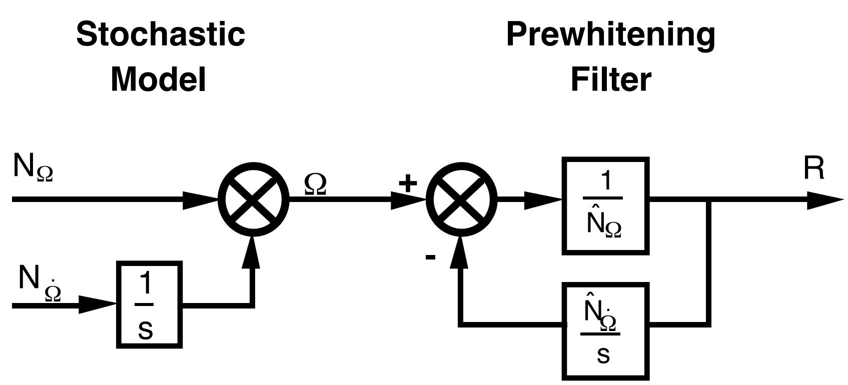


Figure B.3—Example of prewhitening (simplified)

B.4.4 Time series analysis considerations

Subsequent to data acquisition and post-processing, the resulting processed data records are prepared for time series analysis. Whichever method is used, time or frequency domain analysis, there are some suggested guidelines to follow.

Each data record so constructed contains piece-wise information to be extracted and re-assembled in a composite analysis, which will then display the full dynamic range of the desired result. In re-assembling the computed information in the appropriate chart, it may be necessary to undo some of the previous operation to put the output data into the proper format and proper units. If, for example, pre-whitening processing was applied, the corresponding post-darkening operation will be necessary to reconstruct the characteristic signature of the analyzed data.

Prior to this operation however, the model coefficients are first estimated. A first approximation (second approximation if prewhitening has been performed) can be estimated by sketching in the asymptotes to the charted data analysis, and computing approximate model coefficients. A prewhitening filter may be derived and the error coefficients from the residuals may be reestimated. Alternatively, a more rigorous weighted least squares procedure, which weights by the inverse error covariance, may be used. Error bounds on the coefficient should be computed to establish the goodness-of-fit.

With the coefficients thus determined, and the composite data analysis assembled on the appropriate chart, the resulting characteristic curve fit can be superimposed on the charted data, together with the error bounds to give a detailed representation of the stochastic model characterization. The coefficients are also used to construct a block diagram (Figure B.4) and generate the detailed state equations describing the stochastic model.

B.4.5 Example

Figures B.5 and B.6 illustrate the piecewise asymptotic representation of the Allan variance and corresponding PSD of a hypothetical gyro with parameters:

$N = 0.001°/\sqrt{\text{h}}$	angle random walk
$B = 0.001°/\text{h}$	bias instability
$K = 0.0001°/\text{h}^{3/2}$	rate random walk
$Q = 0.577''$	quantization noise (result of 2"/p gyro scale factor)

B.5 Conclusion

Inertial systems design and performance prediction depends on accurate knowledge of sensor level behavior.

This annex has attempted to provide a brief introduction and roadmap to the study of a very extensive subject of dynamic and stochastic modeling as it applies to this purpose.

Through better understanding of the modeling process and standardization of test and reporting of data, the inertial system and gyro designer can more effectively meet their goals.

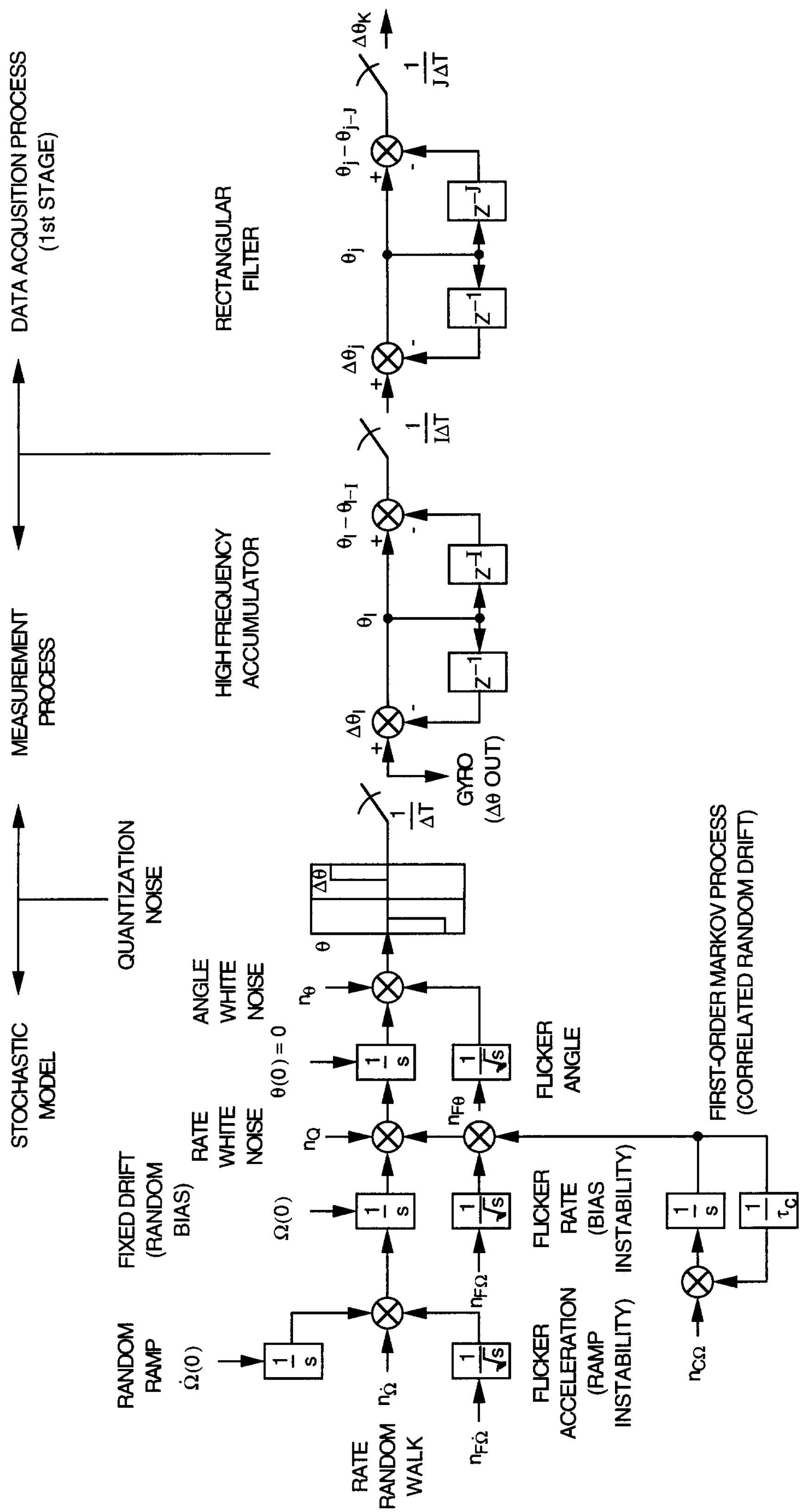


Figure B.4—Block diagram of stochastic model through data acquisition

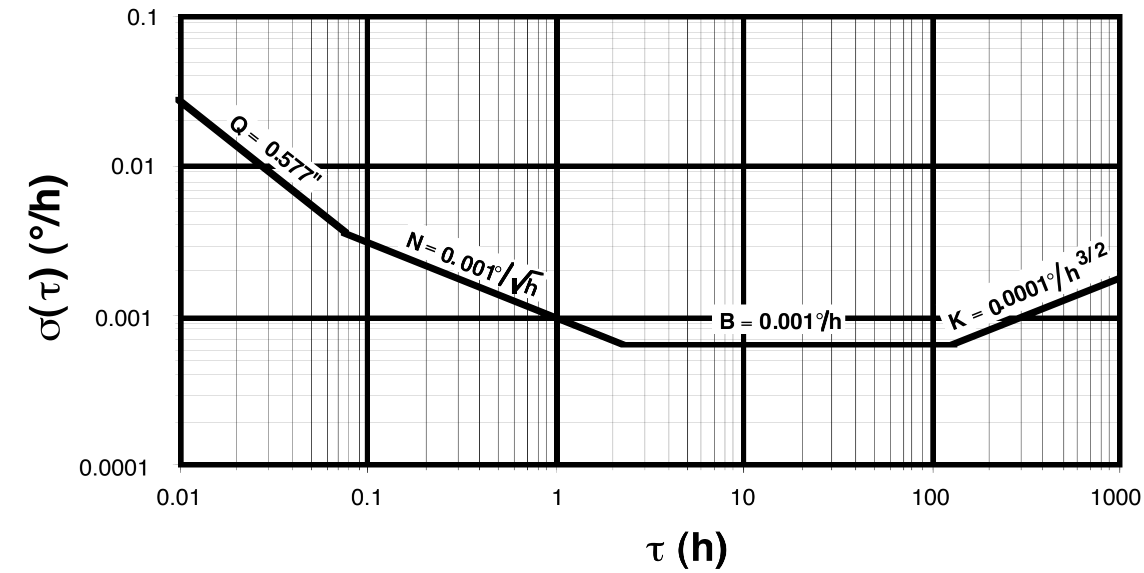


Figure B.5—Placewise representation of hypothetical gryo in Allan variance form

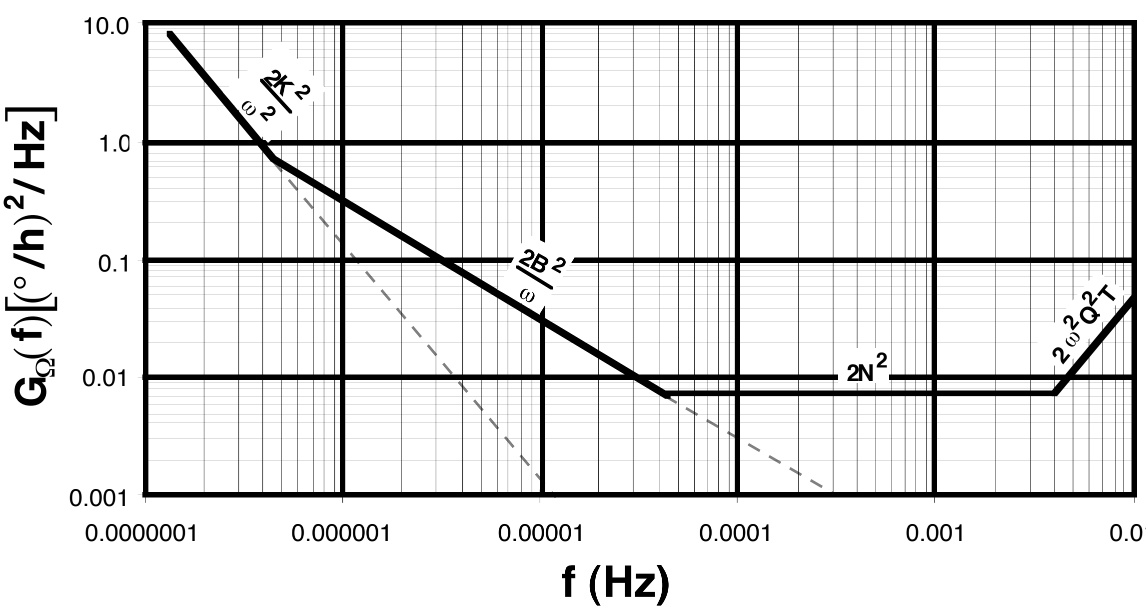


Figure B.6—Piecewise representation of hypothetical gyro in single-sided PSD form

B.6 Chronological bibliography

[B1] Von Neuman, J., and Morgenstern, O., *Theory of Games and Economic Behavior,* New York: John Wiley and Sons, 1967, Princeton University Press, 1944.

[B2] Wiener, N., *Cybernetics: or Control and Communication in the Animal and the Machine*. Cambridge, MA: MIT Press, 1948, Second Edition 1961.

[B3] Kalman, R. E., "A New Approach to Linear Filtering and Prediction Problems," ASME Transactions, vol. 182D, Mar. 1960, pp. 35–45.

[B4] Hannan, E. J., *Time Series Analysis*. Great Britain: Science Paperbacks and Methuen and Co. LTD, 1960, Reprinted 1967.

[B5] Parzen, E., *Stochastic Processes*. San Francisco, CA: Holden-Day, 1962.

[B6] Papoulis, A., *Probability, Random Variables and Stochastic Processes*. New York: McGraw-Hill, 1965.

[B7] Machol, R. E., *Systems Engineering Handbook*. New York: McGraw-Hill, 1965.

[B8] Allan, D. W., "Statistics of Atomic Frequency Standards," *Proceedings of the IEEE,* vol. 54, no. 2, pp. 221–230, Feb. 1966.

[B9] Bendat, J. S., and Piersol, A. G., *Measurement and Analysis of Random Data*. New York: John Wiley and Sons, 1966.

[B10] Gelb, A., and Sutherland, A. A. Jr., "Design of Strapdown Gyroscopes for a Dynamic Environment," TASC report TR101-1, 1967.

[B11] Sutherland, A. A., and Gelb, A., "Applications of the Kalman Filter to Aided Inertial Systems," NWC-TP-4652, China Lake, CA, Aug. 1968.

[B12] Van Trees, H. L., *.Detection, Estimation, and Modulation Theory, Part I*, New York: John Wiley and Sons, 1968.

[B13] Wrigley, et al., *Gyroscopic Theory, Design, and Instrumentation*. Cambridge MA: M.I.T. Press, 1969

[B14] Box, G. E. P., and Jenkins, G. M., *Time Series Analysis: Forecasting and Control*. San Francisco: : Holden-Day, 1970, Revised 1976.

[B15] Britting, K., *Inertial Navigation Systems Analysis*. New York: Wiley-Insterscience, 1971.

[B16] Barnes, J. A., et al., "Characterization of Frequency Stability," *IEEE Transactions on Instrumentation and Measurement,* vol. IM-20, pp. 105–120, May 1971.

[B17] Coffman, V. "On-Line Estimation of Parameters Using Experimentally Developed Gyro Models, and Other Applications," Ph.D. diss., Stanford University, SUDAAR no. 467, Dec. 1973.

[B18] Lesage, P. and Audoin, C., "Characterization of Frequency Stability: Uncertainty due to the Finite Number of Measurements," *IEEE Transactions on Instrumentation and Measurement,* vol. IM-22, no. 2 pp. 157–161, June 1973.

[B19] Brogan W., *Modern Control Theory.* New York: Quantum Publishers, 1974.

[B20] Gelb, A., TASC Staff, Applied Optimal Estimation, Cambridge MA: M.I.T. Press, 1974.

[B21] Giacoletto, L. J., *Electronics Designers' Handbook,* Second Edition. New York: McGraw-Hill, pp.16–20, 1977.

[B22] Hamming, R. W., *Digital Filters*. Englewood Cliffs, NJ: Prentice Hall, 1977.

[B23] Lindsey, W. C., and Chie, C. M., "Identification of Power-Law Type Oscillator Phase Noise Spectra from Measurements," *IEEE Transactions on Instrumentation and Measurement*, vol. IM-27, no. 1, pp. 46–53, Mar. 1978.

[B24] Sargent, D. and Wyman, B.O., "Least Squares and How They Give Us Fits," Second Printing, TRW Report 32143-61010TU-00, 9 June 1978.

[B25] Rutman, J., "Characterization of Phase and Frequency Instabilities in Precision Frequency Sources: Fifteen Years of Progress," *Proceedings of the IEEE,* vol. 66, no. 9, Sept. 1978.

[B26] Kochakian, C. R. "Time-Domain Uncertainty Charts (Green Charts): A Tool for Validating the Design of IMU/Instrument Interfaces," *Proceedings of the AIAA Guidance and Control Conference*, Aug. 11–13, 1980.

[B27] Sargent, D. and Wyman, B. O., "Extraction of Stability Statistic from Integrated Rate Data," *Proceedings of the AIAA Guidance and Control Conference,* Aug. 11–13, 1980.

[B28] Cadzon, J. A., "High Performance Spectral Estimation—A New ARMA Method," *IEEE Transactions on Acoustics, Speech, and Signal Processing,* vol. ASSP-28, ,o. 5, pp. 524–528, Oct. 1980.

[B29] Allan, D. W., and Barnes, J. A., "A Modified 'Allan Variance' with Increased Oscillator Characterization Ability," *Proceedings of the 35th Annual Frequency Control Symposium,* pp. 470–475, May 1981.

[B30] Howe, D. A., et al., "Properties of Signal Sources and Measurement Methods," *Proceedings of the 35th Annual Frequency Control Symposium,* pp. 441–447, May 1981.

[B31] Britting, K., et al., "Statistical Description of Quantization Error", Northrop, PPD, unpublished paper, 1982.

[B32] Keshner, M. S., "1/f Noise," *Proceedings of the IEEE,* vol.70, no. 3, pp. 212–218, Mar. 1982.

[B33] Sinha, N. K. and Kuszta, B., *Modeling and Identification of Dynamic Systems,* New York: Van Nostrand Reinhold, 1983.

[B34] Tehrani, M. M., "Ring Laser Gyro Data Analysis with Cluster Sampling Technique," *Proceedings of SPIE,* vol. 412, 1983.

[B35] King, A. D., "Characterization of Gyro In-Run Drift," *Symposium Gyro Technology 1984,* pp. 10.0–10.56, Oct. 1984.

[B36] Mark, J. and Brown, A., "Laser Gyroscope Random Walk Determination Using a Fast Filtering Technique," *Symposium Gyro Technology 1984,* pp. 9.0–9.21, Oct. 1984.

[B37] Vallot, L., et al., "Short Acceptance Test Procedures for Ring Laser Gyros," *12th Biennial Guidance Test Symposium,* pp. 1–12, 22–24, Oct. 1985.

[B38] Walls, F. L., and Allan, D. W., "Measurements of Frequency Stability," *Proceedings of IEEE,* vol. 74, no. 1, Jan. 1986.

[B39] Stovall, S. H., “Analysis of Ring Laser Gyro Noise Measurement Techniques,” China Lake CA: NWC Technical Report, 1987.

[B40] Allan D., et al., “Standard Terminology for Fundamental Frequency and Time Metrology,” Proposed IEEE Standard Para-P-1139.

[B41] Erickson, G. W., “An overview of Dynamic and Stochastic Modeling of Gyros,” *Proceedings of the 1993 National Technical Meeting of the ION*, Jan. 1993.

Annex C[7]

(informative)

An overview of the Allan variance method of IFOG noise analysis

C.1 Allan variance background

Allan variance is a time domain analysis technique originally developed to study the frequency stability of oscillators [C1].[8] It can be used to determine the character of the underlying random processes that give rise to the data noise. As such, it helps identify the source of a given noise term in the data. The source may be inherent in the instrument, but in the absence of a plausible mechanism within the instrument its origin should be sought in the test set up. The Allan variance adopted in this standard may be used as a stand-alone method of data analysis or to complement any of the frequency domain analysis techniques. It should be mentioned that the technique can be applied to the noise study of any instrument. Its value, however, depends upon the degree of understanding of the physics of the instrument. Following is an overview of the Allan variance and its adaptation to the noise properties of IFOGs, similar to that described in [C6] for ring laser gyros.

In the Allan variance method of data analysis, the uncertainty in the data is assumed to be generated by noise sources of specific character. The magnitude of each noise source covariance is then estimated from the data. The definition of the Allan variance and a discussion of its use in frequency and time metrology is presented in [C1] and [C7].

In this annex, Allan's definition and results are related to five basic gyro noise terms and are expressed in a notation appropriate for gyro data reduction. The five basic noise terms are angle random walk, rate random walk, bias instability, quantization noise, and rate ramp.

Consider N samples of gyro data[9] with a sample time of τ_o. Form data clusters of lengths τ_o, $2\tau_o$, ..., $k\tau_o$ ($k<N/2$) and obtain averages of the sum of the data points contained in each cluster over the length of that cluster. The Allan variance is defined as a function of cluster time.

To be specific, the Allan variance can be defined either in terms of the output rate, $\Omega(t)$, or the output angle

$$\theta(t) = \int^{t} \Omega(t')dt'$$

The lower integration limit is not specified as only angle differences are employed in the definitions. Angle measurements are made at discrete times given by $t = k\tau_o$, $k = 1, 2, 3, ..., N$. Accordingly, the notation is simplified by writing $\Theta_k = \Theta(k\tau_o)$.

The average rate between times t_k and $t_k + \tau$ is given by:

$$\bar{\Omega}_k(\tau) = \frac{\theta_{k+m} - \theta_k}{\tau}$$

where

$\tau = m\tau_o$

[7]This annex is adapted from Annex C in IEEE Std 647-1995, IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Laser Gyros.

[8]The numbers in brackets preceded by the letter C correspond to those of the bibliography in C.4.

[9]Sometimes referred to as time series or data streams.

The Allan variance[10] is defined as:

$$\sigma^2(\tau) = \frac{1}{2}\langle(\overline{\Omega}_{k+m} - \overline{\Omega}_k)^2\rangle$$

$$= \frac{1}{2\tau^2}\langle(\theta_{k+2m} - 2\theta_{k+m} + \theta_k)^2\rangle$$

where

$\langle\ \rangle$ is the ensemble average

The Allan variance is estimated as follows:

$$\sigma^2(\tau) = \frac{1}{2\tau^2(N-2m)}\sum_{k=1}^{N-2m}(\theta_{k+2m} - 2\theta_{k+m} + \theta_k)^2$$

The Allan variance obtained by performing the prescribed operations, is related to the PSD of the noise terms in the original data set. The relationship between Allan variance and the two-sided PSD[11], $S_\Omega(f)$ is given by:

$$\sigma^2(\tau) = 4\int_0^\infty S_\Omega(f)\frac{\sin^4(\pi f\tau)}{(\pi f\tau)^2}df \tag{C.1}$$

Equation (C.1) is the key result that will be used to calculate the Allan variance from the rate noise PSD. An interpretation is that the Allan variance is proportional to the total noise power of the gyro rate output when passed through a filter with the transfer function of the form $\sin^4(x)/(x)^2$. This particular transfer function is the result of the method used to create and operate on the clusters.

It is seen from Equation (C.1) and the above interpretation that the filter bandpass depends on τ. This suggests that different types of random processes can be examined by adjusting the filter bandpass, namely by varying τ. Thus, the Allan variance provides a means of identifying and quantifying various noise terms that exist in the data. It is normally plotted as the square root of the Allan variance versus τ, $[\sigma(\tau)]$, on a log-log plot.

Subclauses C.1.1 through C.1.7 show the application of Equation (C.1) to a number of noise terms that are either known to exist in the IFOG or otherwise influence its data. Detailed derivations are given in [C6]. The physical origin of each noise source term will be discussed.

[10] Frequently the term Allan variance is also used to refer to its square root, $\sigma(\tau)$.

[11] Unless specifically stated, the term PSD is Annex C refers to the two-sided PSD. Note that $S_\Omega(f)$ is the PSD of stationary random processes. For nonstationary processes, such as flicker noise, the time average PSD should be used.

C.1.1 Angle random walk

The main source for this error is spontaneous emission of photons. This component of the IFOG angle random walk is caused by the spontaneously emitted photons that are always present in the source output. The angle random walk due to spontaneously emitted photons is called the quantum limit [C4].

Other high frequency noise terms that have correlation time much shorter than the sample time, can also contribute to the gyro angle random walk. However, most of these sources can be eliminated by design. These noise terms are all characterized by a white noise spectrum on the gyro rate output.

The associated rate noise PSD is represented by:

$$S_{\Omega}(f) = N^2 \tag{C.2}$$

where

N is the angle random walk coefficient[12]

Substitution of Equation (C.2) in Equation (C.1) and performing the integration yields:

$$\sigma^2(\tau) = \frac{N^2}{\tau} \tag{C.3}$$

As shown in Figure C.1, Equation (C.3) indicates that a log-log plot of $\sigma(\tau)$ versus τ has a slope of –1/2. Furthermore, the numerical value of N can be obtained directly by reading the slope line at $\tau = 1$.

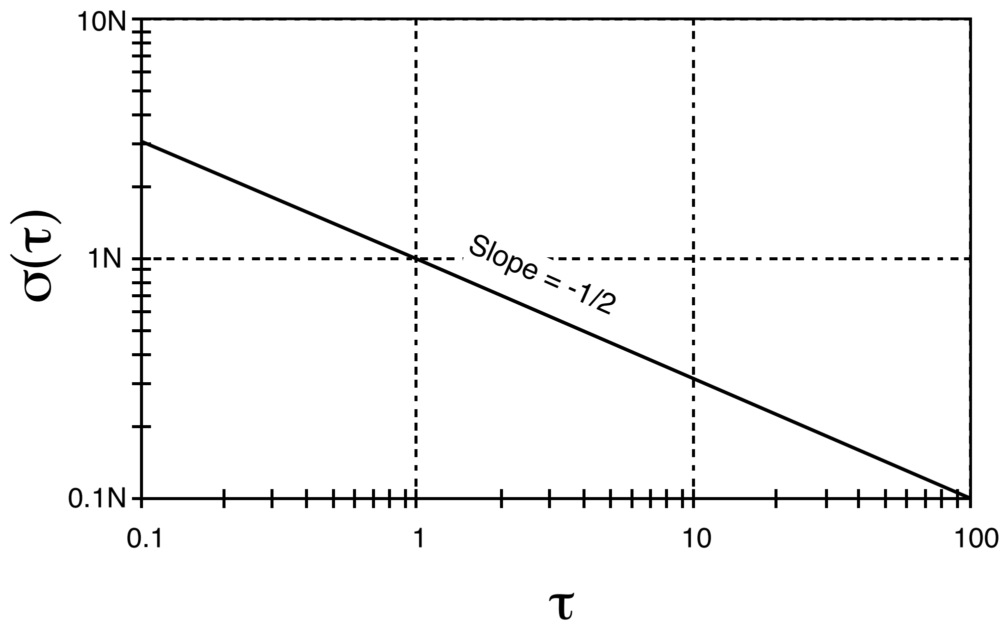


Figure C.1—$\sigma(\tau)$ Plot for angle random walk

[12]The zero slop portion of the rate PSD in $(°/\mathrm{h})^2/\mathrm{Hz}$ represents angle random walk. The relationship between angle random walk coefficient N and the PSD is

$$N(°/\sqrt{\mathrm{h}}) = \frac{1}{60}\sqrt{\mathrm{PSD}\left[\left(\frac{°}{\mathrm{h}}\right)^2/\mathrm{Hz}\right]}$$

C.1.2 Bias instability

The origin of this noise is the electronics, or other components susceptible to random flickering [C5]. Because of its low-frequency nature it shows up as the bias fluctuations in the data. The rate PSD associated with this noise is:

$$S_{\Omega}(f) = \begin{cases} \left(\frac{B^2}{2\pi}\right)\frac{1}{f} & f \le f_0 \\ 0 & f > f_0 \end{cases} \tag{C.4}$$

where

- B is the bias instability coefficient
- f_0 is the cutoff frequency

Substitution of Equation (C.4) in Equation (C.1) and performing the integration yields:

$$\sigma^2(\tau) = \frac{2B^2}{\pi}\left[\ln 2 - \frac{\sin^3 x}{2x^2}(\sin x + 4x\cos x) + Ci(2x) - Ci(4x)\right] \tag{C.5}$$

where

- x is $\pi f_0 \tau$
- Ci is the cosine-integral function [C2]

Figure C.2 represents a log-log plot of Equation (C.5) that shows that the Allan variance for bias instability reaches a plateau for τ much longer than the inverse cut off frequency. Thus, the flat region of the plot can be examined to estimate the limit of the bias instability as well as the cutoff frequency of the underlying flicker noise.

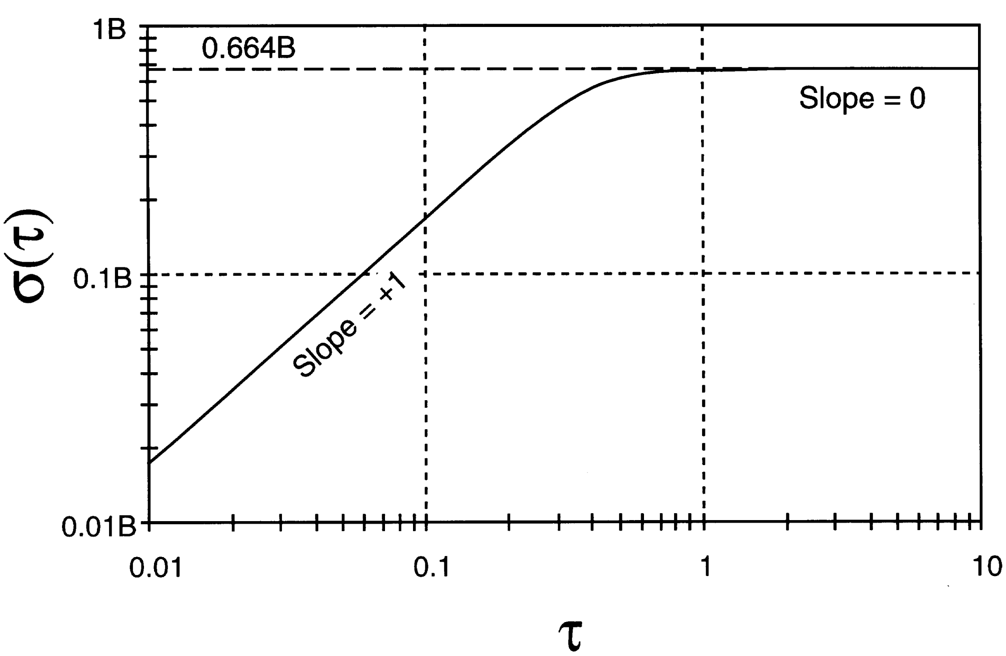


Figure C.2—$\sigma(\tau)$ Plot for bias instability (for $f_0 = 1$)

C.1.3 Rate random walk

This is a random process of uncertain origin, possibly a limiting case of an exponentially correlated noise with a very long correlation time, as discussed in Clause 3.

The rate PSD associated with this noise is:

$$S_\Omega(f) = \left(\frac{K}{2\pi}\right)^2 \frac{1}{f^2} \tag{C.6}$$

where

K is the rate random walk coefficient

Substitution of Equation (C.6) in Equation (C.1) and performing the integration yields:

$$\sigma^2(\tau) = \frac{K^2\tau}{3} \tag{C.7}$$

This indicates that rate random walk is represented by a slope of +1/2 on a log-log plot of $\sigma(\tau)$ versus τ, as shown in Figure C.3. The magnitude of this noise can be read off the slope line at $\tau = 3$.

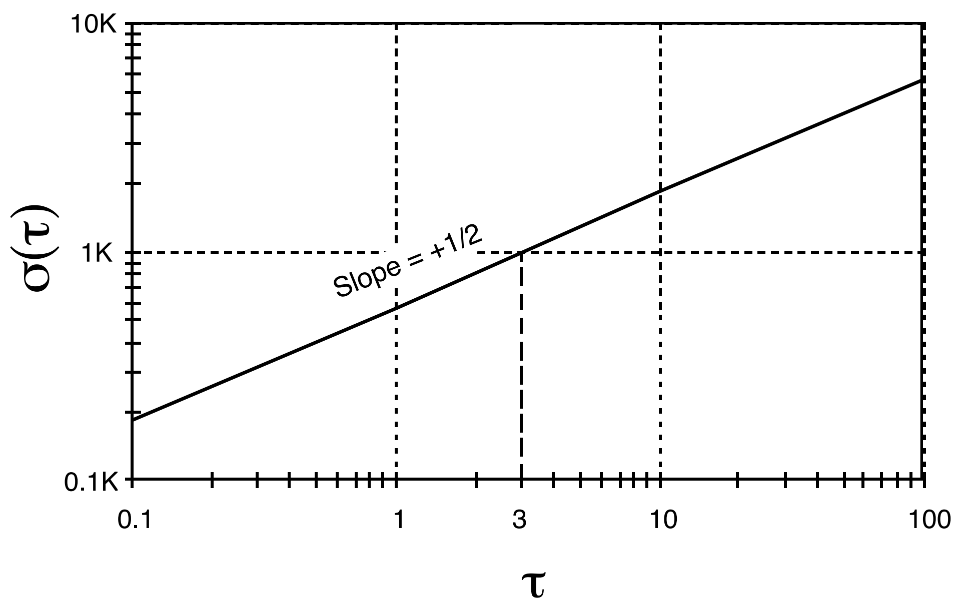


Figure C.3—$\sigma(\tau)$ Plot for rate random walk

C.1.4 Rate ramp

For long, but finite time intervals this is more of a deterministic error rather than a random noise. Its presence in the data may indicate a very slow monotonic change of the IFOG source intensity persisting over a long period of time. It could also be due to a very small acceleration of the platform in the same direction and persisting over a long period of time. It appears as a genuine input to the IFOG given by:

$$\Omega = Rt \tag{C.8}$$

where

R is the rate ramp coefficient

By forming and operating on the clusters of data containing an input given by Equation (C.8), we obtain:

$$\sigma^2(\tau) = \frac{R^2\tau^2}{2} \tag{C.9}$$

This indicates that the rate ramp noise has a slope of +1 in the log-log plot of $\sigma(\tau)$ versus τ, as shown in Figure C.4. The magnitude of rate ramp R can be obtained from the slope line at $\tau = \sqrt{2}$.

The rate PSD associated with this noise is:

$$S_{\Omega}(f) = \frac{R^2}{(2\pi f)^3} \tag{C.10}$$

The user should be aware that there may be a flicker acceleration noise with $1/f^3$ PSD that leads to the same Allan variance τ dependence. See Annex B for a discussion.

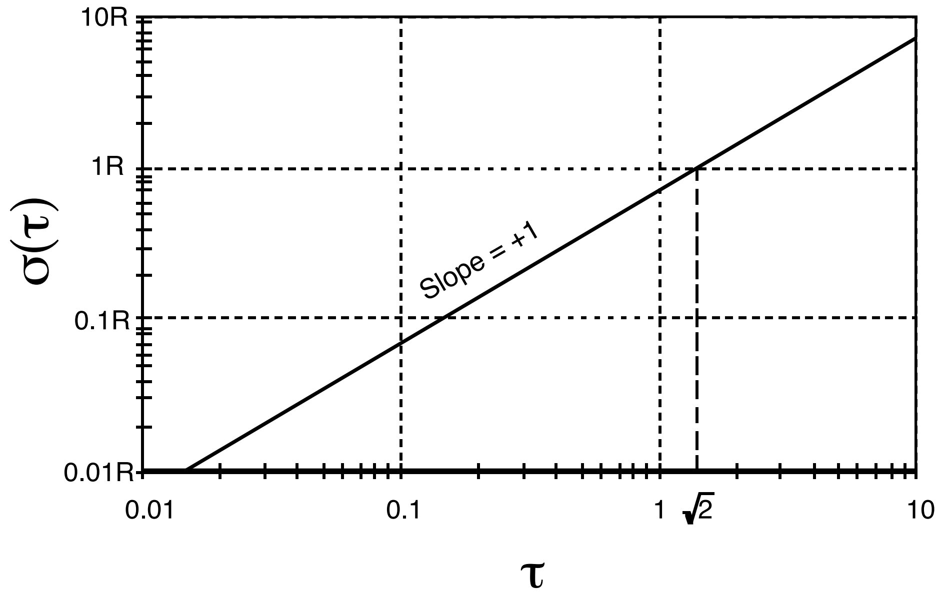


Figure C.4—$\sigma(\tau)$ plot for rate ramp

C.1.5 Quantization noise

This noise is strictly due to the digital nature of the IFOG output. The readout electronics registers a count only when the gyro phase changes by a predetermined amount, e.g., $2\pi/2^n$, where $n = 0, 1, 2, ...$

The angle PSD for such a process, given in [C8] is:

$$S_{\theta}(f) = \begin{cases} \tau_0 Q^2 \left(\dfrac{\sin^2(\pi f \tau_0)}{(\pi f \tau_0)^2}\right) \\ \approx \tau_0 Q^2 & f < \dfrac{1}{2\tau_0} \end{cases} \tag{C.11}$$

where

Q is the quantization noise coefficient

The theoretical limit for Q is equal to $S/\sqrt{12}$ where S is the gyro scale factor, for tests with fixed and uniform sampling times. The rate PSD is related to the angle PSD through the equation:

$$S_\Omega(2\pi f) = (2\pi f)^2 S_\theta(2\pi f) \tag{C.12}$$

and is

$$S_\Omega(f) = \begin{cases} \dfrac{4Q^2}{\tau_0}\sin^2(\pi f \tau_0) \\ \approx (2\pi f)^2 \tau_0 Q^2 \qquad f < \dfrac{1}{2\tau_0} \end{cases} \tag{C.13}$$

Substitution of Equation (C.13) in Equation (C.1) and performing the integration yields:

$$\sigma^2(\tau) = \frac{3Q^2}{\tau^2} \tag{C.14}$$

This indicates that the quantization noise is represented by a slope of –1 in a log-log plot of $\sigma(\tau)$ versus τ, as shown in Figure C.5. The magnitude of this noise can be read off the slope line at $\tau = \sqrt{3}$.

The user should be aware that there are other noise terms with different spectral characteristics, such as flicker angle noise and white angle noise, that lead to the same Allan variance τ dependence. See Annex B for a discussion of these noise terms.

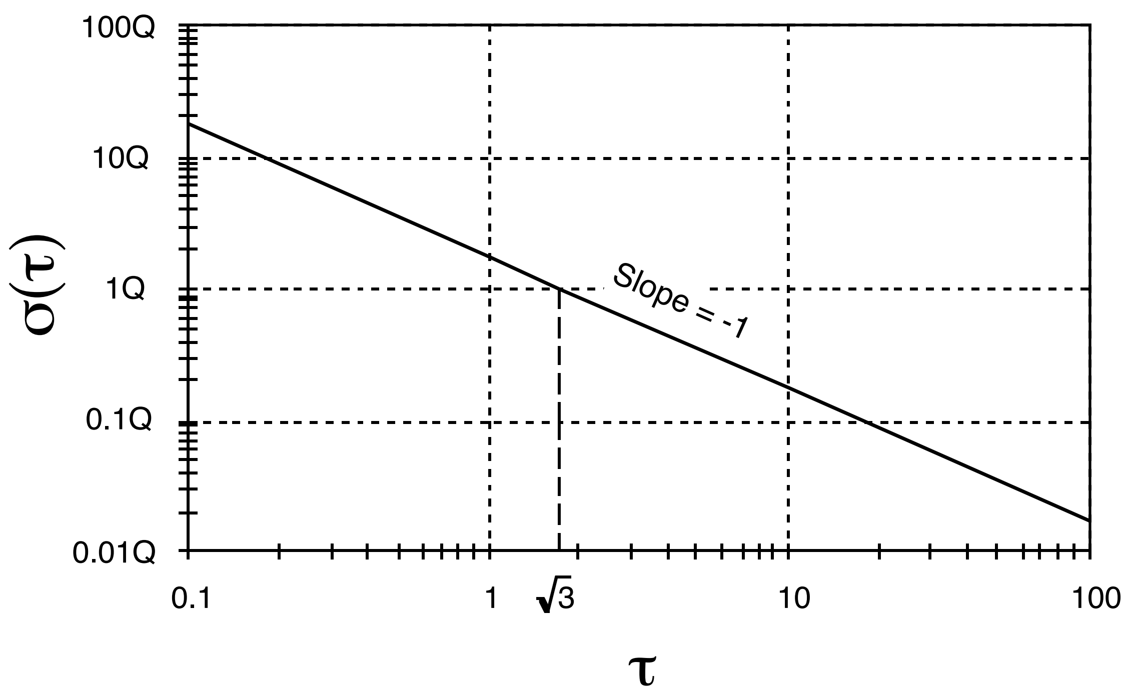


Figure C.5—$\sigma(\tau)$ Plot for quantization noise

C.1.6 Other noise terms

C.1.6.1 Exponentially correlated (Markov) noise

This noise is characterized by an exponential decaying function with a finite correlation time.

The rate PSD for such a process:

$$S_{\Omega}(f) = \frac{(q_c T_c)^2}{1 + (2\pi f T_c)^2} \tag{C.15}$$

where

q_c is the noise amplitude
T_c is the correlation time

Substitution of Equation (C.15) in Equation (C.1) and performing the integration yields:

$$\sigma^2(\tau) = \frac{(q_c T_c)^2}{\tau}\left[1 - \frac{T_c}{2\tau}\left(3 - 4e^{-\frac{\tau}{T_c}} + e^{-\frac{2\tau}{T_c}}\right)\right] \tag{C.16}$$

Figure C.6 shows a log-log plot of Equation (C.16). It is instructive to examine various limits of this equation. For τ much longer than the correlation time, it is found that:

$$\sigma^2(\tau) \Rightarrow \frac{(q_c T_c)^2}{\tau} \qquad \tau \gg T_c \tag{C.17}$$

which is the Allan variance for angle random walk where $N = q_c T_c$ is the angle random walk coefficient. For τ much smaller than the correlation time, Equation (C.16) reduces to:

$$\sigma^2(\tau) \Rightarrow \frac{q_c^2}{3}\tau \qquad \tau \ll T_c \tag{C.18}$$

which is the Allan variance for rate random walk.

C.1.6.2 Sinusoidal noise

The PSD of this noise is characterized by one or more distinct frequencies. A low-frequency source could be the slow motion of the test platform due to periodic environmental changes. A representation of the PSD of this noise containing a single frequency is given as:

$$S_{\Omega}(f) = \frac{1}{2}\Omega_0^2[\delta(f - f_0) + \delta(f + f_0)] \tag{C.19}$$

where

Ω_0 is the amplitude
f_0 is the frequency
$\delta(x)$ is the Dirac delta function

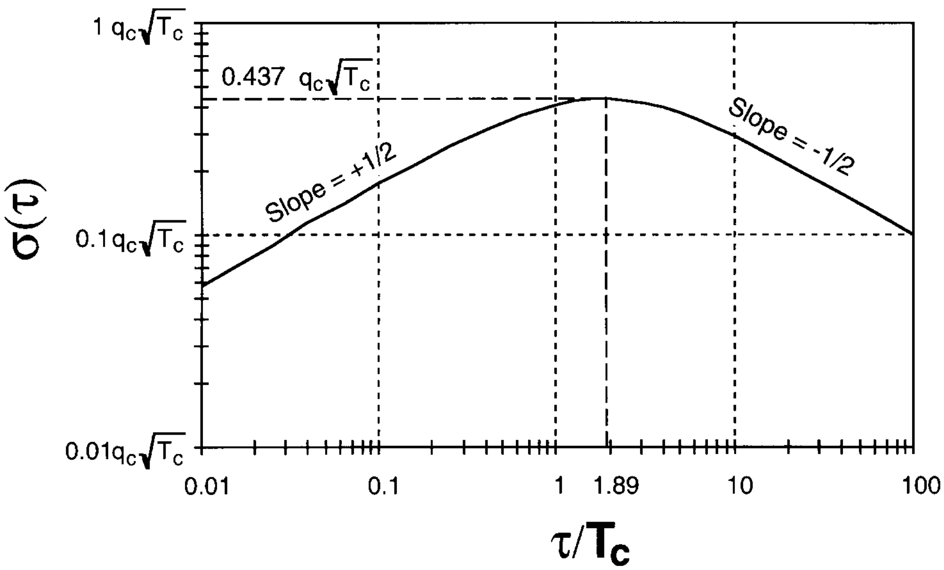


Figure C.6—$\sigma(\tau)$ Plot for correlated noise

Multiple frequency sinusoidal errors can be similarly represented by a sum of terms such as Equation (C.19) at their respective frequencies and amplitudes. Substitution of Equation (C.19) in Equation (C.1) and performing the integration yields:

$$\sigma^2(\tau) = \Omega_0^2\left(\frac{\sin^2\pi f_0\tau}{\pi f_0\tau}\right)^2 \quad \text{(C.20)}$$

Figure C.7 shows a log-log plot of Equation (C.20). Identification and estimation of this noise in IFOG data requires the observation of several peaks. As is seen however, the amplitudes of consecutive peaks fall off rapidly and may be masked by higher order peaks of other frequencies making observation difficult.

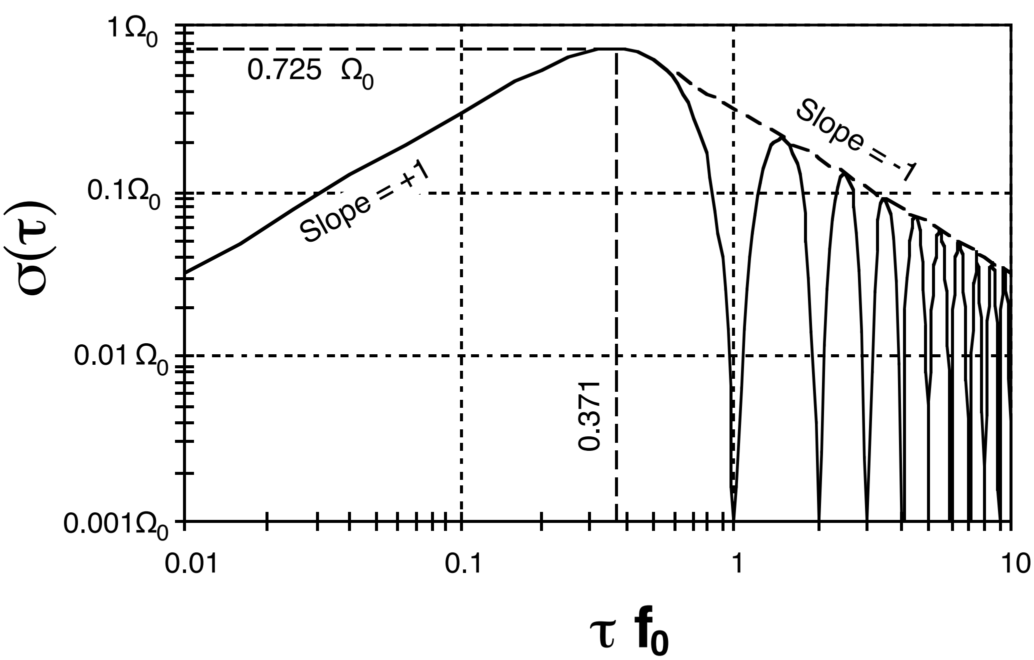


Figure C.7—$\sigma(\tau)$ Plot for sinusoidal error

C.1.7 Combined effects of all processes

In general, any number of the random processes discussed above (as well as others) can be present in the data. Thus, a typical Allan variance plot looks like the one shown in Figure C.8. Experience shows that in most cases, different noise terms appear in different regions of τ. This allows easy identification of various random processes that exist in the data. If it can be assumed that the existing random processes are all statistically independent then it can be shown that the Allan variance at any given τ is the sum of Allan variances due to the individual random processes at the same τ. In other words,

$$\sigma^2_{tot}(\tau) = \sigma^2_{ARW}(\tau) + \sigma^2_{quant}(\tau) + \sigma^2_{BiasInst}(\tau) + \ldots \tag{C.21}$$

Thus estimating the amplitude of a given random noise in any region of τ requires a knowledge of the amplitudes of the other random noises in the same region.

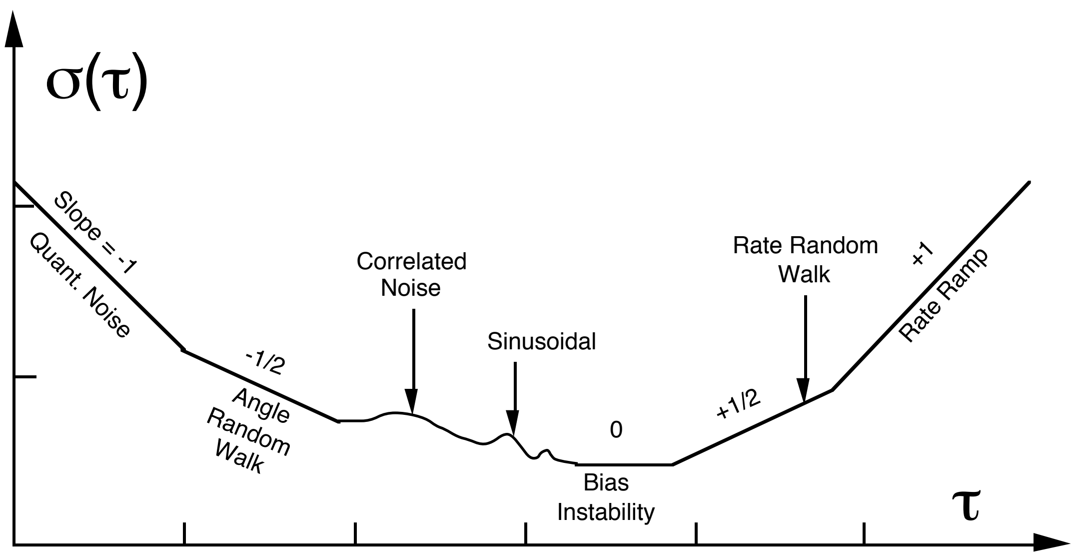


Figure C.8—$\sigma(\tau)$ Sample plot of Allan variance analysis results

C.2 Estimation accuracy and test design

A finite number of clusters can be generated from any finite set of data. Allan variance of any noise term is estimated using the total number of clusters of a given length that can be created. Estimation accuracy of the Allan variance for a given τ, on the other hand, depends on the number of independent clusters within the data set.

It can be shown that the percentage error, σ, in estimating $\sigma(\tau)$ when using clusters containing K data points from a data set of N points is given by:

$$\sigma = \frac{1}{\sqrt{2\left(\frac{N}{K} - 1\right)}} \tag{C.22}$$

Equation (C.22) shows that the estimation errors in the regions of short (long) τ are small (large) as the number of independent clusters in these regions is large (small). In fact, this equation can be used to design a test to observe a particular noise of certain characteristics to within a given accuracy. For example, to verify the existence of a random process with a characteristic time of 24 h in the data to within an error of 25%. We first set $\sigma = 0.25$ in Equation (C.22) and obtain:

$$K_{max} = \frac{N}{9} \tag{C.23}$$

Since the suspected characteristic time is 24 h, clusters of the same length are created. Thus the total test length needed for such a test is 24 × 9 = 216 h.

C.3 Tabulation of some variance analyses

A summary comparison of some variance analyses for noise processes is made in Table C.1. This table presents only a sample of analyses available, and is not meant to be a survey of all analyses. The polynomial variance terms in the left hand column are identified using gyro terminology. The individual terms relating to each author's publication are given with the same symbology as contained in that author's publication, including the definitions of symbols. For ease in recognition of similarities, the coefficients of interest are shown as the first symbol in each polynomial expression. For example, the variance coefficient for the rate random walk term in the third column of Table C.1, is K^2.

Table C.1—Summary comparison of publishing variance analyses for noise processes

	Allan [C1] (rate domain)	**This standard (rate domain)**	**Sargent, Wyman [C3] (angle domain)**	**Tehrani [C6] (rate domain)**
Terms in variance expression for noise processes	τ = sampling time = $m_{\tau o}$ where τ_o = sample time of original measurements	$1/T_0$ = data sample rate n = 1, 2, 3,...	γ = time interval separating raw data points $(2L+1)$ = number of data points combined into an average data point τ = time length of data span = $(2L+1)\gamma n$ n = 1, 2, 3,...	$Q = qT_c$ T_c = correlation time T = cluster time v_o = cutoff frequency for $1/v$ rate noise
Rate ramp	Not addressed	$R^2\left[\frac{(nT_o)^2}{2}\right]$	$R^2[\tau^4]$	$R^2[T^2]$
Rate random walk	$h_{-2}\left[\frac{(2\pi)^2\tau}{6}\right]$	$K^2\left[\frac{nT_o}{3}\right]$	$K^2\left[\frac{2\tau^3}{3} - \frac{2L(L+1)\gamma^2\tau}{3} + \frac{L(L+1)(12L^2+12L+1)\gamma^3}{15(2L+1)}\right]$	$q^2\left[\frac{2T}{3}\right]$ for $T \le T_0$
Bias instability	$h_{-1}[2\ln 2]$	$B^2\left[\frac{2}{\pi}\ln 2\right]$	Analysis considers only time-dependent rate terms	$B^2\left[\frac{4}{\pi}\ln 2\right]$ for $T \gg \frac{1}{v_o}$
Angle random walk	$h_{-1}\left[\frac{1}{2\tau}\right]$	$N^2\left[\frac{1}{nT_o}\right]$	$\sigma^2\left[2\tau - \frac{4\gamma L(L+1)}{2L+1}\right]$	$Q^2\left[\frac{2}{T}\right]$
Quantization noise	Not addressed	$Q^2\left[\frac{3}{(nT_o)^2}\right]$	$\Phi^2\left[\frac{6}{2L+1}\right]$	Not addressed

C.4 Bibliography for Annex C

[C1] Allan, D. W., “Statistics of Atomic Frequency Standards,” *Proceedings of the IEEE,* vol. 54, no. 2, pp. 221-230, Feb 1966.

[C2] Gradshteyn, I. S. and Ryzhik, I. M., *Table of Integrals, Series, and Products*. Academic Press, 1980.

[C3] Sargent, D., and Wyman, B. O., “Extraction of Stability Statistic from Integrated Rate Data,” *Proceedings of the AIAA Guidance and Control Conference*, Aug. 11–13, 1980.

[C4] Simpson, J. H., *Proc. NAECON,* vol. 1, p. 80, 1980.

[C5] Keshner, M. S., “1/f Noise,” *Proceedings of the IEEE,* vol. 70, no. 3, pp. 212–218, Mar. 1982.

[C6] Tehrani, M. M., “Ring Laser Gyro Data Analysis with Cluster Sampling Technique,” *Proceedings of SPIE,* vol. 412, 1983.

[C7] IEEE Std 1139-1988, IEEE Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology.[13]

[C8] Papoulis, A., *Probability, Random Variables, and Stochastic Processes,* Third Edition. McGraw-Hill, Inc., 1991.

[13]IEEE Std 1139-1988 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

Annex D

(informative)

Compliance matrix

Clause 5 #	Clause 5 requirement	Clause 6 #	Clause 6.6 test method
5	Requirements	N/T	
5.1	Description	N/T	
5.2	General requirements	N/T	
5.2.1	Precedence	N/T	
5.3	Performance	N/T	
5.3.1	Input Rate limits	6.6.10	Input rate test series
5.3.1.1	Maximum	6.6.10.1	Maximum input rate
5.3.1.2	Minimum (dead band)	6.6.10.2	Minimum input rate
5.3.2	Gyro scale factor, S	6.6.9.1	Gyro scale factor
5.3.2.1	Gyro scale factor errors	6.6.9.2	Gyro scale factor errors
5.3.2.2	Gyro scale factor sensitivities	6.6.9.3	Gyro scale factor sensitivities
5.3.3	Drift rate, D, E	6.6.11	Drift rate test series
5.3.3.1	Bias and random, D	6.6.11	Drift rate test series
5.3.3.1.1	Bias, D_F	6.6.11.1	Bias
5.3.3.1.2	Random, D_R	6.6.11.3	Random drift
5.3.3.1.3	Measurement noise, D_Q	6.6.11.2	Measurement noise
5.3.3.2	Environmentally sensitive, E	6.6.11.1	Bias
5.3.3.2.1	Thermal	6.6.11.1	Bias
5.3.3.2.2	Magnetic	6.6.11.1	Bias
5.3.3.2.3	Other sensitivities	6.6.11.1	Bias
5.3.4	IA alignment characteristics	6.6.12	IA alignment test series
5.3.4.1	IA misalignment	6.6.12.1	Misalignment (nominal)
5.3.4.2	IA alignment repeatability	6.6.12.2	Misalignment repeatability
5.3.4.3	IA alignment sensitivities	6.6.12.3	Alignment sensitivities

Clause 5 #	Clause 5 requirement	Clause 6 #	Clause 6.6 test method
5.3.5	Operating temperature	6.6.8.2	Operating temperature
5.3.6	Warm-up time	6.6.6	Warm-up time
5.3.7	Turn-on time	6.6.5	Turn-on time
5.3.8	Polarities	6.6.7	Polarity
5.3.8.1	IA	6.6.7	Polarity
5.3.8.2	Output signals	6.6.7	Polarity
5.3.9	Reference constants	N/T	
5.3.9.1	Light source wavelength	N/T	
5.3.9.2	Number of turns	N/T	
5.3.9.3	Effective area per turn	N/T	
5.3.9.4	Physical pathlength	N/T	
5.4	Mechanical requirements	6.6.1	Examination of product (mechanical)
5.4.1	Exterior surface	6.6.1	Examination of product (mechanical)
5.4.2	Outline and mounting dimensions	6.6.1	Examination of product (mechanical)
5.4.3	Gyro axes	6.6.1	Examination of product (mechanical)
5.4.4	Weight	6.6.1	Examination of product (mechanical)
5.4.5	Seal	6.6.3	Leak test
5.4.6	Identification of product	6.6.1	Examination of product (mechanical)
5.4.7	Acoustic noise	6.6.13.2	Acoustic noise
5.5	Electrical requirements	6.6.2	Examination of product (electrical)
5.5.1	Schematic	N/T	
5.5.2	Impedances	6.6.2.2	Impedances
5.5.3	Input power	6.6.4	Input power
5.5.4	Test points	N/T	
5.5.5	Grounding	N/T	

Clause 5 #	Clause 5 requirement	Clause 6 #	Clause 6.6 test method
5.5.6	Output signals	6.6.2, 6.6.10	Examination of product (electrical), Input rate test series
5.5.7	Temperature sensors	6.6.8.1	Temperature sensor characteristics
5.5.8	Insulation resistance	6.6.2.1	Insulation resistance
5.5.9	Dielectric strength	6.6.2.3	Dielectric strength
5.5.10	Electromagnetic interference	6.6.13.1	Electromagnetic interference
5.5.11	Electromagnetic compatibility	6.6.14.17	Electromagnetic fields
5.6	Environmental requirements	N/T	
5.6.1	Storage	6.6.14	Environmental test series
5.6.2	Transport	6.6.14	Environmental test series
5.6.3	Operation	6.6.14	Environmental test series
5.6.3.1	Operating environment	6.6.14	Environmental test series
5.6.3.2	Survival environment, operating	6.6.14	Environmental test series
5.6.3.3	Survival environment, nonoper- ating	6.6.14	Environmental test series
5.6.4	Environments	N/T	
5.6.4.1	Vibration	6.6.14.5	Vibration
5.6.4.1.1	Linear	6.6.14.5.1	Linear
5.6.4.1.2	Angular	6.6.14.5.2	Angular
5.6.4.2	Mechanical shock	6.6.14.3	Mechanical shock
5.6.4.3	Acceleration	6.6.14.6	Acceleration
5.6.4.3.1	Linear acceleration	6.6.14.6.1	Linear acceleration
5.6.4.3.2	Angular acceleration	6.6.14.6.2	Angular acceleration
5.6.4.4	Temperature	6.6.14.1	Temperature
5.6.4.5	Thermal shock	6.6.14.4	Thermal shock
5.6.4.6	Time-dependent temperature gradient	6.6.11.1	Bias
5.6.4.7	Thermal radiation	6.6.14.12	Thermal radiation
5.6.4.8	Ambient air pressure	6.6.14.15	Pressure
5.6.4.9	Acoustic noise	6.6.14.11	Acoustic noise

Clause 5 #	Clause 5 requirement	Clause 6 #	Clause 6.6 test method
5.6.4.10	Humidity	6.6.14.9	Humidity
5.6.4.11	Air currents	6.6.14.13	Air currents
5.6.4.12	Fungus	6.6.14.8	Fungus
5.6.4.13	Salt spray	6.6.14.10	Salt spray
5.6.4.14	Nuclear radiation	6.6.14.14	Nuclear radiation
5.6.4.15	Magnetic fields	6.6.14.16	Magnetic fields
5.6.4.16	Electromagnetic fields	6.6.14.17	Electromagnetic fields
5.6.4.17	Sand and dust	6.6.14.18	Sand and dust
5.6.4.18	Solar radiation	6.6.14.19	Solar radiation
5.6.4.19	Rain	6.6.14.20	Rain
5.6.4.20	Excitation variation	6.6.14.2	Excitation variation
5.6.4.21	Life	6.6.14.7	Life
5.6.4.21.1	Storage	6.6.14.7.1	Storage
5.6.4.21.2	Operating	6.6.14.7.2	Operating
5.6.4.21.3	Start cycles	6.6.14.7.3	Start cycles
5.7	Reliability	N/T	
5.7.1	Reliability program	N/T	
5.7.2	Mean time between failure (MTBF)	6.4.2	Demonstration testing