ITEM 9
Navigation Equipment

Navigation

Produced by companies in

- China
- France
- Germany
- Israel
- Italy
- Japan
- Norway
- Russia
- South Africa
- Spain
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

Instrumentation, navigation and direction finding equipment and systems, and associated production and test equipment as follows; and specially designed components and software therefor:

(a) Integrated flight instrument systems, which include gyrostabilizers or automatic pilots and integration software therefor, designed or modified for use in the systems in Item 1;

Notes to Item 9:

(1) Items (a) through (f) may be exported as part of a manned aircraft, satellite, land vehicle or marine vessel or in quantities appropriate for replacement parts for such applications.

Nature and Purpose: Integrated flight instrument systems use a variety of sensors as well as inertial instruments (accelerometers and gyroscopes) to track a missile's flight path. Because they collect and use more data than purely inertial guidance sets, they are often more accurate. The additional sensor data often allow the use of less expensive inertial instruments without a reduction in accuracy. These systems utilize all available information in various and often innovative schemes to navigate accurately. Because manufacturers have used a variety of names for integrated flight instrument systems (e.g., navigation systems), items with other names may actually be MTCR-controlled integrated flight instrument systems.

Method of Operation: Integrated flight instrument systems collect and process in-flight data from active and passive sensors, receivers, and inertial instruments in order to track the missile's flight path. They use one of several hierarchical or voting schemes to derive the best estimate of position and heading for comparison with the preprogrammed flight path. The results are used to generate signals to steer the vehicle along the intended flight path and to trigger other preprogrammed functions at their appropriate time.

Typical Missile-Related Uses: Integrated flight instrumentation systems are required equipment in unmanned air vehicles (UAVs), including cruise

Photo Credit: Litton Guidance and Control Systems

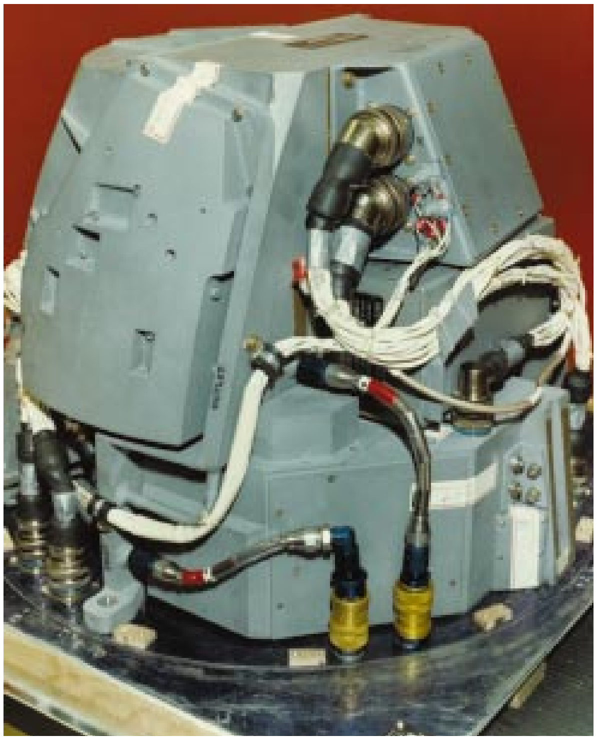

Figure 9-1: The main body of a cruise missile integrated flight instrumentation system.

Photo Credit: Litton Guidance and Control Systems

Figure 9-2: Another view of the same integrated flight instrument system shown in Figure 9-1.

missiles. Systems capable of achieving system accuracy of 3.33 percent or less of the range may be controlled as Category I under Item 2 (d).

Other Uses: Integrated flight instrumentation systems are used in both civilian and military aircraft.

Appearance (as manufactured): The size of integrated flight instrumentation systems varies with the type of vehicle and the vintage of design. Recent designs have been reduced in size to about a half meter on a side and reduced in weight to several kilograms or less. Integrated flight instrument systems vary greatly in appearance because they are designed for different interior configurations of different vehicles, and they use different combinations of subsystems. Like missile guidance sets controlled under Category I, Item 2 (d), most integrated flight instrumentation systems are enclosed in metallic boxes, which often have removable access panels. However, because integrated flight instrumentation systems use more than just an inertial measurement unit (IMU) for navigation information, they often look much more modular than ballistic missile guidance sets that depend exclusively on an IMU. Examples of this modular appearance are shown in Figures 9-1 and 9-2. The components of the system may be distributed throughout the missile with some of their sensors and antennas located well apart from the computer and IMU.

Appearance (as packaged): Although integrated flight instrument systems are not as delicate and expensive as some of the more expensive ballistic missile guidance sets, their packaging is usually robust and includes desiccants and air-tight wrappers for protection against moisture. These systems are usually shipped in cushioned containers with labels indicating the need for careful handling.

(b) Gyro-astro compasses and other devices which derive position or orientation by means of automatically tracking celestial bodies or satellites;

Notes to Item 9:

(1) Items (a) through (f) may be exported as part of a manned aircraft, satellite, land vehicle or marine vessel or in quantities appropriate for replacement parts for such applications.

Produced by companies in

- France
- Germany
- Russia
- United Kingdom
- United States

Nature and Purpose: Gyro-astro compasses are precision assemblies of sensitive optical and electro-mechanical equipment used for navigation. They provide an in-flight orientation update and thereby increase the navigational accuracy.

Method of Operation: These devices use an optical sensor to detect a distant point-source of light in a known direction. Typically, these sensors rely on stars, but they can also use satellites travelling in known orbits. The guidance computer compares the expected direction of the star on the current trajectory with its measured direction and sends signals to the flight control system to make any necessary course corrections.

Typical Missile-Related Uses: Gyro-astro compasses are used in missiles that fly a portion of their trajectory above the atmosphere.

Other Uses: Gyro-astro compasses are used in space probes and some aircraft as well as on some ships to aid in navigation.

Appearance (as manufactured): Improvements in optical sensor technology have reduced the size and weight of such sensors, and are likely to continue to do so. Although gyro-astro compasses vary considerably in design, the optical sensors, or telescopes, all have a visible optical lens, which may be protected by an automatic shutter or trap door. Many telescopes are gimbal-mounted (i.e., mounted inside one or more pivoting cages) and thus can be automatically pointed to locate an optical reference. A typical unit might measure less than half a meter and weigh less than 10 kg. A photograph of a gyro-astro compass is shown in Figure 9-3. Compasses without gimbals consist of little more than an optical sensor with precision mounting surfaces, a shutter, and supporting electronics. Their metal cases often measure only 5 to 7 cm on a side and weigh approximately 0.5 kg.

Photo Credit: Litton Alenia Difesa

Figure 9-3: A high resolution gyro-astro compass.

Appearance (as packaged): Because gyro-astro compasses are delicate mechanisms, they are usually packed in robust shipping containers that prevent damage from moisture and mild shock. Shipping containers usually have warning labels indicating that they contain costly assemblies of sensitive optical, electrical, or mechanical equipment.

Produced by companies in

- China
- France
- Germany
- Israel
- Italy
- Japan
- North Korea
- Norway
- Russia
- South Africa
- Sweden
- United Kingdom
- United States

(c) Accelerometers with a threshold of 0.05 g or less, or a linearity error within 0.25 percent of full scale output, or both, which are designed for use in inertial navigation systems or in guidance systems of all types;

Notes to Item 9:

(1) Items (a) through (f) may be exported as part of a manned aircraft, satellite, land vehicle or marine vessel or in quantities appropriate for replacement parts for such applications.

(3) Accelerometers which are specially designed and developed as MWD (Measurement While Drilling) Sensors for use in downhole well service operations are not specified in Item 9 (c).

Nature and Purpose: Accelerometers are sensitive pieces of electromechanical equipment used in measuring acceleration, which is the rate of change of speed in a given direction. Acceleration is integrated once to provide velocity and integrated again to provide distance traveled from the point of origin or launch. Two of the most important performance parameters are the threshold, the smallest measurement detectable, and the linearity error, the maximum error from the actual value measured.

Missile accuracy is directly dependent on the quality of the missile's accelerometers and gyros; missiles that fly for a long time without external updates require high quality accelerometers. Missiles that use sensor systems like Global Positioning System receivers, stellar fixes, or terrain-matching sensors to make mid-flight corrections can use lower quality accelerometers. Much of the cost of inertial-grade accelerometers results from the extensive calibration testing that must be performed on each unit.

Method of Operation: Accelerometers receive electrical power, sense acceleration and gravity, and provide measurement information as an electric signal. Information from the accelerometer, along with information on time, local gravity, orientation, and possibly other measurements, allows vehicle speed, heading, and position to be estimated by the guidance set or integrated flight instrumentation system. Several different types of accelerometers exist, each with its own method of operation.

Many pendulous accelerometers (often referred to as force balance, force to balance, or force rebalance accelerometers) use a small weight on a flexible hinge that is supported against the forces of gravity and acceleration by a magnetic field. Numerous variations of this design exist, but the principles are much the same. The small weight is held in a null position by an electromagnet. As the acceleration changes, the weight moves, and control circuitry changes the current in the electromagnet to bring the weight back to the null position. The amount of current required for this repositioning, or rebalancing, is proportional to the acceleration.

A spinning mass gyroscope with an unbalanced mass added along its spin axis can be used as an accelerometer. The gyroscope revolves about a pivot perpendicular to its axis of spin at a rate proportionate to acceleration including gravity. The sum of these revolutions serves as a mechanical integration of acceleration to provide an output proportionate to velocity rather than acceleration. Accelerometers of this type are known as pendulous integrating gyroscopic accelerometers (PIGAs). PIGAs can be very expensive and have been used in some of the most accurate long-range ballistic missile systems.

Other accelerometer designs also exist such as vibrating element accelerometers that vary the tension and frequency of a vibrating element. Chip accelerometers use a flexible portion of the microcircuit semiconductor to vary electrical resistance and produce an electrical output. Accelerometers of this type are currently at the low end of the performance range, but design efforts will continue because of the potential for substantial cost reduction. Such modern accelerometers are already used in IMUs requiring less accuracy such as UAVs, including cruise missiles.

Typical Missile-Related Uses: Accelerometers are used in missile guidance sets or integrated flight instrumentation systems. Typically, three accelerometers mounted perpendicular to each other provide all the acceleration measurement information necessary for inertial navigation. They can be installed in a gimbal structure (see Item 2 (d)), mounted in a floating ball, or affixed (strapped down) to the missile frame. Combined with gyroscopes, they make up an IMU or inertial sensor assembly (ISA). Depending upon mission requirements, some UAVs, including cruise missiles, can make due with only one or two accelerometers.

Other Uses: Accelerometers are used in both civilian and military aircraft and space systems, in oil well drilling stress testing, as inertial navigators in cars and other land vehicles, and in electronic equipment, manufacturing, gravity meters, robotics, and carnival rides (roller coasters). However, most of these uses do not require the high stability and highly calibrated accuracy of inertial-grade accelerometers.

Appearance (as manufactured): Accelerometers vary greatly in appearance because many designs exist. They are usually cylindrical, metallic, and shiny from precision machining. The larger accelerometers used in ballistic missiles are several centimeters in length and can weigh up to several kilograms. Those used in UAVs, including cruise missiles, are smaller and lighter; they may measure only a few centimeters on a side and weigh less than a kilo-

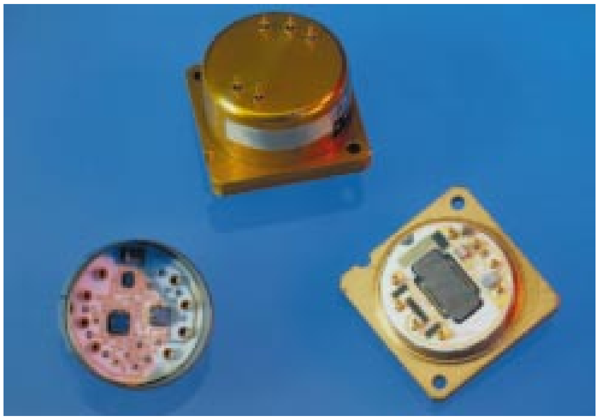

Photo Credit: Litton Sextant Avionque

Figure 9-4: An integrated circuit accelerometer.

Photo Credit: Lockheed Martin Federal Systems

Figure 9-5: Two force rebalance accelerometers that can be built with any of a wide range of performance capabilities.

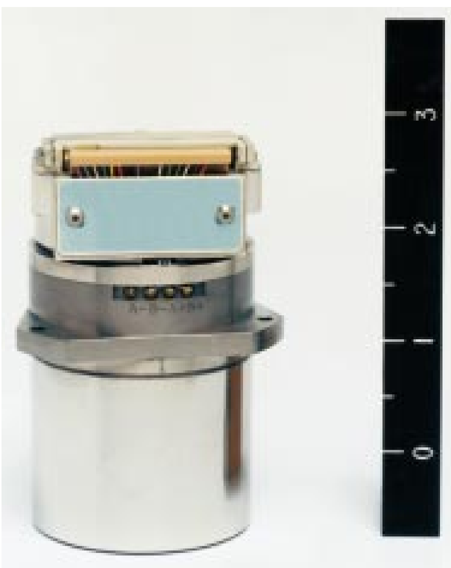

Photo Credit: The Charles Stark Draper Laboratories, Inc.

Figure 9-6: A pendulous integrating gyro accelerometer (PIGA) next to an inch scale.

gram. Many accelerometers of MTCR concern have high quality electrical connections and precision mounting surfaces for accurate alignment. Many accelerometers are factory-sealed instruments, not usually disassembled or even opened for service by any customer. A modern integrated circuit accelerometer is shown in Figure 9-4. The model and serial number on the exterior of the accelerometer should appear on the associated documentation, which contains information about accuracy.

Distinguishing MTCR-controlled from other accelerometers simply by visual inspection can be difficult because, although different models of an accelerometer have different performance capabilities, they may look identical. Two force rebalance accelerometers covering a wide range of performance are shown in Figure 9-5. One variant of a sophisticated gyroscopic accelerometer is the PIGA shown next to an inch scale in Figure 9-6. Relevant information unique to each model- and serial-numbered accelerometer can be derived from the associated documentation (often called calibration sheet or cal-data), including the g-threshold and linearity error. A major factor that makes an accelerometer accurate enough for use in sophisticated missile guidance sets is the exhaustive testing needed to compile the calibration data. Thus, the detail and amount of the calibration and error modeling data associated with each accelerometer are key indicators for determining the missile-related use of an accelerometer.

Appearance (as packaged): Because they are designed to be sensitive to acceleration, precision accelerometers are vulnerable to damage from relatively minor impact. They are usually protected from physical shock in small, high quality packages with thick, contour-fitted foam lining much like a package for a fine pocket watch. For shipping, one or more of these special boxes are packed in yet another box or other container with cushioned lining of some sort. The documentation on the accuracy of each model- and serial-numbered accelerometer is usually contained in its package.

(d) All types of gyros usable in the systems in Item 1, with a rated drift rate stability of less than 0.5 degree (1 sigma or rms) per hour in a 1 g environment;

Notes to Item 9:
(1) Items (a) through (f) may be exported as part of a manned aircraft, satellite, land vehicle or marine vessel or in quantities appropriate for replacement parts for such applications.
(2) In subitem (d):
 (a) Drift rate is defined as the time rate of output deviation from the desired output. It consists of random and systematic components and is expressed as an equivalent angular displacement per unit time with respect to inertial space.
 (b) Stability is defined as standard deviation (1 sigma) of the variation of a particular parameter from its calibrated value measured under stable temperature conditions. This can be expressed as a function of time.

Produced by companies in

- Austria
- Canada
- China
- France
- Germany
- Israel
- Italy
- Japan
- North Korea
- Russia
- South Africa
- Sweden
- United Kingdom
- United States

Nature and Purpose: Gyroscopes, or gyros, are sensitive pieces of electromechanical or electro-optical equipment that measure rotation about one or more sensitive axis. Gyroscopes are usually mounted with accelerometers in the guidance set or integrated flight instrumentation system. They measure any change in the angular orientation of the accelerometers, so that the direction of the accelerometer measurements is known. One of the most important performance parameters is drift rate stability, usually measured in fractions of a degree per hour. This determines how quickly the gyro loses knowledge of its orientation. For gyros used in strapdown guidance systems, the stability of the scale factor—the factor relating the sensed rotation rate or angle and the gyro output signal—is also critical.

Missile accuracy is directly dependent on the quality of the missile's accelerometers and gyros; missiles that fly for a long time without external updates require high quality gyros. Missiles that use sensor systems like Global Positioning System receivers, stellar fixes, or terrain-matching sensors to make mid-flight corrections can use lower quality gyros. Much of the cost of inertial-grade gyros results from the extensive testing that must be performed on each unit.

Method of Operation: Gyros sense angular shifts (changes in orientation) and provide measurement information, usually as some form of electric signal. The orientation information from the gyros, along with information on time, local gravity, acceleration, and possibly other measurements, allows vehicle speed, heading, and position to be estimated by the guidance set or integrated flight instrumentation system. Several different types of gyros exist, each with its own method of operation. Most inertially guided missiles use either spinning mass gyros or electro-optical gyros.

Spinning mass gyros contain a spinning disk and operate on the gyroscopic principle whereby a proportionate measurable torque is generated perpendicular to the angular disturbance. There are two common types of spinning mass gyros. Single degree-of-freedom (SDF) gyros sense rotation about only one axis, while two degree-of-freedom (TDF) gyros sense rotation about two axes. Since missile guidance systems usually require orientation knowledge for all three axes, three SDF gyros are required, but only two TDF gyros (one axis will be redundant).

An SDF gyro has the spinning mass suspended cross-axis inside a cylinder that floats inside yet another slightly larger cylinder fixed to the guidance platform. Many designs float the inner cylinder in a liquid while others suspend it with gaseous flow. Rotations of the floated inner cylinder are related to input orientation changes by the gyroscopic effect of the spinning mass. Measurement of those rotations or measurement of the force needed to prevent those rotations is the output of the SDF gyro.

The most commonly used TDF gyro is the dynamically tuned gyro (DTG). It uses no floatation fluid, so it is sometimes referred to as a “dry” tuned gyro. A DTG has the spinning mass suspended on a complex gimbaled flex-hinge assembly, essentially an ultra-precision universal joint. The complex hinge assembly is tuned so its error torques cancel at one specific speed, often in excess of 10,000 rpm. Naturally, DTGs need very good speed regulation to operate reliably at the tuned rpm. Older types of TDF gyros consist of a series of mechanical gimbals that isolate the spinning rotor from the case. The angular position of the spinning mass with respect to the case is used to measure the platform’s orientation changes.

Electro-optical gyros generate counter-rotating beams of laser light around a closed path to form an interference pattern that is sensed by a detector. When rotation about an axis not in the plane of the loop occurs, the difference in the effective lengths of the respective paths creates a relative shift of the interference pattern. This shift (known as the Sagnac effect) is observed by the detector, which provides an output proportional to the rotation of the gyro.

There are two common types of optical gyros, the ring laser gyro (RLG) and the fiber optic gyro (FOG), and there are several variations of each. RLGs create their counter-rotating beams of laser light inside gas tubes that are cavities configured in a closed polygonal path, often triangular, but sometimes four or five sided. These cavities are made in glass with a near-zero thermal expansion for higher accuracy. FOGs use long spools of fiber optic cable to carry the counter-rotating beams. An important difference between RLGs and FOGs is that the spool of fiber optic cable gives the FOG a much longer optical path length and, at least theoretically, better accuracy. In practice, however, this improvement is offset by imperfections in the fiber optic cable and cable interfaces. FOGs are under development in several countries, and their performance characteristics are continually improving. They hold much promise for becoming the lowest cost gyro yet devised.

FOGs are designed as single-axis gyros so most missiles that use them will need three to track rotations about all three axes; the same is true of single-ring RLGs. Sometimes multi-axis RLGs are used that contain three or more rings in a single block of glass; only one such unit would be required in a guidance set.

Other types of gyros include the hemispherical resonating gyro, which establishes and monitors a standing vibration wave in a hemispherical cup (somewhat like a small wineglass). There are also designs like small tuning forks that operate by a method that involves Coriolis force. However, any gyro capable of meeting MTCR performance specifications is controlled regardless of its method of operation.

Typical Missile-Related Uses: Gyros are used in a missile's guidance set or integrated flight instrumentation system to sense changes in accelerometer orientation. Designs may use two, three, or four gyros. They usually are mounted perpendicular to each other in order to provide angular measurement information about all three axes. They can be used in a gimbal structure (see Item 2 (d)), mounted in a floating ball, or affixed to a block which is in turn affixed to the missile airframe in a strapdown configuration. Combined with accelerometers, they make up the IMU or ISA.

Other Uses: Gyros are used in non-missile guidance sets, integrated flight instrumentation systems, gyrostabilizers, automatic pilots, and in navigational equipment. Military applications include artillery, tanks, ships, and aircraft. Commercial applications include ships, aircraft, and oil drilling. In most non-missile applications, gyros can be smaller, cheaper, and less complex because operating environments and accuracy requirements are usually less demanding.

Appearance (as manufactured): Modern SDF gyros can be 5 to 8 cm in diameter and 8 to 12 cm long, and weigh up to one kg. DTGs are usually cylindrical with diameters of 4 to 6 cm and lengths of 4 to 8 cm, and generally weigh less than one kg. Older gyros can be somewhat larger, approximately twice the size and weigh several kilograms. Gyros used in UAVs, including cruise missiles, can be much smaller and lighter, perhaps tens of grams.

Many gyros of MTCR concern have precision mounting surfaces for accurate alignment and high quality electrical connections. Because many designs exist, a gyro's appearance can vary greatly. Spinning mass gyros are usually cylindrical, metallic, heavy for their size, and shiny from precision machining. A dynamically tuned spinning mass gyro is shown in Figure 9-7.

Photo Credit: The Charles Stark Draper Laboratory, Inc.

Figure 9-7: A DTG dynamically tuned spinning mass gyro.

Photo Credit: British Aerospace Ltd.

Figure 9-8: A vibrating structure gyro.

Photo Credit: Honeywell

Figure 9-9: Three exposed ring laser gyros without their associated electronics.

Photo Credit: Honeywell

Figure 9-10: A fiber optic gyro with its top removed.

Photo Credit: LITEF

Figure 9-11: A fiber optic, rate sensing gyro. It is 2 × 6.5 × 8 cm.

A vibrating structure gyro is shown in Figure 9-8. Individual optical gyros are usually pad-like and mounted in a low profile, sealed box. A three-ring RLG unit will tend to be cubic and between 4 and 10 cm on a side. It may weigh between fractions of a kilogram to over a kilogram. Some single-axis designs resemble cylinders with diameters exceeding 20 cm. Three exposed RLG bodies are shown in Figure 9-9; an electrode for the gas laser can be seen at the bottom of each ring. The laser light travels the triangular path machined into the glass. Some FOG designs are only 2 to 4 cm in diameter, contain a fiber several hundred meters long, and weigh fractions of a kilogram. A FOG with its top removed is shown in Figure 9-10. A more typical exterior appearance for FOGs and RLGs is shown in Figure 9-11.

MTCR-controlled and uncontrolled gyros may look identical. Relevant information unique to each model- and serial-numbered gyro can be derived from the associated documentation (calibration sheet or cal-data), including the drift rate stability. As with accelerometers, the exhaustive testing needed to compile this calibration data is a substantial part of what makes a gyro accurate enough for use in a missile guidance set. Thus, the detail and amount of the calibration and error modeling data associated with each gyro are critical to determining the missile-related use of a gyro. The cal-data normally cites a serial number that is visible on the gyro.

Appearance (as packaged): Spinning mass gyros are vulnerable to damage from shock, but optical gyros are fairly rugged. Spinning mass gyros are packed in high quality, cushioned containers. Optical gyros do not need as much cushioning material in the package, but they are still likely to be shipped in high quality packages typical of expensive electronic instruments and sensors.

(e) Continuous output accelerometers or gyros of any type, specified to function at acceleration levels greater than 100 g;

Note to Item 9:

(1) Items (a) through (f) may be exported as part of a manned aircraft, satellite, land vehicle or marine vessel or in quantities appropriate for replacement parts for such applications.

Produced by companies in

- China
- France
- Germany
- Israel
- Italy
- Japan
- North Korea
- Russia
- United Kingdom
- United States

Nature and Purpose: Continuous output accelerometers and gyros specified to function at acceleration levels greater than 100 g are a special category of accelerometers and gyros, which may include those in Item 9 (c) and (d), respectively. These devices produce uninterrupted signals throughout their specified range and are designed to operate under extreme accelerations in excess of 100 g. All such instruments are controlled under this item regardless of performance specifications. Their purpose is to provide inertial instrument data under heavy accelerations like those experienced by reentry vehicles (RVs) during defense avoidance and reentry deceleration. These instruments may also be used as part of a fuzing system. No accuracy specifications are included because instruments with significantly lower accuracy can be used due to the relatively short period of operation.

Method of Operation: These inertial instruments operate in much the same way as those covered in Item 9 (c) and (d), but they are ruggedized and have a greater operating range (in excess of 100 g).

Typical Missile-Related Uses: These accelerometers can be used as fuses in RVs, and continuous output accelerometers and gyros are used in the guidance sets that steer maneuvering RVs as they evade defenses or terminally guide themselves to a target. Such accelerometers and gyros are fairly accurate and probably nuclear hardened. Continuous output accelerometers rated in access of 100 g are also used in fusing and firing mechanisms for cruise missiles with penetrating warheads.

Other Uses: Continuous output accelerometers and gyros able to operate in a 100-g environment can be used in guided munitions such as artillery shells. Such accelerometers are also used in laboratories for high-g tests that require continuous output.

Appearance (as manufactured): Continuous output accelerometers, as shown in Figure 9-12, may look identical to those covered in Item 9 c. Similarly, gyros specified to function at levels greater than 100 g may also be virtually identical in appearance to those covered in Item 9 d. They all are usually cylindrical or pad-like with precision mounting flanges and high quality

Photo Credit: Lockheed Martin Federal Systems

Figure 9-12: Two continuous output accelerometers, visually identical to those of Figure 9-5, rated at 100 g.

Photo Credit: Litton Guidance and Control Systems

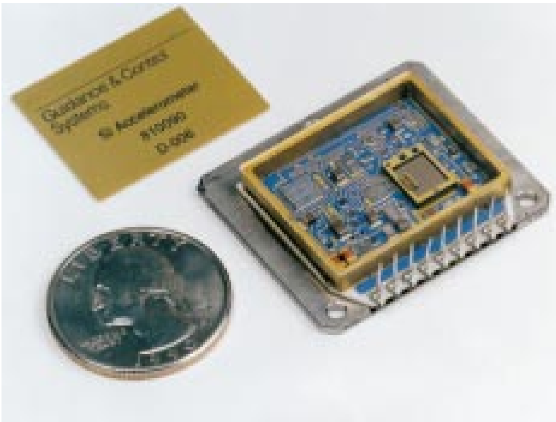

Figure 9-13:
An integrated circuit accelerometer rated at over 100 g.

electrical connectors. Because smaller instruments are inherently more g-tolerant, they tend to be smaller than most other accelerometers and gyros. There are even miniature high-g accelerometers integrated into circuit elements, as shown in Figure 9-13.

Appearance (as packaged): Because of their rugged nature, these instruments do not need special handling. They are shipped as small hardware items. The documentation on the operating g range of each model- and serial-numbered unit is usually contained in its package.

Produced by companies in

- China
- France
- Germany
- Israel
- Italy
- Japan
- Norway
- Russia
- South Africa
- Spain
- Sweden
- Switzerland
- Ukraine
- United Kingdom
- United States

(f) Inertial or other equipment using accelerometers described by subitems (c) or (e) above or gyros described by subitems (d) or (e) above, and systems incorporating such equipment, and specially designed integration software therefor;

Notes to Item 9:

(1) Items (a) through (f) may be exported as part of a manned aircraft, satellite, land vehicle or marine vessel or in quantities appropriate for replacement parts for such applications.

Nature and Purpose: This MTCR Annex item ensures that any of the accelerometers and gyros controlled in Item 9 remain controlled when they are components of a larger assembly or a non-guidance related assembly. Examples of such assemblies include gimbal assemblies with the instruments installed, IMUs, complete guidance sets not controlled under Category I, Item 2 (d), gravity meters, and stabilized platforms for cameras, antennas, or other equipment. Any inertial system, subsystem, or other equipment, regardless of its intended use, is controlled as Category II under this item if it contains one or more of Items 9 (c), 9 (d), or 9 (e).

Typical Missile-Related Uses: This equipment is used in guidance sets and integrated flight instrumentation systems for ballistic missiles and cruise missiles, as described in Item 2 (d) and Item 9 (a).

Other Uses: This equipment can also be used in guidance sets and navigation systems for a whole range of space flight, aviation, gravity mapping, ocean navigation, land navigation, and well drilling uses.

Appearance (as manufactured): The appearance of inertial or other equipment using accelerometers or gyros varies widely. IMUs can be gimbaled; a gimbaled IMU is shown in Figure 9-14. These can be designed to be spherical so as to float inside a liquid-filled chamber, as shown in Figure 9-15.

Photo Credit: The Charles Stark Draper Laboratory, Inc.

Figure 9-14: A gimbaled IMU that contains three accelerometers and three gyros (gimbals are internal).

Figure 9-15: A model of an inertial measurement sphere that contains three accelerometers and three gyros, designed to float inside a liquid-filled chamber (chamber shown open).

Photo Credit: Honeywell

Figure 9-16: A strapdown IMU that contains three accelerometers and three ring laser gyros (in the end opposite the cables).

Photo Credit: Honeywell

Figure 9-17: A strapdown IMU containing three accelerometers and three ring laser gyros.

IMUs can also be designed to be rigidly mounted in a strapdown configuration, as shown in Figures 9-16 and 9-17. Equipment using accelerometers and gyros may also use optical sensors, Global Positioning System satellite receivers, radar units, horizon sensors, computers and software, and other items, depending on the specific application. The equipment has electrical connectors and mounting surfaces, and may have removable access panels for replacing accelerometers, gyros, or other subelements. They vary in size from a few centimeters to a meter on a side.

Appearance (as packaged): Because many accelerometers and gyroscopes are inherently delicate, they are packed in robust shipping containers with cushioning and insulation to prevent damage from shock and moisture. Containers may be wood, metal, or plastic with foam cushioning. The shipping packages are likely to have the cautionary labels usually used on containers of costly assemblies of sensitive electrical or mechanical equipment.

Produced by companies in

- China
- France
- Germany
- Italy
- Japan
- Russia
- Switzerland
- United Kingdom
- United States

(g) Production equipment and other test, calibration and alignment equipment, other than that described in 9(h), designed or modified to be used with equipment specified in a-f above, including the following:
- (1) For laser gyro equipment, the following equipment used to characterize mirrors, having the threshold accuracy shown or better:
  - (i) Scatterometer (10 ppm);
  - (ii) Reflectometer (50 ppm);
  - (iii) Profilometer (5 Angstroms).
- (2) For other inertial equipment:
  - (i) Inertial Measurement Unit (IMU Module) Tester;
  - (ii) IMU Platform Tester;
  - (iii) IMU Stable Element Handling Fixture;
  - (iv) IMU Platform Balance fixture;
  - (v) Gyro Tuning Test Station;
  - (vi) Gyro Dynamic Balance Station;
  - (vii) Gyro Run-In / Motor Test Station;
  - (viii) Gyro Evacuation and Filling Test Station;
  - (ix) Centrifuge Fixture for Gyro Bearings;
  - (x) Accelerometer Axis Align Station;
  - (xi) Accelerometer Test Station.

(h) Equipment as follows:
- (1) Balancing machines having all the following characteristics:
  - (i) Not capable of balancing rotors / assemblies having a mass greater than 3kg;
  - (ii) Capable of balancing rotors / assemblies at speeds greater than 12,500 rpm;
  - (iii) Capable of correcting unbalance in two planes or more; and
  - (iv) Capable of balancing to a residual specific unbalance of 0.2 gram mm per kg of rotor mass;
- (2) Indicator heads (sometimes known as balancing instrumentation) designed or modified for use with machines specified in 9(h) 1;
- (3) Motion simulators / rate tables (equipment capable of simulating motion) having all the following characteristics:
  - (i) Two axis or more;
  - (ii) Slip rings capable of transmitting electrical power and / or signal information; and
  - (iii) Having any of the following characteristics:
    - (a) For any single axis:
      - (1) Capable of rates of 400 degrees / sec or more; or 30 degrees / sec or less; and
      - (2) A rate resolution equal to or less than 6 degrees / sec and an accuracy equal to or less than 0.6 degrees / sec;

(b) Having a worst-case rate stability equal to or better (less) than plus or minus 0.05 percent averaged over 10 degrees or more; or

(c) A position accuracy equal to or better than 5 arc second;

(4) Positioning tables (equipment capable of precise rotary positioning in any axes) having the following characteristics:

(i) Two axes or more; and

(ii) A positioning accuracy equal to or better than 5 arc second;

(5) Centrifuges capable of imparting accelerations above 100 g and having slip rings capable of transmitting electrical power and signal information.

Notes to Item 9:

(4) The only balancing machines, indicator heads, motion simulators, rate tables, positioning tables, and centrifuges specified in Item 9 are those specified in 9 (h).

(5) 9 (h) (1) does not control balancing machines designed or modified for dental or other medical equipment.

(6) 9 (h) (3) and (4) do not control rotary tables designed or modified for machine tools or for medical equipment.

(7) Rate tables not controlled by 9 (h) (3) and providing the characteristics of a positioning table are to be evaluated according to 9 (h) (4).

(8) Equipment that has the characteristics specified in 9 (h) (4) which also meets the characteristics of 9 (h) (3) will be treated as equipment specified in 9 (h) (3).

Nature and Purpose: Alignment, calibration, and test equipment is used to build, calibrate, test, and characterize these instruments to meet the requirements. Gyroscopes, accelerometers, and IMUs are precision instruments that must be accurate and reliable over time. Particularly important is test equipment that subjects an instrument to accelerations and orientation changes while measuring the instrument’s response over time. This equipment is essential to the manufacture of high quality inertial instruments. Any specially designed test, calibration, alignment, and production equipment is controlled even if it is not specified on the list.

Typical Missile-Related Uses: This equipment is required to produce and calibrate inertial instruments for use in missiles of all types.

Other Uses: Most spacecraft, aircraft, and other vehicles using inertial navigation or guidance units require similar equipment and technologies for development, production, test, and calibration. However, many other non-missile applications can use inertial instruments with higher drift rates, lower vibration and acceleration tolerances, and lower stability requirements. Thus, the test, calibration, alignment, and production equipment for non-missile inertial equipment is often less sophisticated and less precise than that required for accurate missiles.

Photo Credit: Digital Instruments

Figure 9-18: A profilometer system used for measuring mirrors.

Photo Credit: Honeywell

Figure 9-19: A typical IMU module tester.

Photo Credit: Litton Guidance and Control Systems

Figure 9-20: Another portable IMU tester connected to a miniature IMU.

Appearance (as manufactured): Specially designed alignment, calibration, test, and production equipment for these guidance and navigation items described in (a) through (f) are usually limited-production items. They are as diverse in size, weight, and appearance as in function, and these features change as the technology changes. Although far from a complete list, short descriptions of some examples are provided below.

Because ring laser gyros sense the phase change of minute wavelengths in light, their accuracy is determined by the quality of their mirrors. The mirrors must be a precise shape and reflect almost all the light falling on them and neither absorb nor scatter it. The following three pieces of equipment are designed to characterize mirrors for use in such gyros.

- A scatterometer (10 ppm) measures the tendency of a mirror to scatter light away from its intended direction to an accuracy of 10 ppm or less. It provides a beam of known intensity and measures the intensity of scattered rays.
- A reflectometer (50 ppm) measures the ability of a mirror to reflect light to a measurement accuracy of 50 ppm or less. It works by shining a beam of known intensity on the mirror and measuring the intensity of the reflected light.
- A profilometer (5 Angstroms) measures the profile of the optical surface of a mirror to an accuracy of 5 Angstroms (5×10^{-10} m) or less. Various methods are used to map the minute variations in optical surface height. This mapping helps determine the localized deviations from theoretical perfect geometry, whether it is designed flat, concave, or convex. A complete profilometer system is shown in Figure 9-18.

The accuracy of inertial guidance systems is determined by the quality of their accelerometers and gyroscopes. Most of the following equipment either characterizes or tests these instruments as they operate separately, as an assembly, or as a complete IMU.

- An IMU Module Tester operates an IMU module electrically, simulates inputs, and collects response data to confirm proper electrical operation. Typical IMU module testers are shown in Figures 9-19 and 9-20.

- An IMU Platform Tester operates a complete IMU platform, that is, the stable element or fully operational strapdown IMU. A three-axes rate table, also referred to as a motion simulator, often is used as part of an IMU platform tester; an example is shown in Figure 9-21. Such tables are controlled under Item 9 (h) (3). An IMU tested by this equipment should correctly sense the earth's gravity and rotation through all orientation changes without misinterpreting it as lateral or vertical movement and without losing track of its initial alignment with respect to a fixed coordinate reference frame.

Figure 9-21: A three-axis rate table for testing IMUs or gyros.

- An IMU Stable Element Handling Fixture safely handles the IMU stable element, that is, the inner portion of a gimbaled or floated IMU, which contains the inertial instruments. Careful handling facilitates numerous necessary manipulations without degrading the stable element during its assembly, test, and adjustment.

Photo Credit: Ideal Aerosmith, Inc.

Figure 9-22: A typical rate table used for tuning gyros.

- An IMU Platform Balance Fixture determines IMU platform imbalance and thereby facilitates adjustments to establish balance. The center of balance must be established accurately to avoid torques under acceleration and vibration during flight.

- A Gyro Tuning Test Station energizes the gyro at the desired voltage over a range of speeds to determine the best operating rate of rotation, or rpm. The best rpm is achieved when the effects of gyro error sources are minimized as indicated by data collected. A typical rate table used as part of a gyro tuning test station is shown in Figure 9-22.

- A Gyro Dynamic Balance Station precisely balances the high-speed rotating members of spinning mass gyroscopes. Balance is critical to gyro performance and longevity. These balancing machines are subject to control under Item 9 (h) (1) if they have the specified performance characteristics.

- A Gyro Run-In / Motor Test Station energizes the gyro or gyro motor at the desired voltage and frequency to accumulate run time and thereby break in the gyro bearings and measure motor performance at the design rpm.

- A Gyro Evacuation and Filling Test Station purges a gyro internal cavity and fills it with the design pressure of a desired liquid or blend of gases. Most gyros and accelerometers will be filled with an inert dry gas to improve long term performance. In addition, certain gyros have internal cavities that need either a specific liquid of a given density and viscosity or a specific blend of gases to function properly.

- A Centrifuge Fixture for Gyro Bearings facilitates testing of gyros in a centrifuge to confirm the ability of the bearings to withstand the acceleration forces expected during flight. Centrifuge fixtures are also used to remove excess lubricant from a gyro's bearing retainer rings. A centrifuge is shown in Figure 9-23.

Photo Credit: A.G. Davis Gage & Engineering

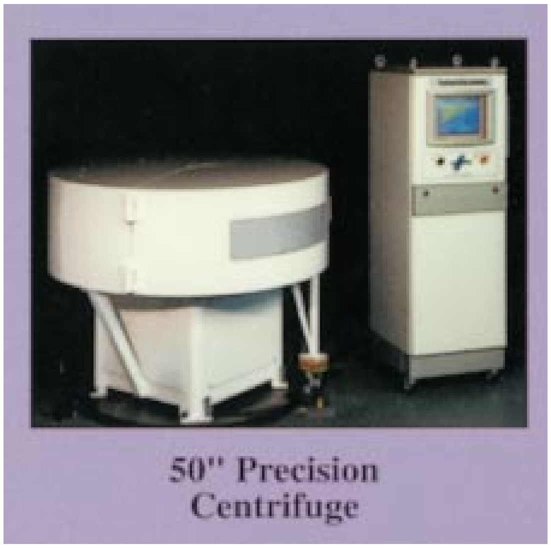

Figure 9-23: A centrifuge used for gyro-bearing testing and its controller.

- An Accelerometer Axis Align Station checks accelerometer axis alignment by rotating the accelerometer about its input axis while the input axis is horizontal. This test is often repeated after vibration tests or temperature cycles to determine input axis alignment stabilities. Accelerometer input axis alignment is again checked after installation at the IMU level to determine the slight but important deviations from desired mutual perpendicularity of the input axis. The electronics associated with a pendulous integrating gyro accelerometer (PIGA) alignment station are shown in Figure 9-24.

Photo Credit: Boeing North American, Inc.

Figure 9-24: PIGA accelerometer alignment station control electronics.

- Accelerometer Test Stations are used to test the accuracy with which an accelerometer can measure gravity over a range of positions and angles. These data are then used to calibrate the instrument. Accelerometers are mounted to a vertical table surface and tumbled to experience gravitational acceleration while upright and alternately upside down. Several PIGA test stations are shown in Figure 9-25. Accelerometer test stations can run tests that include temperature control, as shown in Figure 9-26. The tests use data recording equipment that take data over a long period of time.

Photo Credit: Boeing North American, Inc.

Figure 9-25: PIGA accelerometer test stations.

- Balancing machines are used primarily to balance spinning mass gyroscopes to a high level of precision. Balancing machines are controlled under Item 9 (h) (1).

- Indicator heads are precision round steel tables that can be rotated and locked in a specific direction repeatedly without loss of accuracy. They are also known as tumble testers, indexing heads, positioning tables, and dividing heads. Indicator heads modified for use in Item 9 (h) (1) controlled balancing machines are controlled under Item 9 (h) (2), and high precision, multi-axis indicator heads (i.e., positioning tables) are controlled under Item 9 (h) (4).

- Controlled motion simulators and rate tables are precision machines that rotate a mounting table about multiple axes at precisely known speeds and angles. They are normally used in guidance development to test instruments and IMU assemblies as described above. Figure 9-21 shows such a rate table; Figure 9-27 shows a two-axis, rate-integrating gyro motion simulator. Rate tables are controlled under Item 9 (h) (3).

- A centrifuge, as shown in Figure 9-23, is used as part of an accelerometer test station in order to determine accelerometer non-linearities over a range substantially in excess of the plus and minus one g available in tumble tests. Centrifuges are controlled under Item 9 (h) (5).

Photo Credit: Litton Guidance & Control Systems

Figure 9-26: A dividing head with a temperature control chamber for testing an accelerometer inside the chamber.

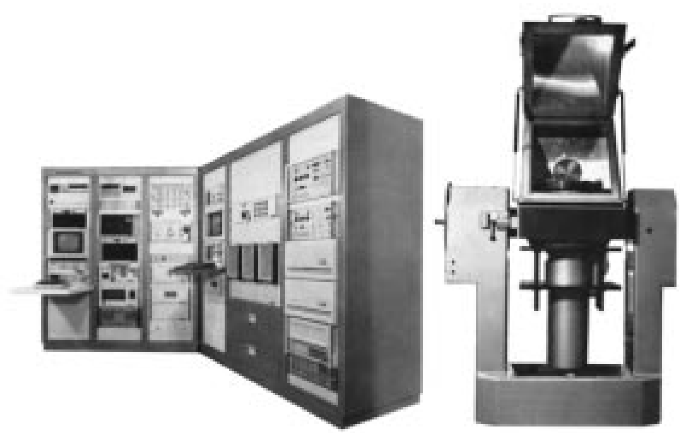

Photo Credit: Contraves Inc.

Figure 9-27: A two-axis rate integrating gyro test station utilizing a motion simulator/rate table.

Appearance (as packaged): Packaging varies greatly with the size, weight, and sensitivity of the specific equipment. However, because most of these items are precision equipment sensitive to shock or rust, packaging is likely to be robust, with padding and coverings to protect against shock and moisture. Much of the equipment can be disassembled and shipped in separate containers or crates.