DEPARTMENT OF DEFENSE

DEVELOPING CRITICAL TECHNOLOGIES/SCIENCE & TECHNOLOGY (DCT/S&T)

SECTION 16: POSITIONING, NAVIGATION, AND TIME TECHNOLOGY

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PREFACE

Developing Critical Technologies/Science & Technology (DCT/S&T) is a product of the Defense Critical Technologies Program (DCTP) process. This process provides a systematic, ongoing assessment and analysis of a wide spectrum of technologies of potential interest to the Department of Defense. DCT/S&T focuses on worldwide government and commercial scientific and technological capabilities that have the potential to significantly enhance or degrade U.S. military capabilities in the future. It includes new and enabling technologies as well as those that can be retrofitted and integrated because of technological advances. It assigns values and parameters to the technologies and covers the worldwide technology spectrum.

DCT/S&T is oriented towards advanced research and development including science and technology. It is developed to be a reference for international cooperative technology programs. A key component is an assessment of worldwide technology capabilities. S&T includes basic research, applied research and advanced technology development.

SECTION 16—POSITIONING, NAVIGATION, AND TIME TECHNOLOGY

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Highlights

- Positioning, navigation, and time (PNT) technology usage has doubled every five years, mostly because of the U.S. Global Positioning System (GPS) program and the miniaturization of electromechanical components. Future PNT usage is expected to double every two years because of telecommunication and automobile navigation commercial markets. On 1 May 2000, the President discontinued Selective Availability of GPS. "*The decision to discontinue Selective Availability is the latest measure in an ongoing effort to make GPS more responsive to civil and commercial users worldwide. This increase in accuracy will allow new GPS applications to emerge and continue to enhance the lives of people around the world.*"[1]
- The economic engine for PNT is both the nonmilitary commercial community sector and the expanding need for more accurate position and especially precise time.
- Military exploitation and harnessing of a 3–D position (latitude, longitude, and altitude) and precise time (POSITIME) common battlespace grid reference and use of hybrid multisensor arrays are in the embryonic stage. The impact on the military in terms of situational awareness—that is, the use of multiple sensor data to reduce fratricide and positively identify friendly forces, foe targets, and neutrals—will be significant.
- Significant advances in PNT technologies should be anticipated from developed nations and less developed nations. This will allow more nontraditional sources in manufacture of PNT products.

OVERVIEW

Included in this section are descriptions of the technologies necessary to achieve dominant battlespace awareness, including autonomous and cooperative positioning, data-based navigation systems, positive combat identification, and nonintrusive detection of military force elements. Figures 16.0-1 and 16.0-2 show battlespace awareness for two warfare scenarios: sophisticated conventional warfare and military operations in urban terrain, respectively. The latter is the more complex and resource-intensive environment; it requires very precise situational awareness.

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[1] President Bill Clinton, the White House.

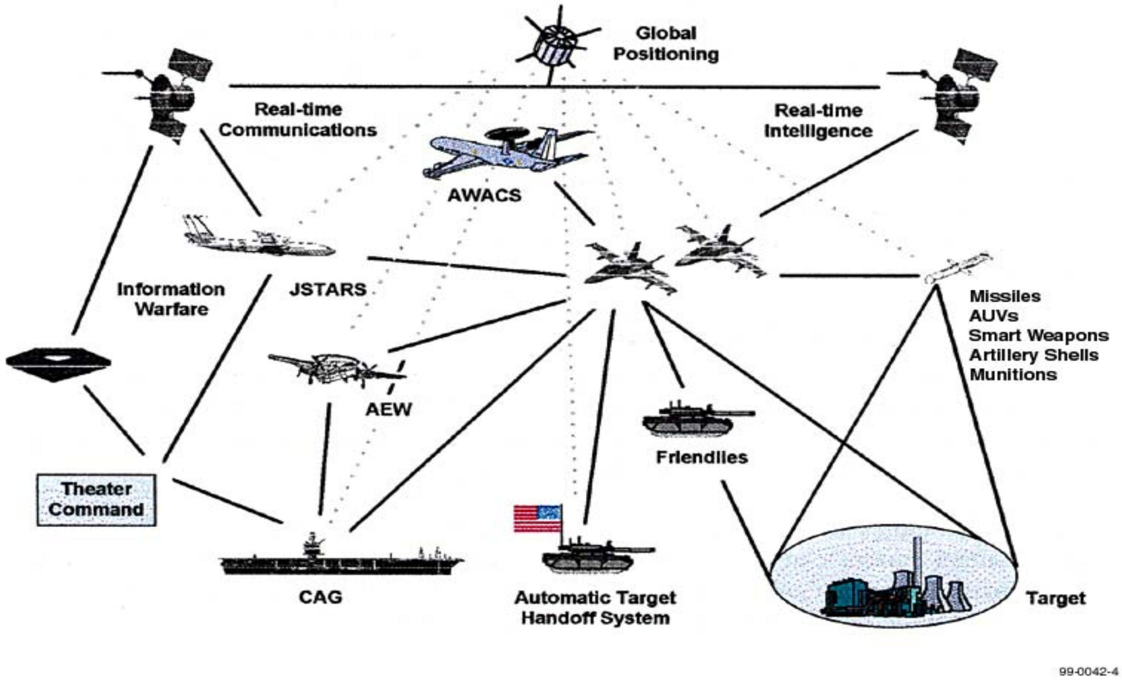

Figure 16.0-1. Concept—Sophisticated Conventional Warfare

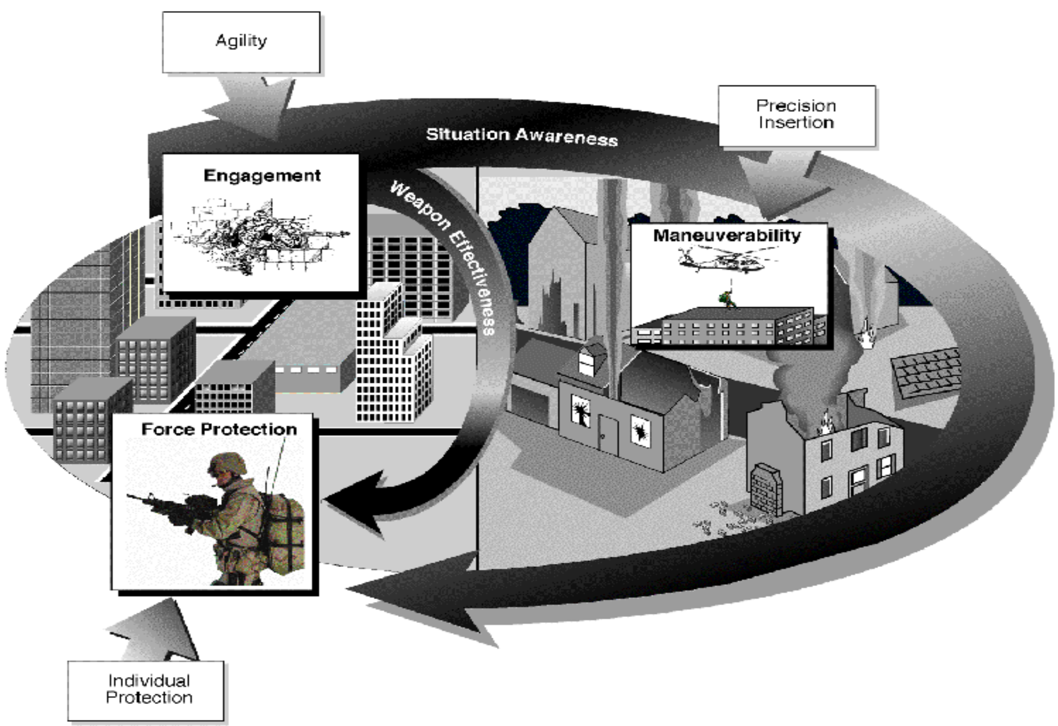

Figure 16.0-2. Concept—Military Operations in Urban Terrain

SECTION 16.1—INERTIAL NAVIGATION SYSTEMS AND RELATED COMPONENTS

Highlights

- Inertial navigation technologies provide an autonomous, covert, and nonjammable 3–D position and velocity reference for land, sea, and space platforms, which will enhance the ability of the military to achieve mission goals.
- Major reduction in manufacturing complexity, size, and cost of INS will be realized by use of MEMS sensors, electronics, and radio-frequency (RF) interfaces. This will allow expanded applications, thereby providing a larger market for more nontraditional manufacturers of inertial navigation technology.
- Through better noise compensation techniques, RLG and FOG will continue to improve free inertial performance (1.0–0.1 nm/hr).
- Future developments in nanotechnology, particularly NEMS accelerometers, may eliminate the need for gyroscopes if quantum noise measurement techniques are resolved.
- Military application of INS with embedded GPS, LORAN, and data-based referenced navigation systems (DBRNS) will increase. These hybrid systems bound the time-dependent errors of the inertial gyroscopes.
- Built-in redundancy through low cost, small size, lightweight, and highly reliable components will allow an affordable, throwaway logistics concept. This will enable a rapid affordable technology insertion of INS technology.

OVERVIEW

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The current major obstacle of more universal INS use is its loss of accuracy over time and high cost. Figures 16.1-1 and 16.1-2 address the key gyroscope and accelerometer performance requirements for military applications, as well the key commercial automotive uses. INS technology has been enormously affected by advances in computer technology (memory and throughput), sensors, power quality, and electronics. Most current INS use optical gyroscopes: RLG or FOGs. RLG and FOG INS technology will continue to improve free inertial sensor performance from 1.0 nmph to less than 0.1 nmph, while decreasing costs.

Future key critical technologies are the emergence of low-cost, microminiaturized INS using MEMS (MEMS could revolutionize navigation). The commercial automotive markets are driving the MEMS technology development. Current MEMS gyroscopes are less than 5 × 1 cm, with an accuracy of 100 deg/hr at a cost of under $50. Industry expectations are to achieve 10 deg/hr by the end of 2000. Depending on military investments in that market, over the next 5–10 years MEMS-type gyroscopes could achieve tactical accuracy of 1.0–0.1 deg/hr.

Future miniaturization using NEMS sensors may be possible. The advantage would be the elimination of the gyroscope, using only accelerometers for sensing linear and rotational acceleration in a 360-deg cluster per axis. The issue is the sensitivity of the accelerometer to detect Earth's gravity because of the sensor's small mass and ability to detect quantum noise levels. Currently, the NEMS market driver is focused on medical commercial applications. Figure 16.1-3 shows the INS technology trends and costs projections over the next 10–20 years across multiple INS users. Figure 16.1-3 also shows that more sensor hybridization will occur over the next 5–10 years as GPS and other telecommunication functions are tightly coupled and integrated with INS. This massive production base, as well as the low cost of MEMS and NEMS sensors, could significantly reduce the cost of many military INS to less than $500. As the cost of INS decreases, their use in commercial applications will increase dramatically, cameras (analogous to weapon sight stabilization) and automotive ride and stability control (analogous to turret stabilization).

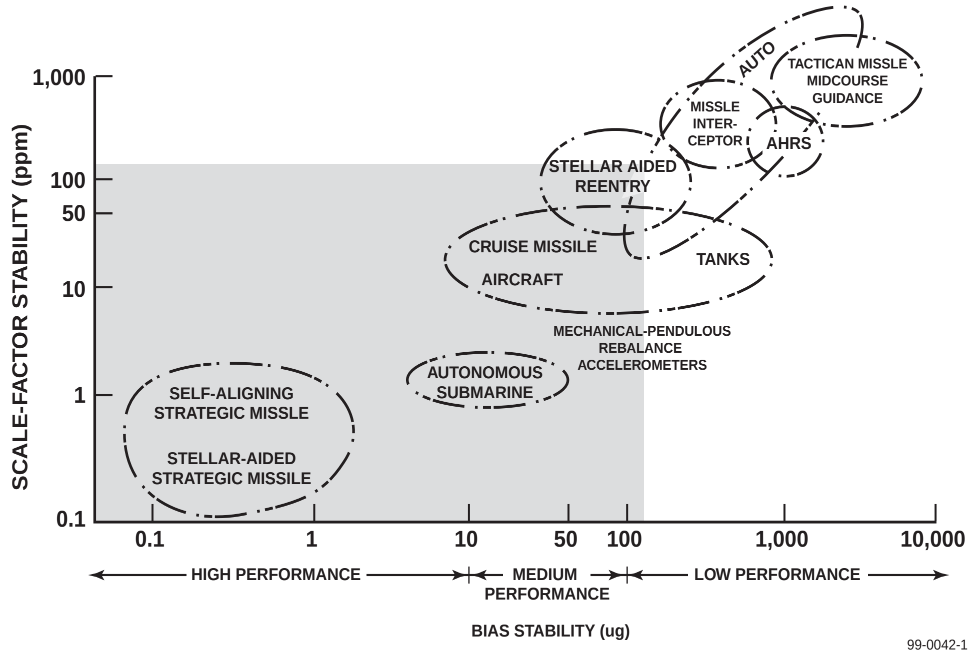

Figure 16.1-1. Accelerometer Technology Applications (shaded area is militarily critical region)

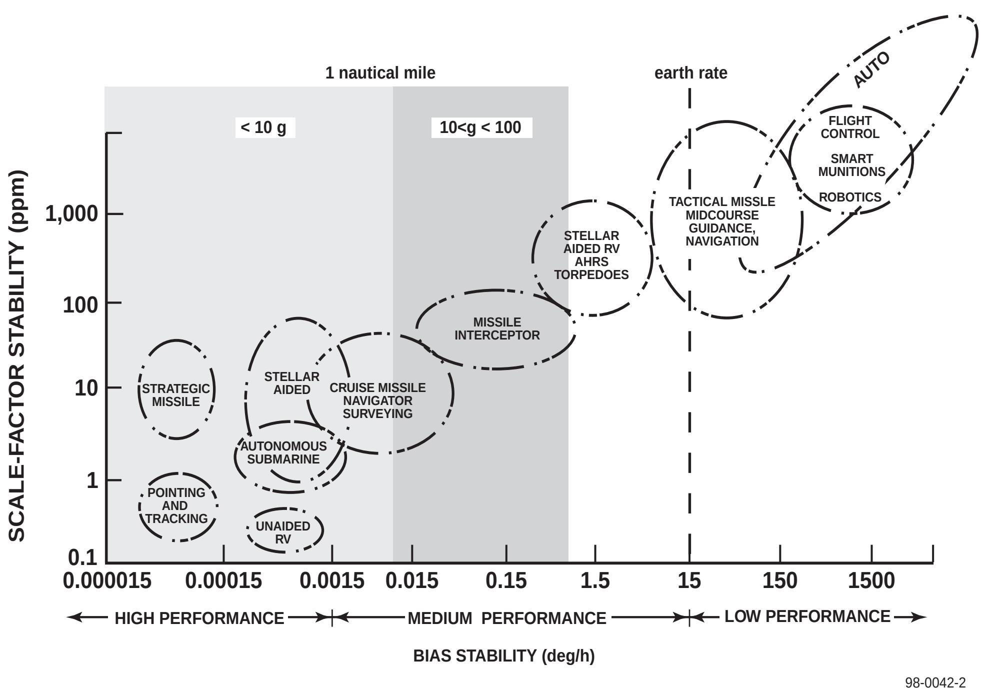

Figure 16.1-2. Gyroscope Technology Applications (shaded areas are militarily critical regions)

Future technology advances in electronic miniaturization, such as GPS on a chip (refer to subsection 16.3), as well as satellite-based telecommunication systems using trilateration timing signals (i.e., Celestri, Teledesic and 911 Cellular), will result in further combination of navigation and communications functions. The degree of coupling of these external and internal sources and the amount of filtering and state vectors in these filters all play a role in determining the accuracy of the resultant hybrid system. Hybrid navigation system technology is now a common topic at international navigation conferences, and the theory and practice of Kalman filters is well known throughout the world. It is possible to procure simulators from a wide range of commercial sources, and the algorithms are published in textbooks and journals.

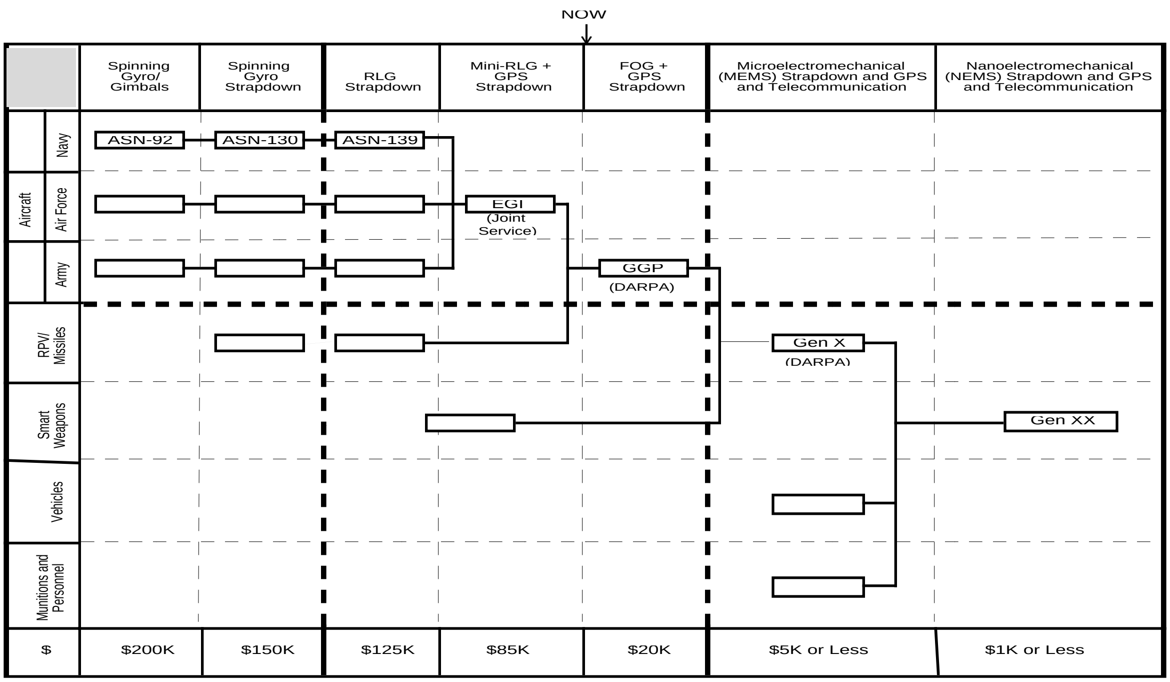

Figure 16.1-3. INS Technology Transition Trends[2]

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2 Excludes ship/submarine INS technology evolution because of its unique performance requirements.

DATA SHEET 16.1. INERTIAL NAVIGATION SYSTEMS

Developing Critical Technology Parameter	In next 5–10 years: For aircraft, vehicle, or spacecraft for attitude, guidance, and control—navigation error < 0.2 nmi/hr 90% CEP. For ships—navigation error of <1.0 nmi in 30 hrs. For missiles—navigation error of <0.8 nmi/hr. Or specified to function at linear acceleration >10 g on any platform. In addition, developing technology will be lighter and cheaper.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment. Ships motion simulator.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. INS alignment time for moving platform and transfer alignment techniques. Algorithms for gyro compensation, Kalman filter implementations, and sensor data processing.
Major Commercial Applications	Aviation, ships, spacecraft.
Affordability	Miniaturization and larger volume markets will significantly reduce costs. Accuracy is a cost driver.

BACKGROUND

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The current major obstacle of more universal INS use is its loss of accuracy over time and high cost. These obstacles are being reduced or eliminated by more accurate gyroscope and accelerometer sensors, as well as advances in computer technology (memory and throughput), power quality, and electronics. Tuned rotor gyros, however, continue to be improved, and the size is decreasing. Land navigation that uses many of the older technologies is still viable, using hybridization with GPS. Over the next 5–10 years, RLG and FOG INS technology will continue to improve its free inertial performance from 1.0 nmph to less than 0.1 nmph, while decreasing costs. Future trends toward using MEMS sensors will continue to significantly decrease the cost of this technology.

Military applications of this technology will enhance the following:

- Vehicle, aircraft, spacecraft, ship, and submarine navigation
- Weather balloon navigation
- AUV navigation
- Air vehicle heading, attitude, and angle of attack
- Accurate velocity for weapon release/targeting
- Search and rescue
- Nuclear reset

- Situation awareness.

This technology supports the Joint Vision 2010 precision engagement by providing both delivery application and low-observable technology. The use of INS during GPS jamming and/or loss and its all-weather capability will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements (such as a cooperative agreement) for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

DATA SHEET 16.1. HYBRID INERTIAL NAVIGATION SYSTEMS (INCLUDING GNSS)

Developing Critical Technology Parameter	In next 5–10 years: For aircraft, vehicle, ship, missile or spacecraft—navigation error <1 m 50-percent spherical error probable (SEP) in position, Or specified to function at linear acceleration >10 g on any platform. In addition, developing technology will be lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Source code for combining INS with Doppler, GNSS, or DBRN. INS initial alignment software for moving platform, transfer align techniques, and reference to geoid.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Accuracy and autonomy are the key drivers. Reduced processor costs and memory will significantly reduce costs.

BACKGROUND

Hybrid INS/GNSS systems combine the best features of different navigation systems to provide an autonomous, covert, and nonjammable system the INS outputs can be optimally combined with GPS to produce a smooth, blended output, and if GPS is lost (or jammed), then the INS will produce a seamless navigation output. In this latter case increased INS performance will result in a more accurate navigation solution after loss of GPS. GPS by itself does not provide a north direction unless the sensor is moving. Therefore, a north reference from a gyrocompass, an INS, or a simple magnetic compass is needed. Using multiple GPS antennas, adequately spaced on a rigid body, will provide position information which can be used to derive an estimate of geographical heading. Future technology advances in electronic miniaturization, as well as satellite-based telecommunication systems using trilateration timing signals, will result in further combination of navigation and communications functions. The degree of coupling of these external and internal sources and the amount of filtering and state vectors in these filters all play a role in determining the accuracy of the resultant hybrid system. Hybrid navigation system technology is now a common topic at international navigation conferences, and the theory and practice of Kalman filters, modern control theory, and other alternative estimation techniques are well known throughout the world. Simulators from a wide range of commercial sources are available, and the algorithms are published in textbooks and journals. Advanced alternative techniques to Kalman filters are routinely presented at international symposia and in the international academic community.

DATA SHEET 16.1. GYRO ASTRO-TRACKING INERTIAL NAVIGATION SYSTEMS

Developing Critical Technology Parameter	In next 5–10 years: Navigation error <0.1 nmph 50% CEP; Azimuth accuracy <50 arc seconds; Or specified to function at linear acceleration >10 g on any platform. In addition, developing technology will be lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters.
Major Commercial Applications	Spacecraft stabilization and basic geodetic research.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

DATA SHEET 16.1. RING LASER GYROSCOPES (RLG)

Developing Critical Technology Parameter	In next 5–10 years: Drift rate stability of <0.005 deg/hr for <10 g, or Drift rate stability of <25 deg/hr for 10 to 100 g, or Specified to function at linear acceleration levels >100 g on any platform. In addition, developing technology will be lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

BACKGROUND

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. RLG inertial sensor improvements are critical to improving accuracy and reducing cost. Targeting, surveillance, and C3 systems require high navigation accuracy. Over the next 5–10 years, RLG technology will continue to improve free inertial sensor performance from 1.0 nmph to less than 0.1 nmph, while decreasing costs. Applications include single-axis and multi-axis (cube) sensors.

DATA SHEET 16.1. FIBER-OPTIC GYROSCOPES (FOG)

Developing Critical Technology Parameter	In next 5 to10 years: Drift rate stability of <0.01 deg/hr for <10 g, or Drift rate stability of <0.25 deg/hr for 10 to 100 g, or Specified to function at acceleration levels >100 g on any platform. In addition, developing technology will be lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

BACKGROUND

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. FOG inertial sensor improvements are critical to improving accuracy and reducing cost. Most current INS use RLGs. INS with FOG are significantly lower in cost than RLGs, and are just now being introduced in applications requiring less accuracy than RLGs. In the next 5–10 years, however, FOG INS technology will continue to improve INS performance from 2.0 nmph to less than 0.4 nmph, while decreasing costs. Further accuracy improvement requires a better gravity model for INS with FOG sensors.

DATA SHEET 16.1. MICROELETROMECHANICAL SYSTEMS (MEMS) GYROSCOPES AND ACCELEROMETERS

Developing Critical Technology Parameter	In next 5–10 years: Gyroscope: Drift rate stability of <0.05 deg/hr for <10 g, or Drift rate stability of <0.5 deg/hr for 10 to 100 g, or Specified to function at linear acceleration levels >100 g on any platform. Accelerometer: Bias stability of 400 µg, or Scale factor stability of 300 ppm.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed manufacturing test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization will increase application of this technology. Larger volume markets will significantly reduce costs.

BACKGROUND

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The current major obstacle of more universal INS use is its loss of accuracy over time and high cost. Improvements of MEMS gyroscopes and accelerometers are critical to improving accuracy and reducing cost. The combination of size, weight, power, and cost requirements are driving the development of MEMS technology. Most current INS use optical gyroscopes such as RLGs or FOGs. MEMS gyroscope and accelerometer technology could continue to improve free inertial sensor performance over the next 5–10 years from 10 nmph to less than 3.0 nmph, while decreasing costs, if quantum noise and frequency measurement issues are resolved. Future trends toward using NEMS sensors will continue to decrease the cost of these sensors. Applications include single-axis and multi-axis (cube) sensors.

DATA SHEET 16.1. ACCELEROMETERS OTHER THAN MICRO-MACHINED DEVICES

Developing Critical Technology Parameter	In next 5–10 years: Bias stability of <100 µg, or Scale factor stability of <80 ppm, or Specified to function at linear acceleration levels > 100 g on any platform. In addition, developing technology will be lighter and less expensive by factor of ten.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment; accelerometer axis align stations; ion milling; Plaza Arc; electronic sputtering.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

BACKGROUND

This technology is a major component of an INS that is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The current major obstacle of more universal INS use is its loss of accuracy over time and high cost. Improvements in accelerometers other than micro-machined devices are critical to improve accuracy and reduce cost. Future trends toward using MEMS sensors will continue to decrease the cost of this technology.

DATA SHEET 16.1. NANOELECTROMECHANICAL SYSTEMS (NEMS) ACCELEROMETERS

Developing Critical Technology Parameter	In next 10 to 20 years: Bias stability of <200 µg, or Scale factor stability of <200 ppm, or Specified to function at linear acceleration levels > 100 g on any platform. In addition, developing technology will be lighter and less expensive by factor of ten.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment; accelerometer axis align stations.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters Error compensation for environmental effects and technology characteristics
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

BACKGROUND

This technology has the potential of providing a significant reduction in the cost of an INS. INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs This technology is currently in its embryonic stage, with limited R&D investments. Over the next 10–20 years, however, development of NEMS accelerometers has the greatest potential to bring INS technology to applications, providing autonomous navigation at significantly reduced cost.

SECTION 16.2—GRAVITY METERS AND GRAVITY GRADIOMETERS

Highlights

- Gravity sensor arrays will be more viable due to accurate time sequencing, computer speed, and memory advances.
- Uncompensated gravity disturbances are a large error source for INS initialization and subsequent field operation. Future gravity models will enable more accurate INS compensation.
- Use of a worldwide gravity database based on better instrumentation and storage/access capabilities, in conjunction with on-board gravity sensors, will provide autonomous and continuous updates to INS, yielding comparable accuracy with projected INS/GPS hybrid systems.
- A developing technology to compute real-time gravity data from a moving platform may use the difference in acceleration data from an uncompensated INS and the GNSS.

OVERVIEW

This evolving and developing technology is used to measure a body's gravity field (such as Earth's), which in turn has applications for detection and localization of mass distributions, covert position determination, and inertial navigation compensation. Increasingly, gravity data will play a major and critical role in future navigation systems. Accurate geodetic and geophysical data (G&G) can improve the performance of inertial navigation systems to what may be near-GPS accuracy. G&G-enhanced INS could prove to be a significant navigation asset when GPS is not available.

Present aircraft and ship INS use coarse models of Earth's gravity to correct for the sensed acceleration of gravity by the system sensors. Gravity anomalies that are not modeled are a major error source and limit the dynamic performance of deployed INS. Gravity meters and gravity gradiometers are used in static or mobile modes to measure gravity disturbances, deflections of the vertical, and to characterize the 3–D gravity vector.

G&G data is used to ground align and provide real-time, in-flight updates of local gravity to navigation systems. Commercially, gravity meters and gradiometers are used to assist in exploration for oil, gas, or minerals by measuring the variations in the magnitude of the gravity vector or the variation in the gravity gradients. Furthermore, G&G data can be assimilated into "gravity maps" in support of data-based, POSITIME-referenced navigation systems (see subsection 16.3).

International cooperative efforts through the International Association of Geodesy (IAG) exist for comparing absolute gravity standards.

BACKGROUND

The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect—and most common—compensation technique uses vertical deflection map data computed from gravity-meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. In the latter mode, the spatial gravity gradients are multiplied (scalar product) by the velocity vector and integrated to obtain the vertical deflection in real time.

This technology involves the use of gravity meter or gravity gradiometer in a map-matching mode for accurate position determination using previously surveyed map data. Due to roll off of the high frequencies in the gravity anomaly field with altitude, these accuracies could only be obtained at low altitude, if at all. Navigation at GPS accuracy through turns and acceleration is questionable, but could potentially be recovered afterward. These map-matching techniques using sensors giving data only along the flight path are questionable for long-term navigation, as there are likely to be areas where the data does not have adequate spatial variance to achieve these accuracies. In a local area, with proper conditions for the sensor type being used, these POSITIME methods might be useful. Gravity meters and gravity gradiometers require stabilization and the associated software to maintain a stable reference frame. The resulting hybrid system has the potential to provide the military with a non-emanating, nonjammable, totally covert system that can be used worldwide for navigation. As noted, the system will require previously surveyed gravity map data as well as a sufficiently distinct gravity signature that can be detected in the background noise. When there is not an adequate signature, the system may be augmented with magnetic signature map matching (see subsection 16.4). Another developing method of determining gravity is by computing the acceleration difference between an uncompensated INS and a GNSS. As measured by a GNSS, the computed acceleration of the platform is the pure acceleration of the vehicle, while the acceleration measured by an uncompensated INS contains the gravity vector and the platform acceleration vector. The difference is the gravity vector.

LIST OF TECHNOLOGY DATA SHEETS
16.2. GRAVITY METERS AND GRAVITY GRADIOMETERS

Gravity Meters (Gravimeters), Nonmobile Use.................... 16-17

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Gravity Gradiometers, Mobile Use.................... 16-20

DATA SHEET 16.2. GRAVITY METERS (GRAVIMETERS), NONMOBILE USE

Developing Critical Technology Parameter	In next 5–10 years: Accuracy of <50 μgals with a time-to-steady-state registration of less than 2 minutes under any combination of attendant corrective compensation. Continuing development of arrays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	SQUID sensors require superconducting temperature Dewars.
Unique Software	Algorithms and verified data for real-time gravity compensation and detection (improvement >10–1) for operation using arrays.
Major Commercial Applications	Resource exploration. Detection of underground structures.
Affordability	Cost is proportional to usage. This is not a large-volume production technology. One of the largest manufacturers has sold only about 1,500 units in the last 40 years.

BACKGROUND

Gravity meters are a POSITIME-influenced technology because of the interrelationship of gravity data with position and time and the need for verticality for sensor stabilization.

The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect, and most common, compensation technique uses vertical deflection map data computed from gravity meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. This technology involves the use of a gravity meter in a map-matching mode for accurate position determination using previously surveyed map data. Due to roll off of the high frequencies in the gravity anomaly field with altitude, this accuracy could only be obtained at ground level or low altitude, if then. In a local area, with proper conditions for the sensor type being used, these methods might be useful.

DATA SHEET 16.2. GRAVITY METERS (GRAVIMETERS), MOBILE USE

Developing Critical Technology Parameter	In next 5–10 years: Moving platform accuracy of <75 µgals with a time-to-steady-state registration of less than two minutes under any combination of attendant corrective compensation. Continuing development of arrays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test, calibration, modeling, compensation, or alignment equipment to obtain mobile accuracy. Accelerometer axis align stations.
Unique Software	Algorithms and verified data for real-time gravity compensation and detection (improvement >10–1) for operation on mobile platforms or using arrays and time compensation, or both.
Major Commercial Applications	Resource exploration. Underwater terrain estimation. Detection of underground structures.
Affordability	Cost is proportional to usage. This is not a large-volume production technology.

BACKGROUND

Gravity meters on a moving platform are a POSITIME-influenced technology because of the interrelationship of gravity data with position and time and the need for velocity and verticality compensation for sensor stabilization.

The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect—and most common—compensation technique uses vertical deflection map data computed from gravity meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. In the latter mode, the spatial gravity gradients are multiplied (scalar product) by the velocity vector and integrated to obtain the vertical deflection in real time.

This technology involves the use of a gravity meter in a map-matching mode for accurate position determination using previously surveyed map data. Due to roll off of the high frequencies in the gravity anomaly field with altitude, this accuracy could only be obtained at low altitude, if at all. Navigation at GPS accuracy through turns and acceleration is questionable, but could potentially be recovered afterward. These map-matching techniques using sensors giving data only along the flight path are questionable for long-term navigation, as there are likely to be areas where the data does not have adequate spatial variance to achieve this accuracy. In a local area, with proper conditions for the sensor type being used, these methods might be useful.

Gravity meters require stabilization and the associated software to maintain a stable reference frame. As noted, the system will require previously surveyed gravity map data as well as a unique gravity signature, which can be detected in the background noise. When there is not an adequate signature, the system may be augmented with magnetic signature map matching (see subsection 16.4).

Another developing method of determining gravity is by computing the acceleration difference between an uncompensated INS and a GNSS. The computed acceleration of the platform, as measured by a GNSS, is the pure acceleration of the vehicle, while the acceleration measured by an uncompensated INS contains the gravity vector and the platform acceleration vector. The difference is the gravity vector. Advanced filtering using optical correlators/processors and GNSS time synchronization are enabling technologies to obtain the gravity vector.

DATA SHEET 16.2. GRAVITY GRADIOMETERS, NONMOBILE USE

Developing Critical Technology Parameter	In next 5–10 years: Static platform <0.02 Eotvos/√Hz. Continuing development of arrays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test, calibration, modeling, compensation, or alignment equipment to obtain static accuracy of sensor. Accelerometer axis align stations. SQUID sensors require superconducting temperature Dewars.
Unique Software	Algorithms and verified data for real time gravity compensation and detection (improvement > 10–1) for operation using arrays.
Major Commercial Applications	Resource exploration. Detection of underground structures such as sink holes.
Affordability	Cost is proportional to usage. This is not a large-volume production technology.

BACKGROUND

Gravity gradiometers are a POSITIME-influenced technology because of the interrelationship of gravity data with position and time and the need for verticality for sensor stabilization.

The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect—and most common—compensation technique uses vertical deflection map data computed from gravity-meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. Gravity gradiometers require stabilization and the associated software to maintain a stable reference frame.

DATA SHEET 16.2. GRAVITY GRADIOMETERS, MOBILE USE

Developing Critical Technology Parameter	In next 5–10 years: Moving platform <5 Eotvos/√Hz. Continuing development of arrays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test, calibration, modeling, compensation, or alignment equipment to obtain mobile accuracy of <5 Eotvos/√Hz. Accelerometer axis align stations.
Unique Software	Algorithms and verified data for real-time gravity compensation and detection (improvement >10–1) for operation on mobile platforms, using arrays and time compensation, or both.
Major Commercial Applications	Resource exploration. Underwater terrain estimation. Detection of underground structures such as sink holes.
Affordability	Cost is proportional to usage. This is not a large-volume production technology.

BACKGROUND

Gravity gradiometers are a POSITIME-influenced technology because of the interrelationship of gravity data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. Gravity meters can be used to correct, either directly or indirectly, for the local gravity disturbances or vertical deflection on a moving base/platform. The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect—and most common—compensation technique uses vertical deflection map data computed from gravity-meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. In the latter mode, the spatial gravity gradients are multiplied (scalar product) by the velocity vector and integrated to obtain the vertical deflection in real time.

This technology involves the use of a gravity gradiometer in a map-matching mode for accurate position determination using previously surveyed map data. Due to roll off of the high frequencies in the gravity anomaly field with altitude, this accuracy could only be obtained at ground level and at low altitude, if then. Navigation at GPS accuracy through turns and acceleration is questionable, but the errors could perhaps be rectified afterward. These map-matching techniques using sensors giving data only along the flight path are questionable for long-term navigation, as there are likely to be areas where the data does not have adequate spatial variance to achieve this accuracy. In a local area, with proper conditions for the sensor type being used, these methods might be useful.

Another developing method of determining gravity is by computing the acceleration difference between an uncompensated INS and a GNSS. As measured by a GNSS, the computed acceleration of the platform is the pure acceleration of the vehicle, while the acceleration measured by an uncompensated INS contains the gravity vector and the platform acceleration vector. The difference is the gravity vector. Accurate time is required for compensation. A controlled vibration and acceleration environment is required to improve accuracy. Advanced filtering using optical correlators/processors and GNSS time synchronization are enabling technologies to obtain the gravity vector with better accuracy.

SECTION 16.3—RADIO AND DATA-BASED REFERENCED NAVIGATION (DBRN) SYSTEMS

Highlights

- With the discontinuance of the U.S. GPS Selective Availability (S/A)[3] and the use of Differential GPS (DGPS) combined with LORAN and improved LORAN, a navigation accuracy of less than 1 m (6 sigma)/0.3 m (SEP) can be provided to both friends and foes.
- Autonomous and common 3–D POSITIME grid reference will improve battlespace situational awareness by providing a precise POSITIME tag on all battlespace information collected to provide real-time knowledge of location and movement across battlespace of allied and enemy assets.
- Significant commercial and military growth and dependence on GNSS for position and time will increase as GNSS receivers decrease in cost, weight, and power.
- International GNSS (GLONAS, European Union 2, and Teledesic) capabilities will continue to be developed as alternatives to the U.S. GPS, as a means of providing better redundancy and integrity monitoring, or both.
- Increased combination of hybrid navigation and adaptive antenna systems will significantly reduce military dependence on GPS in a jamming combat environment or during signal loss. Future increased combinations of navigation, communication, imaging, and computer functions will improve situational awareness in urban terrain.
- Data-based referenced navigation technology, leveraged by increased computer speed and memory, will have increased commercial and military usage.

OVERVIEW

Radio navigation, particularly GPS and LORAN, will continue to be used both by military and commercial users in the foreseeable future. Radio navigation continues to be the smallest and least expensive of the POSITIME systems. The ratio of commercial to military use of GPS and LORAN will probably be greater than 100:1. There is a definite trend to transition GPS from a DoD system to a commercial system. With S/A off, the 10 m accuracy will be available worldwide for all commercial users, who previously were limited to 100-m accuracy. The S/A had previously limited this 10 m accuracy to U.S. and allied military use only.

Another issue is the emergence of DGPS, which uses a small ground station outfitted with a GPS receiver whose geographic location is precisely determined, and the difference between surveyed and GPS position transmitted to another user. This procedure can provide an accuracy of better than 5 m. In Europe, a novel technique that transmits DGPS signals on an existing LORAN C, called Eurufix, has demonstrated position-fixing accuracy of better than 3 m. Localized jamming by friendly forces will deny these accurate GPS capabilities to an enemy only if the basic GPS signal is completely jammed. Antijam GPS components and systems, such as an adaptive antenna system, combined with high-speed digital signal processing (DSP) and a closely coupled hybrid GPS/INS will optimize antenna coverage patterns to specific signal and interference environments. This will produce an antenna pattern with nulls in the direction of broadband jammers very quickly. Better time accuracy (see subsection 16.5) will allow rapid GPS direct-Y code acquisition, and the use of autonomous, low-power clocks will minimize GPS jamming and loss of satellite signal. In urban areas, loss of GPS signals due to signal blockage and multipath problems is a challenge to be overcome. Like all time difference of arrival (TDOA) systems, the LORAN system

[3] President Bill Clinton, the White House, 1 May 2000.

accuracy can be improved by more accurate clocks. Similar to GPS receiver improvements and miniaturization, LORAN antenna and electronic miniaturization technology continues to improve LORAN receiver capability. Funding for continuation of LORAN ground stations because of the growing number of commercial applications continues to force the Federal Radio Navigation Plan to be revised, and the demise of LORAN is not as evident as it was five years ago.

Further GNSS improvements include:

- Upgrades to U.S. GPS/NAVSTAR capabilities to include incorporation of unencrypted C/A codes on L2, inclusion of third civilian frequency, inclusion of new encrypted military codes on L1 and L2, increase in transmission power, and potential increase in number of space vehicles.
- Integration of European Union Galileo public/private GNSS with the U.S. GPS system.
- Improvements in space vehicle orbital definition, increased ground station update frequency, and incorporation of more accurate ionospheric correction models on GNSS accuracy.
- Use of ground-based transmitters to provide wide area DGNSS corrections.
- Use of satellites (GEO and LEO) to provide wide area DGNSS corrections, particularly to aviation.
- Impact of FAA efforts to utilize DGNSS-based en-route and precision landing guidance through the WAAS and LAAS programs and the worldwide proliferation of compatible technology.
- The use of pseudolites (airborne and ground based) for military application and precision landing support (as envisioned in LAAS).

Further improvements to GPS accuracy, as well as reducing susceptibility to jamming, will be obtained by integration with the following Digital Terrain Data Based Navigation Systems:

- Digital Terrain Elevation Data (DTED)
- Digital Feature Analysis Data (DFAD)
- The World Geodetic System (WGS 84)
- The Earth Gravitational Model (EGM 96)
- The International Terrestrial Reference Frame (ITRF).

One of the deficiencies of GPS is that map referencing is not viable unless the receiver is moving to compute directional referencing (north). A magnetic compass or an INS is required for map referencing.

The Shuttle Radar Topography Mission (SRTM) will collect radar data over more than 80% of the earth. Table 16.3-1 shows the projected improvements in DTED accuracy.

Table 16.3-1. Comparison of Current and Projected Digital Terrain Elevation Data (DTED) Accuracy

	Absolute Horizontal	Absolute Vertical	Time Frame
Current DTED	50 m 90% CE	30 m 90% LE	Now
Expected DTED w/SRTM	20 m 90% CE	16 m 90% LE	2000+
Future Possibilities*	5–10 m 90% CE	5–10 m 90% LE	2015+

* Requires more accurate determination of the space vehicle’s attitude/altitude for images.

Recent improvement in the EGM 96 has decreased absolute height uncertainty from 2–6 m (1 σ) to 0.5–1 m (1 σ) worldwide. This will benefit not only GPS but also INS accuracy. Figure 16.3-1 shows hybrid INS/GPS accuracy with use of geomapping data after loss of GPS. Closely monitoring WGS and ITRF has led to improvements in the level of agreement between WGS 84 and the ITRF, with the determination that they can now be considered equivalent.[4] While the GPS reference is WGS-84, the Russian GLONASS reference is PZ-90. The transformation model is developed and is being refined by the United States and Russians.[5]

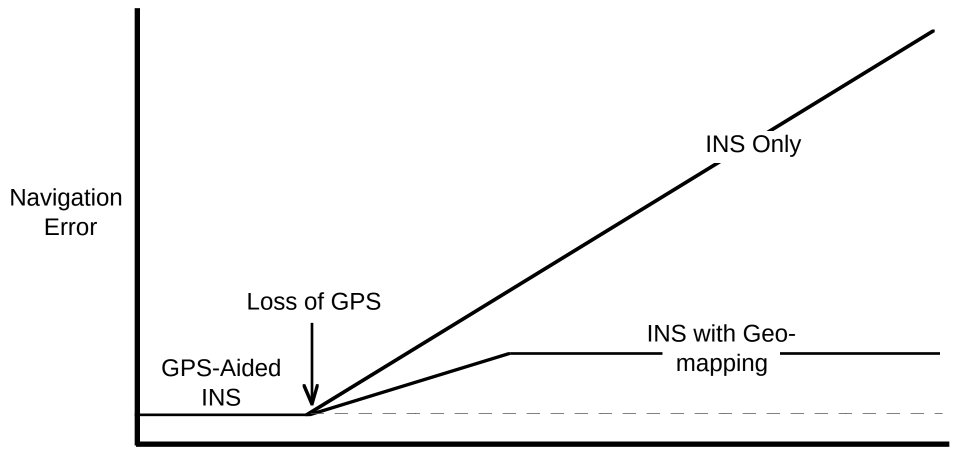

Figure 16.3-1. Hybrid INS Performance with Loss of GPS

The integration of 3–D digital terrain maps and other geo-mapping data [provided by NIMA and U.S. Geological Survey's National Mapping Division's Earth Resources Observation Systems (EROS)] with hybrid INS/GPS systems could subsequently provide highly accurate position, velocity, and track under dynamic and covert conditions, even after loss of GPS signals.

In addition, future improvements to 3–D digital map data could include global magnetic and gravity data. As a point of reference, given a gravity map having an accuracy of 1 Eotvos/√Hz) and resolution of 0.5 km, an aircraft flying at 200-m altitude at 360 km/hr constant velocity, having a 10 Eotvos/√Hz) gravimeter on board with a 0.0001 deg/hr drift rate gyro, could navigate with 5–10 m horizontal error and 5-m vertical error. All of these capabilities (by use of prestored ground and undersea terrain contour, acoustic, electromagnetic spectrum, magnetic, and gravity sensor data) will significantly increase the hybrid INS accuracy on a continuous basis to that currently provided by GPS at a rate of 1.0 Hz.

BACKGROUND

Accurate positioning, control, and redundancy for platforms are essential for effective coordination of military activities. Individual system accuracy depends on mission requirements. Encrypted signals of the GPS deny non-authorized users the full capability of the systems. Null-steerable antennas are a military response to jamming. Hybrid and DBRN systems combine the best features of different navigation systems to provide autonomous, covert, nonjammable information. DBRN technology is partially derived from sensor and Geographic Information Systems (GIS) technology. DBRN technology, leveraged by computer speed and memory, resolves data ambiguities and optimizes navigational sensor and stored data. Three-dimensional position ambiguities and other properties, such as magnetic and gravity signatures, will be resolved and optimized as stored geodetic data for navigation reference using sensors such as radar altimeters, magnetometers, gravity meters, and acoustic sensors. The use of power management and phase-shift key modulation reduces the emitted signal, resulting in a decreased detectability and covert (stealth) operation. Military uses for GPS will enhance the following:

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[4] *Refinements to the World Geodetic System*, 1984, by Stephen Malys, et al., NIMA.

[5] *GPS World*, January 1999, p. 54.

- Supply location systems
- Spacecraft navigation
- Parachute insertion
- Air vehicle attitude
- Angle of attack
- Battlefield targeting
- Helicopter hover positioning
- Gravity measuring system
- HF communications frequency management
- Encryption/decryption
- DGPS
- Ship cargo management
- Situation awareness
- Minefield positioning
- Search and rescue
- Weather balloon navigation
- Power and communication line failures
- Inertial navigator reset and mapping
- System integration of sensors
- Pseudolite positioning system
- Position reporting for high-value assets
- AUV navigation
- Imaging
- Artillery smart round
- DGPS for heading
- Nuclear reset
- Construction

FAA's WAAS corrects the standard GPS signal to provide the accuracy, integrity, and availability needed for civil aviation navigation and precision approaches (Category 1) over a very large geographical area. Some of the critical functions include corrections for navigation satellite clock, satellite orbital data, and the effects of the ionosphere on the GPS and WAAS signals and ensuring the validity of WAAS messages. WAAS will use Geostationary satellites (space-based) transmitting GPS look-alike ranging signals, but with integrity messages and wide-area differential corrections. The LAAS is a ground-based augmentation system providing local area DGPS corrections. DGPS is based on providing corrections of errors that are common to both ground-based and aircraft receivers in the local area. LAAS has the capability of providing integrity using pseudolites (ground-based, low-powered satellites) and DGPS for accuracy of about 1 m on final approach and taxi. LAAS complements WAAS and will operate independently. For decades, the dismounted soldier's navigation tools have consisted of maps, compass, and individual pace count. Recently, GPS technology has been added to the tool set to improve position determination. Although a significant improvement, GPS can be jammed or blocked (terrain or man-made obstructions), and GPS does not provide accurate azimuth information at slow speeds for map north referencing. Integrated navigation (INAV) technology introduces a new tool to help compensate for those times when GPS is either unavailable or unreliable—automated dead reckoning. INAV dead-reckoning capability is supplied by a dead-reckoning module (DRM), a small, low-power navigator consisting of an electronic compass and a pedometer using MEMS technology accelerometers.

LIST OF TECHNOLOGY DATA SHEETS
16.3. RADIO AND DATA-BASED REFERENCED NAVIGATION SYSTEMS

Global Navigation Satellite Systems (GNSS) 16-26
Differential Global Navigation Satellite Systems (DGNSS) 16-27
Hybrid Radio Navigation Systems 16-28
Low Probability of Intercept (LPI) Radar Altimeters 16-30
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GNSS Anti-jam Components and Systems (Adaptive Narrowband Filters) 16-34
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DATA SHEET 16.3. GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

Developing Critical Technology Parameter	In next 5–10 years: Signal decryption (antispoof) and/or null-steerable antenna, jamming protection; Accuracy (w/o S/A) of <1 m 50% SEP in position and <1 picosecond in time. <0.1 m/s velocity for >60,000 ft and for > 1,000 kts—lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Antispoofing (A-S); signal simulators and A-S < 1 picosecond measurement capability; electronic counter-countermeasures (ECCM) or interference resistance receivers.
Unique Software	Algorithms including classified, encrypted algorithms and verified data; vehicle attitude determination; direct Y-code algorithms verified through tests; A-S source code verified.
Major Commercial Applications	Ground vehicle navigation, aircraft navigation, surveying.
Affordability	Accuracy and autonomy are the key drivers. Reduced processor costs and memory will significantly reduce costs.

BACKGROUND

FAA's WAAS corrects the standard GPS signal to provide the accuracy, integrity, and availability needed for civil aviation navigation and precision approaches (Category 1) over a very large geographical area. Some of the critical functions include corrections for navigation satellite clock, satellite orbital data, and the effects of the ionosphere on the GPS and WAAS signals and ensuring the validity of WAAS messages. WAAS uses Geostationary satellites (space-based) transmitting GPS look-alike ranging signals with integrity messages and wide-area differential corrections. The LAAS is a ground-based augmentation system providing local area DGPS corrections. DGPS is based on providing corrections of errors that are common to both ground-based and aircraft receivers in the local area. LAAS has the capability of providing integrity using pseudolites (ground-based, low-powered satellites) and DGPS for accuracy of less than 1 m on final approach and taxi. LAAS complements WAAS and will operate independently. The implementation of these functions combined with the growing reliance on GPS by the world commercial airline industry has created a special area of concern for military planners.

DATA SHEET 16.3. DIFFERENTIAL GLOBAL NAVIGATION SATELLITE SYSTEMS (DGNSS)

Developing Critical Technology Parameter	In next 5–10 years: Accuracy of <0.3 m 50% SEP in position and <1 picosecond in time; <0.01 m/s velocity >60,000 ft and >1,000 kts—lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Algorithms including classified, encrypted algorithms and verified data; differential techniques that provide accuracy of <0.3 m.
Unique Software	Algorithms including classified, encrypted algorithms and verified data needed to exceed military critical parameters; differential techniques that provide accuracy of <0.3 meter; Algorithms that handle corrected pseudorange, delta range, and satellite start/stop position (corrected ephemeris) data and the source code for combining INS with GPS.
Major Commercial Applications	Ground vehicle navigation, aircraft navigation, and surveying.
Affordability	Accuracy and autonomy are the key cost drivers.

BACKGROUND

DGPS uses a small ground station outfitted with a GPS receiver, the geographic location of which is precisely determined; the difference between surveyed and GPS position is transmitted to another user via a different frequency. This procedure can provide an accuracy of much better than 1 m. In Europe, a novel technique that transmits DGPS signals on an existing LORAN C, called Eurufix, has demonstrated position-fixing accuracy of better than 3 m.

DATA SHEET 16.3. HYBRID RADIO NAVIGATION SYSTEMS (OTHER THAN INERTIAL NAVIGATION)

Developing Critical Technology Parameter	In next 5–10 years: Accuracy of <1 m 50% SEP in position. Jamming protection <0.01 m/s velocity >60,000 ft and >1,000 kts. For spacecraft—Pointing accuracy of <10 arc sec—lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment; GNSS receivers require special simulator testing systems. Specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters Source code for combining GNSS with Doppler, LORAN, or DBRN.
Major Commercial Applications	Ground vehicle navigation, aircraft navigation.
Affordability	Accuracy and autonomy are the key cost drivers.

BACKGROUND

GPS accuracy will improve from 3 m–1 m as a result of recent efforts to link the GPS tracking networks, upgraded Kalman filtering, and reduced prediction error in broadcast NAV messages. Using fixed location sites, DGPS can further improve the GPS accuracy to less than 0.3 m. The use of DGPS, however, is currently limited to a localized area and the use of communications that may also be susceptible to jamming. In addition, hybrid GPS systems have better redundancy and integrity monitoring capabilities.

Like all TDOA systems, the LORAN system accuracy can be improved by more accurate clocks. Similar to GPS receiver improvements and miniaturization, LORAN antenna and electronic miniaturization technology continues to improve LORAN receiver capability. Funding for continuation of LORAN ground stations because of the growing commercial applications continues to force the Federal Radio Navigation Plan to be revised, and the demise of LORAN is not as evident as five years ago.

Radio ranging using normal tactical or commercial communications systems will be a mature technology within 5–10 years.

Further improvements to GPS accuracy, as well as reducing susceptibility to jamming, will be obtained by integration with other radio ranging systems and the following Digital Terrain Data-Based Navigation Systems:

- Digital Terrain Elevation Data (DTED)
- Digital Feature Analysis Data (DFAD)
- The World Geodetic System (WGS 84)
- The Earth Gravitational Model (EGM 96)
- The International Terrestrial Reference Frame (ITRF).

In addition, future improvements to 3–D digital map data could include global magnetic and gravity data. As a point of reference, given a gravity map having an accuracy of 1 Eotvos/√Hz and resolution of 0.5 km, an aircraft flying at 200-m altitude at 360 km/hr constant velocity, having a 10 Eotvos/√Hz gravimeter on board with a 0.0001 deg/hr drift rate gyro, could navigate with 5–10 m horizontal error and 5 m vertical error. All of these capabilities (by use of prestored ground and undersea terrain contour, acoustic, electromagnetic spectrum, magnetic, and gravity sensor data) will significantly increase the hybrid INS accuracy on a continuous basis to that currently provided by GPS at a rate of 1.0 Hz.

DATA SHEET 16.3. LOW PROBABILITY OF INTERCEPT (LPI) RADAR ALTIMETERS

Developing Critical Technology Parameter	In next 5–10 years: Nondetectable in radar frequency range. Integrated with LPI limited-range, forward-looking sensor and terrain databases for better situational awareness in low-altitude terrain avoidance. Altitude accuracy: ±1 foot at 0–5,000 ft. ±25 feet at 5,000–60,000 ft.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Cross-correlation algorithms and verified data.
Major Commercial Applications	General aviation, particularly helicopters. However, commercial applications are very limited at this time.
Affordability	The all-digital approach will result in decreasing cost and increasing applications, including commercial.

BACKGROUND

The use of power management and phase-shift key modulation reduces the emitted power of the radar altimeter system. Altitude above ground is a critical parameter for aircraft. LPI imaging radars use a millimeter-wave radar that is scanned to provide all-weather imaging. The application is for terrain following and landing approaches.

DATA SHEET 16.3. DATA-BASED REFERENCED NAVIGATION SYSTEMS (Data-Based Digital Terrain, Acoustic, Bathymetric, Electromagnetic Spectrum, Magnetic, Gravity, and Stellar Referenced Navigation)

Developing Critical Technology Parameter	In next 5–10 years: Accuracy < 5- to 10-m grid accuracy.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Unique computer test models for optimization of database manipulation and extraction.
Unique Software	Algorithms for image correlation and pattern recognition. Integration and data analysis algorithms and verified data.
Major Commercial Applications	Ground vehicle navigation, aircraft navigation, ship and submersible navigation surveying.
Affordability	Lighter and less expensive will open more commercial applications.

BACKGROUND

Further improvements to DBRNS is expected to provide an autonomous navigation capability, when GPS is jammed or unavailable (i.e., urban areas). The following are the key data bases that could provide improved accuracy with or without GPS, as an autonomous navigation or terminal guidance system:

- Digital Terrain Elevation Data (DTED)
- Digital Feature Analysis Data (DFAD)
- The World Geodetic System (WGS 84)
- The Earth Gravitational Model (EGM 96)
- The International Terrestrial Reference Frame (ITRF).

The SRTM will collect radar data over more than 80 percent of the Earth. This is a major step toward the multi-Service requirement for DTED accuracy of 30 m by 2000. Table 16.3-1 shows the projected improvements in DTED accuracy.

Recent improvement in the EGM 96 has decreased absolute height uncertainty from 2–6 m (1 σ) to 0.5–1 m (1 σ) worldwide. This will benefit not only GPS but also INS accuracy. Closely monitoring WGS and ITRF has led to improvements in the level of agreement between WGS 84 and the ITRF with the determination that they can now be considered equivalent.[6]

[6] *Refinements to the World Geodetic System*, 1984, by Stephen Malys, et al., NIMA.

Table 16.3-1. Comparison of Current and Projected Digital Terrain Elevation Data (DTED) Accuracy

	Absolute Horizontal	Absolute Vertical	Time
Current DTED	50 m 90% CE	30 m 90% LE	now
Expected DTED w/SRTM	20 m 90% CE	16 m 90% LE	2000+
Future Possibilities*	5–10 m 90% CE	5–10 m 90% LE	2015+

* Requires more accurate determination of the space vehicle attitude/altitude for images.

The integration of 3–D digital terrain maps and other geo-mapping data (provided by NIMA and U.S. Geological Survey's National Mapping Division's EROS) with hybrid INS/GPS systems could provide highly accurate position, velocity, and track under dynamic and covert conditions, even after loss of GPS signals.

DATA SHEET 16.3. GNSS ANTI-JAM COMPONENTS AND SYSTEMS (ADAPTIVE ANTENNA SYSTEMS)

Developing Critical Technology Parameter	In next 5–10 years: Fully integrated multiple-element antenna array and antenna electronics (e.g., signal processing unit). Interface to GPS receiver: RF or intermediate frequency (IF) signal. Creates nearly uniform hemispherical gain pattern when there is no external RF interference. Gain better than – 3.5 dB (over a 160-deg solid angle). Creates, in the presence of multiple RF sources, a null in the direction of unintentional or intentional interference signals. Null depth >25 dB. Adaptive speed <10 microseconds. Creates, in the presence of multiple RF sources, an antenna gain in the direction desired GPS satellite: gain >10 dB. Overall processing gain: GPS receiver, antenna, and antenna electronics: >61 dB total.
Critical Materials	Materials to implement low-observable requirements may or may not be used.
Unique Test, Production, Inspection Equipment	Test suppression capability verified at NAVSTAR GPS L2 or L1 frequencies. Test scenario(s) used GPS signal in space (SIS), or GPS signal simulator which generates the GPS wave front. (Simulated RF interference source injected or not injected in test scenario.) Operating bandwidth >20 MHz (centered at L1 or L2). Characteristic or types of RF interference source used (i.e., wideband Gaussian, phase/frequency modulation, spread spectrum, pulse). Key characteristics of interference source or jammer: Range to receiver: 10 to 100 km. Effective radiated power: 10 mW to 100 kW. A signal line replaceable unit design that features a multiple-element antenna: an array of four elements, minimum.
Unique Software	Features validated null-steering, beam-steering, or beam-pointing algorithms. Features validated space-time adaptive processor (STAP) algorithm. Features validated space-frequency adaptive processor (SFAP) algorithms.
Major Commercial Applications	Commercial aviation, maritime, and land navigation. Telecommunications.
Affordability	Increased commercialization will significantly reduce cost.

BACKGROUND

Space time adaptive processing (STAP) for anti-jam capability is an active research area. The technology is critical for optimizing adaptive antenna systems.

DATA SHEET 16.3. GNSS ANTI-JAM COMPONENTS AND SUBSYSTEMS (ADAPTIVE NARROWBAND FILTERS)

Developing Critical Technology Parameter	In next 5–10 years: Receive, condition, and convert GPS RF signal to digital IF signal. Apply time, frequency, or amplitude-domain signal-processing techniques to remove interference signal that exists above thermal noise level. - Temporal (time) adaptive transversal filter performance 30 dB [narrow band (NB)]. - Spectral (frequency) digital excision filter performance 30 dB [continuous wave (CW)]. - Nonlinear amplitude domain processor performance 20 dB (CW).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Need to test against a representative jamming environment (i.e., wide variety of jammer signal characteristics and output powers).
Unique Software	None identified.
Major Commercial Applications	Commercial aviation, maritime navigation.
Affordability	Increased commercialization will significantly reduce cost.

DATA SHEET 16.3. MULTI-CHIP MODULE (MCM) TECHNOLOGY (GPS ON A CHIP)

Developing Critical Technology Parameter	In next 2 to 5 years: Will achieve GPS capability of less than 0.3 m. Ability to track 24 satellites. Dual frequencies. P-code and codeless. Receiver power consumption: <150 mW. Signal and bandwidth processing power >10X current commercial GPS receivers. Weight 0.5 kg.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Spread spectrum technology.
Major Commercial Applications	Commercial land, aviation, and maritime navigation. Cellular phone location, child locator system.
Affordability	Reduced size and increased commercialization will significantly reduce cost.

BACKGROUND

The largest market of this technology is the car navigation system and telecommunications. Its usage is expected to quadruple by year 2001 and substantially reduce the cost of GPS receivers for both commercial and military use.

The foundation has been laid by research done to enable the commercial version of GPS to be built on a chip using CMOS technology. Some further development is required, but it is likely that such a device could be available on the commercial market within three years.

SECTION 16.4—MAGNETOMETERS AND MAGNETIC GRADIOMETERS

Highlights

- Magnetometer and magnetic gradiometer technology varies with applications and cost. Anticipate more use of low-cost fiber-optic and torsion sensors for land-based usage and optically pumped technology for sea-based detection and classification.
- Magnetometer sensor arrays, a covert detection and classification technology, will be more viable because of accurate time sequencing, computer speed, and memory advances, providing increased detection and location of submarines, mines, and mobile missiles.
- Knowledge of position, GNSS time, and better computational capabilities using optical processing/correlation will greatly enhance magnetic array detection performance.
- Newly developed potassium and helium-4 optically pumped magnetometers are demonstrating performance comparable to superconductive quantum interference device (SQUID) magnetometers at low cost. Medical research and diagnostics is major funding source for future of SQUID sensors and possibly for potassium, if sensor can be reduced in size. Magnetic gradiometers, utilizing either the SQUID or potassium technologies, nearly eliminate the natural geomagnetic background noise.
- High T_c SQUID technology has matured since its inception in 1987 to the point where nitrogen-cooled superconducting sensors are rivaling their low T_c counterpart. Use of giant magnetoresistive (GMR) sensors is projected for a number of applications for which cost, size, and power are driving factors.
- Magnetic sensor use for nondestructive testing and inspection of vehicle integrity will increase.

OVERVIEW

Magnetometers and magnetic gradiometers are of interest to the military because of their covert detection, signature classification, and position determination capability. Although magnetic sensing of direction is thought to be of secondary use by the military, there is a need to provide low-cost map referencing of magnetic north and to maintain magnetic databases using magnetic sensors. Magnetic heading can be sensed by a flux value, for instance, or computed by subtracting magnetic variation from the true heading sensed by an INS. Magnetic variation is obtained from a map data base and can be used in many formats and accuracy levels. The use of true heading vice magnetic heading by the majority of navigation applications has been vastly increased by the quantities of INS and GPS in military and commercial applications in the past ten years. Using computational techniques, data bases with prior or real-time magnetic field data from magnetometer arrays can be used to reduce the spatial and temporal background noise. Both the development technology and the production technology are military critical. Magnetic sensor types of special interest include fluxgate, SQUID, nuclear precession, optically pumped, fiber-optic, and induction coil. Figure 16.4-1 provides a comparison of the current spectral density and frequency range of these sensor types. Figure 16.4-2 provides a projected capability for these sensors within the next 15 years.

The performance possible with the more sensitive SQUID, optically pumped, and induction-coil technologies will improve, and the cost and size of these sensors will come down. At the same time, other technologies that have demonstrated limited performance in comparison to the superconducting and total-field technologies will probably become competitive. Thin-film GMR sensor technology appears at present to provide a most promising possibility (see Fig. 16.4-2). Using GMR technology, nonvolatile random access memory will have lower power consumption and faster access speeds. GMR circuits, transformers, and logic gates are also viable.

For details on mine countermeasures, see subsection 17.7.

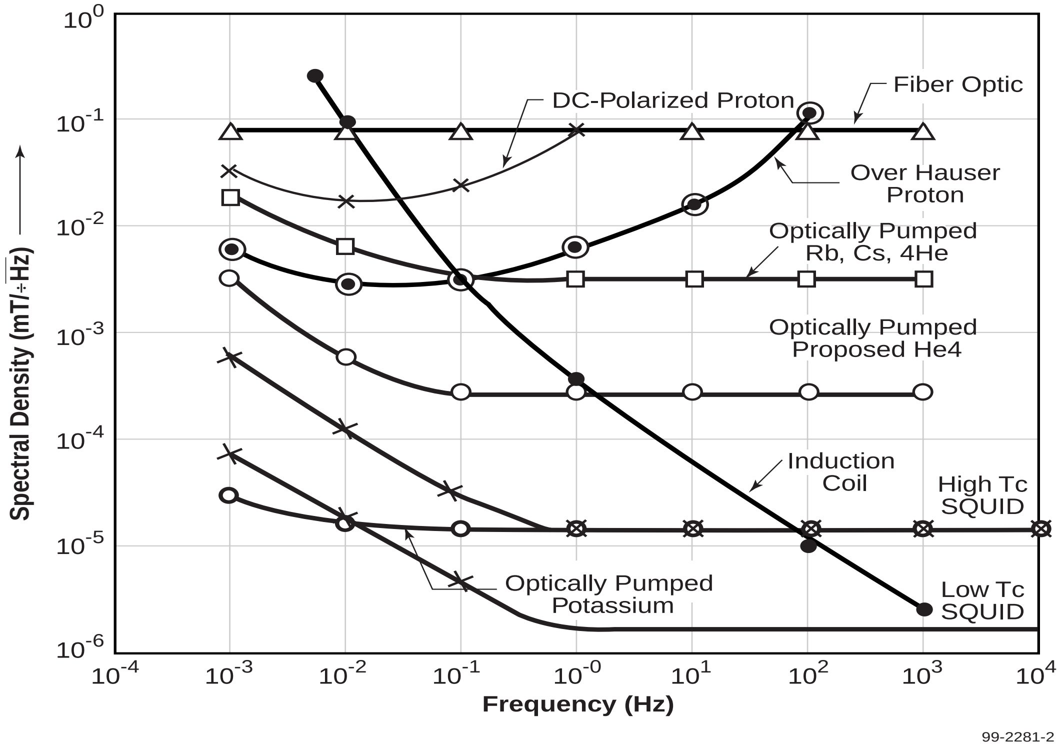

Figure 16.4-1. Comparison of the Current Spectral Density and Frequency Range of Various Sensors

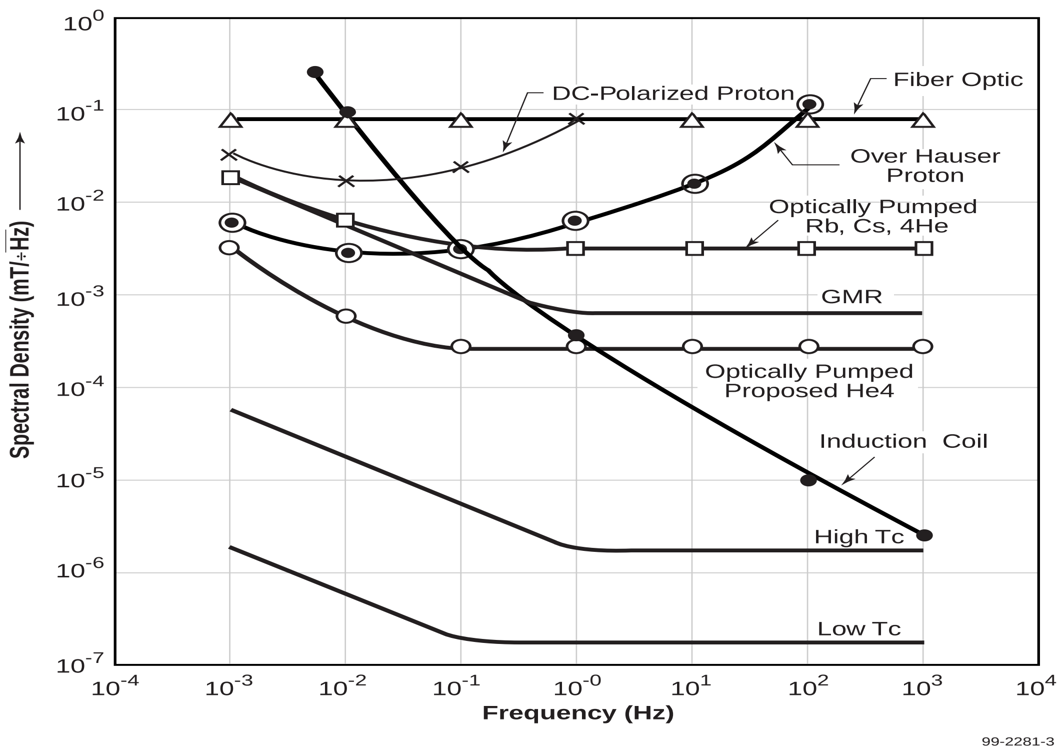

Figure 16.4-2. Comparison of Projected Spectral Density and Frequency Range of Various Sensors

Further advances in microelectronics, most significantly in the area of high dynamic range, multichannel, analog-to-digital converter technology and DSP, will enhance capabilities and significantly reduce cost and complexity of the underlying sensor technologies.

BACKGROUND

Commercial users may adapt the use of magnetometer arrays, but the main initial (developing) application is military. Ocean bottom arrays, are depicted in Fig. 16.4-3, and land-based arrays, as depicted in Fig. 16.4-4.

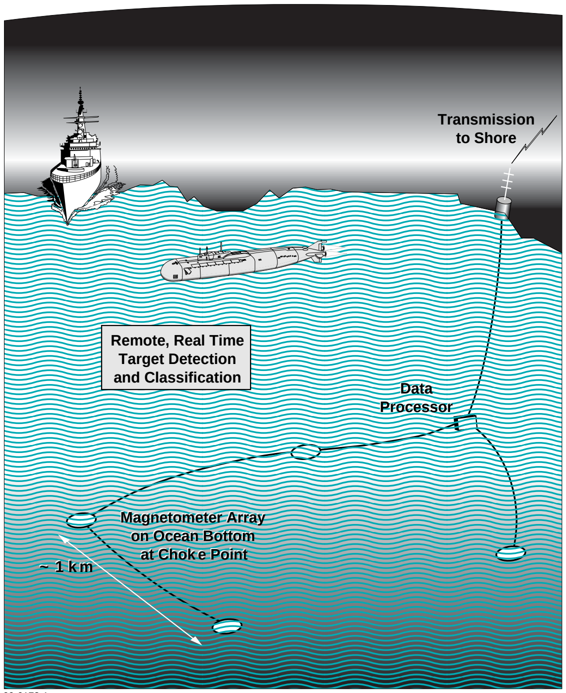

Figure 16.4-3. Ocean Bottom Arrays

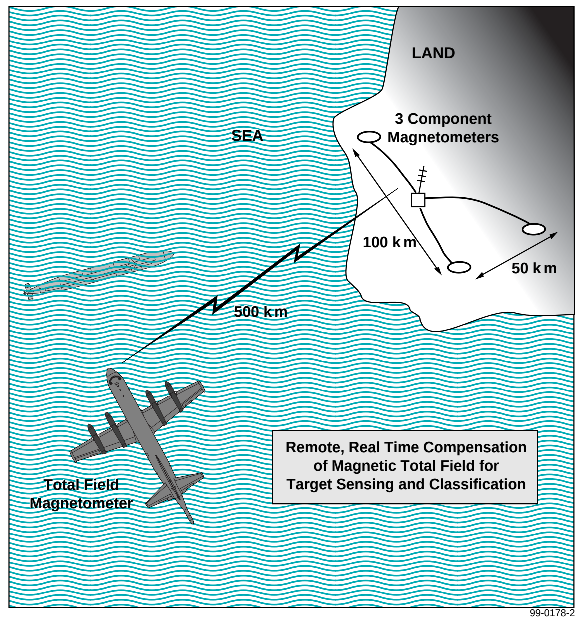

Figure 16.4-4. The Remote Real-Time Compensation Process

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DATA SHEET 16.4. SQUID MAGNETOMETERS

Developing Critical Technology Parameter	In next 5 to10 years: Noise level <0.03 nanotesla (nT) rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms and/or using arrays.
Major Commercial Applications	Resource exploration, nondestructive testing, and medical imaging.
Affordability	Medical imaging is funding driver.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems. SQUID magnetometers, in particular, are very accurate.

DATA SHEET 16.4. MAGNETOMETERS—ELECTRON RESONANCE AND OPTICALLY PUMPED

Developing Critical Technology Parameter	In next 5 to10 years: Noise level <0.03 nT rms/√Hz. Sensitivity 0.005 nT Resolution 0.01 nT
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms and/or using arrays.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems. There have been major advances in the development of electron resonance and optically pumped magnetometers.

DATA SHEET 16.4. MAGNETOMETERS—NUCLEAR PRECESSION

Developing Critical Technology Parameter	In next 5–10 years: Noise level <0.03 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms and/or using arrays.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems. There has not been significant progress in advancing the state of the art of magnetic sensors in the past decade.

DATA SHEET 16.4. MAGNETOMETERS—INDUCTION COIL

Developing Critical Technology Parameter	In next 5–10 years: Noise level <0.03 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms and/or using arrays.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW. There has not been significant progress in advancing the state of the art of this magnetic sensing technology in the past decade.

DATA SHEET 16.4. MAGNETOMETERS—FIBER OPTIC

Developing Critical Technology Parameter	In next 5–10 years: Noise level <0.8 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms and/or using arrays.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems. There has not been significant progress in advancing the state of the art of magnetic sensors in the past decade.

DATA SHEET 16.4. MAGNETOMETERS—FLUX GATE (VALVE)

Developing Critical Technology Parameter	In next 5–10 years: Noise level <0.05 nT rms/√Hz at frequencies <1 Hz and 10^{-2} nT rms per √Hz at >1 Hz. Continuing development.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms and/or using arrays.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade.

DATA SHEET 16.4. MAGNETIC GRADIOMETERS USING MULTIPLE MAGNETOMETERS

Developing Critical Technology Parameter	In next 5–10 years: Noise level of individual magnetometers of <0.05 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms and/or using arrays.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade.

DATA SHEET 16.4. INTRINSIC MAGNETIC GRADIOMETERS

Developing Critical Technology Parameter	In next 5–10 years: Noise level of <0.015 nT/meter rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms and/or using arrays.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade. Magnetic gradiometers can consist of two magnetic sensors or consist of a single intrinsic magnetic gradient sensor. Intrinsic magnetic gradiometers, utilizing either the SQUID or potassium technologies, nearly eliminate the natural geomagnetic background noise.

DATA SHEET 16.4. MAGNETORESISTIVE MAGNETOMETERS

Developing Critical Technology Parameter	In next 5–10 years: Noise level <0.03 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms and/or using arrays.
Major Commercial Applications	Security applications.
Affordability	Not an issue.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade.

Magnetometers on a moving base are a POSITIME-influenced technology because of the interrelationship of magnetic data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. The major advances in magnetometry during the last decade or so have been the emergence of precise location and time information and the availability of greatly enhanced computation capabilities. As these capabilities are introduced into magnetometry systems, the effectiveness of such systems could be significantly enhanced. Thin-film giant magnetoresistive (GMR) sensor technology appears at the present to provide a most promising possibility. On the one hand, the sensitivity of these sensors will likely increase and applications involving multiple units of low-cost, short-range, remote sensors will evolve. As sensitivity (high SNR) and compensation techniques improve, a wide variety of applications should evolve, such as covert detection capability, area surveillance, threat classification, and nondestructive testing.

Thin-film giant magnetometer (GMR) sensor technology appears at the present to provide a most promising possibility (see Fig. 16.4-2). Using GMR technology, nonvolatile random access memory will have lower power consumption and faster access speeds. GMR circuits, transformers, and logic gates are also viable. On the one hand, the sensitivity of these sensors will likely increase and applications involving multiple units of low-cost, short-range, remote sensors will evolve.

DATA SHEET 16.4. NONMAGNETIC CLOSED-LOOP REFRIGERATION EQUIPMENT

Developing Critical Technology Parameter	In next 5–10 years: Operation <103 deg K. Continuing development.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	None.
Major Commercial Applications	Resource exploration and medical applications.
Affordability	Medical imaging is funding driver.

BACKGROUND

SQUID sensors are optimal (most accurate) when the cryogenic support equipment does not induce magnetic noise into the detection process. In the past, medical applications have been the only funded efforts in nonmagnetic closed-loop refrigeration equipment. With the advent during the last decade of high T_c SQUIDs, with critical transition temperatures in excess of 90 K, there has been intensified interest in closed-loop refrigeration for nondestructive evaluation and medical application. The cooling requirements are less stringent than what is required for low T_c technology.

DATA SHEET 16.4. MAGNETIC ARRAYS

Developing Critical Technology Parameter	In next 5–10 years: Decrease of acquisition time and increase of accuracy of detection and location, array spacing, and detection range will increase with improved timing and communication.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient <0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement >10–1) for operation on mobile platforms.
Major Commercial Applications	Intrusion and security control.
Affordability	Not an issue. Availability and use of accurate time is the issue.

BACKGROUND

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade.

SECTION 16.5—PRECISE TIME AND FREQUENCY (PT&F)

Highlights

- The worldwide availability of accurate time via GNSS will increase the combination of communications, imaging, and navigation functions into multihybrid sensor systems. This will provide a common grid reference for battlespace data management. The accuracy of the ionosphere model is a limiting factor on GPS time transfer.
- Autonomous and common 3–D POSITIME grid reference will improve battlespace situational awareness by providing a precise POSITIME tag on all battlespace information collected. This will provide real-time knowledge of the location and movement across battlespace of allied and enemy assets.
- Accurate time is required for autonomous operation of satellite network geolocation systems and enhanced crypto/transec performance in spread-spectrum communication systems.
- The importance of PT&F has only recently been recognized because of the availability of GNSS time. Foreign sources are currently providing the funding engine for future technology improvements in PT&F, as U.S. R&D funding has declined.
- The number of U.S. Atomic Frequency Standard suppliers is declining and may be down to one within five years.

OVERVIEW

PT&F is the key to current and future POSITIME, navigation, communication, and imaging systems. While the need of imaging and communication systems for PT&F is becoming more critical for military use, most current emphasis for PT&F technology is to support navigation and mainly for commercial use. Both the U.S. GPS, with its inherent vulnerabilities (see subsection 16.3), and Russia's GLONASS worldwide navigation systems are actually PT&F systems. Both systems employ atomic clocks in the satellites. A cesium beam frequency standard is utilized aboard each GLONASS satellite. Both systems are capable of time transfer to a precision of 10 to 30 nanoseconds, but the GLONASS system time reference is not coordinated universal time, (UTC), as maintained at the United States Naval Observatory (USNO), the designated time reference for the United States. GPS uses both cesium and rubidium frequency standards in the current satellites, known as Block II/IIA, and rubidium standards in the replacement satellites, Block IIR. PT&F and signal detection and processing technology are required to acquire, synchronize, and track the desired satellite signals for measurement of navigation parameters. Technologies contributing to superior performance include the application of analog and digital correlation filters, DSP and microelectronics. Increased computational effectiveness for a given equipment volume and weight could provide an adversary with two distinct navigation payoffs: (1) certain navigation capabilities could be enhanced by advance computer technologies, and (2) for a given available volume/weight, the navigation performance could be enhanced in terms of accuracy, reliability, and resistance to hostile actions.

The GPS capability to transmit corrections to UTC (USNO) in the navigation message and thereby transfer time is given in the GPS Interface Control Document, ICD-GPS-202, as 28 nanoseconds (1 σ). The capability and conditions of time transfer from GPS depend greatly upon the instrumentation used, user conditions, and period of interest. For example, the time transfer capability of a fixed site, at a well-known position, needing long-term timing, and having the ability to integrate or process data over hours or days is considerably different than for a high-performance aircraft needing time to transfer in real-time or from the individual sensors of an array to a central processor. Time-transfer operational performance of GPS and data quoted is to a fixed site. GPS capabilities for military users under different conditions should be given as a more representative capability for system planning.

Systems-integration technology enables the integration of communication and multiple navigational instruments outputs through advanced digital processing to provide an extended range of operational functions and increased combat performance.

BACKGROUND

The importance of PT&F may be clearer with a description of the overall architecture of systems involved with the generation, dissemination, and maintenance of military common time. The overall process is described below.

- **Reference Time.** The common time scale to be used by U.S. military forces and systems is that generated, coordinated internationally, and maintained by the USNO. This time scale is designated internationally as UTC (USNO), representing the actual time available as a physical signal output of the USNO master clock. USNO maintains a master clock system of various commercial atomic clocks, remote precise time reference stations, and interface to dissemination systems. The alternate master clock became operational in 1996. The alternate master clock provides system redundancy and is linked to the master clock by a two-way satellite time transfer system. A severe handicap to users of UTC time, such as in telecommunications, is the yearly insertion of a nanosecond to account for the rotational changes of the Earth due to increases in the moon's orbital path around the Earth. In the next 5–20 years this correction problem needs to be internationally adjudicated to resolve the communication synchronization problem.
- **Reference Time Dissemination.** The dissemination of UTC (USNO) is accomplished by a collection of methods relying upon various systems, predominately POS/NAV systems. This dissemination function is a secondary mission of these systems, and no operational systems exist that are specifically designed and used for PT&F dissemination. Dependence upon secondary mission requirements or capabilities does not support a cohesive system architecture for the many systems that rely on precise time. Since PT&F is a secondary mission, operational control, coordination, and regulation of the time disseminated is an informal agreement without the impact of operational requirements.
- **User Interfacing.** User systems have an increasing role in the distribution and sharing of time information. The sharing of time information by user platforms and systems will be increasingly more important as higher data rates and crypto requirements (see Section 10) become more stringent. In turn, this will create an increasingly larger problem of controlling or managing intersystem timing exchange or interoperability. Coordination and standardization of these interfaces is part of the overall coordination role needed to produce robust systems synchronized to a common time reference.

The importance of PT&F to military systems as a technology area is becoming more evident with the deployment and operational use of GPS. GPS provides the means for accurate and stable time to be disseminated to forces around the world. The application of GPS for timing is increasing, particularly in telecommunications and data transfer. Because of the small quantity of Atomic Frequency Standard clocks that are needed yearly, the number of U.S. sources may decline to one within 5 years. Also alarming is the potential demise of the precision crystal oscillator suppliers in the United States in the near term. The oscillators are a critical module of the atomic clock system. There is a need for a precise, robust protocol for setting time across networks. A robust precision network time protocol (PNTP) using broadband communication links is needed for future military systems. The following table is an example of the possible types of needs that should be recognized for PT&F.

Table 16.5-1. User Clock Precision/Accuracy Requirements and Benefits

Platform/System	Current Accuracy to UTC (USNO)	Future Accuracy to UTC (USNO)	Benefit of Improved Time Accuracy
Nominal Use			
Time Epoch (second)			
Low-Accuracy Aircraft/Land Mobile	10^{-3}	10^{-9}	Quicker network entry for comms/IFF, enhanced crypto. Improved interoperability.
Ship/Submarines	10^{-6}	10^{-9}	Quicker network entry for comms/IFF, enhanced crypto. Improved interoperability.
Communication Sites/Aircraft	10^{-6}	10^{-9}	Quicker network entry for comms/IFF, enhanced crypto. Improved interoperability.
Radar/Surveillance/Intelligence	10^{-6}	10^{-9}	Better targeting/emitter location such as TDOA. Enable spread spectrum LPI.
Frequency ($\Delta f/f$)			
Low-Accuracy Aircraft/Land Mobile	10^{-12}	10^{-15}	Quicker network entry for comms/IFF. Improved interoperability.
Intermediate Land Reference Sites	10^{-13}	10^{-15}	Comms net access. Frequency calibration source for low-power oscillators.
Long-term Autonomous Timekeeping	10^{-13}	10^{-15}	Extended autonomous periods.
Large TDMA Systems	$\sim 10^{-11}$	10^{-15}	Enhanced network synch. Higher data rates.
Precise Mode (Cesium Calibration Updating)			
Time Epoch (second)			
ECCM Comm, Radar and Surveillance Systems	10^{-9}	10^{-11}	Better targeting/emitter location such as TDOA. Enable spread-spectrum LPI.
Submarine Comm, Ship	10^{-8}	10^{-11}	Enhanced network synch. Higher data rates. Longer autonomy. Enhanced navigation.

LIST OF TECHNOLOGY DATA SHEETS
16.5. PRECISE TIME AND FREQUENCY (PT&F)

Time Distribution Systems 16-50

Atomic/Ion Clocks 16-51

Low-Power Clocks 16-52

Optically Pumped Clocks 16-53

DATA SHEET 16.5. TIME DISTRIBUTION SYSTEMS

Developing Critical Technology Parameter	In next 5–10 years: Provide signal phase (time) common synchronization of $<10^{-9}$ sec, relative to UTC (USNO); intersystem synchronization of $<10^{-8}$ sec relative to battlegroup; coordinated use of platform resources for lower cost and robustness; 10^{-9} for interoperability, surveillance, and high-speed communication.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Frequency references for calibration with $\Delta f/f < 1 \times 10^{-15}$.
Unique Software	Algorithms and verified data to combine clock outputs to improve stability/accuracy performance (i.e., “ ensembling”) Automatically detect phase jumps or frequency perturbations and/or improve reliability from redundancy. Self monitoring.
Major Commercial Applications	Telecommunication, electrical power generation, and grid management.
Affordability	Large volume use.

BACKGROUND

GPS provides the means for accurate and stable time to be disseminated to forces around the world. The use of GPS for timing is increasing, particularly in telecommunications and data transfer.

Sensors, such as magnetometers, magnetic gradiometers, gravity meters, gravity gradiometers, optical, infrared, ultraviolet, and acoustic, especially on a moving base, are POSITIME-influenced technologies because of the interrelationship of sensor data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization.

DATA SHEET 16.5. ATOMIC/ION CLOCKS

Developing Critical Technology Parameter	In next 5–10 years: Provide stability and accuracy approaching 1×10^{-15} sec for reference systems.
Critical Materials	Magnetic shields, low-noise local oscillators, and long-life stabilized lasers.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Telecommunication.
Affordability	High cost because of low-volume use.

BACKGROUND

GPS provides the means for accurate and stable time to be disseminated to forces around the world. The use of GPS for timing is increasing, particularly in telecommunications and data transfer.

This developing class of atomic clocks will improve absolute accuracy to better that 10^{-15} sec. Initially, these clocks will be larger, heavier, and more delicate than current but they have the potential to become competitive or better in size, weight, and power than existing clocks.

Atomic clocks are composed of three general modules: a crystal oscillator, the atomic physics package, and the supporting electronics. Crystal oscillator availability from a U.S. source in the out years is of concern for Atomic Frequency Standard clocks. Crystal oscillators are key to the short-term stability and actual timekeeping because the atomic resonance frequency from the physics package is used to give long-term stability to the crystal clock. There are no issues relative to the physics package or the electronics.

DATA SHEET 16.5. LOW-POWER CLOCKS

Developing Critical Technology Parameter	In next 5–10 years: Provide accuracy and stability typical of current cesium and rubidium clocks at greatly reduced weight and power.
Critical Materials	Laser diodes, battery technology.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Telecommunication.
Affordability	Large volume potential.

BACKGROUND

GPS provides the means for accurate and stable time to be disseminated to forces around the world. The use of GPS for timing is increasing, particularly in telecommunications and data transfer.

A technology currently in development, the MCXO provides the stability of an ovenized crystal oscillator at or below the input power levels of traditional TCXO. Another promising area of development is the miniaturized gas cell clock. This approach trades off some performance of the traditional rubidium clock to provide an atomic clock with a volume of about 25 cm^3 and a power consumption of less than 1 W. These lower power devices can offer a level of performance suitable for GPS direct-Y code acquisition and communications system synchronization in a package suitable in size and power for manpack or low-power mobile-platform users.

DATA SHEET 16.5. OPTICALLY PUMPED CLOCKS

Developing Critical Technology Parameter	In next 5–10 years: Provide stability and accuracy approaching 1×10^{-16} sec for reference systems using smaller and lower power technology than ion clocks.
Critical Materials	Laser diodes.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Telecommunication.
Affordability	Beyond capabilities of most countries—low volume.

BACKGROUND

GPS provides the means for accurate and stable time to be disseminated to forces around the world. The use of GPS for timing is increasing, particularly in telecommunications and data transfer.

The use of laser diodes for optical pumping and cooling of atomic systems to produce clock signals is a developing technology that will be adapted to field or system usable units. Low-power, fixed-mode diode lasers offer a natural means of interrogating and controlling small, ruggedized standards for field or platform use.

SECTION 16.6—SITUATIONAL AWARENESS/COMBAT IDENTIFICATION

Highlights

- RFID technology using secure, encrypted, millimeter waveform in the 33–40 GHz Ka-band will remain the primary NATO IFF capability to identify friendly forces in the battlespace for the foreseeable future. Advances in RFID technology will result in improved performance, cost reduction, and size reduction.
- Advancements in long-range ATR databases, algorithms, and decision-aided tools, reducing the time needed to identify targets by a factor of three, will continue to complement RFID technology for positive identification of friendly, foe, and neutral targets.
- Increased usage of overhead intelligence, navigation, communication, and imaging sensor assets, using a common 3–D position and precise time grid reference, together with RFID/ATR systems, will provide reliable, positive, long-range identification capabilities within the lethality range of weapons.

OVERVIEW

At this time, this new subsection on SA/CID will only focus on the technologies that produce superior CID performance in the air-to-surface and surface-to-surface capability. Future updates of this document may address other SA/CID areas, including:

- Weather
- Air and ground traffic control
- Obstacle/ground/terrain avoidance
- Missile warning
- CID (air to air and surface to air)

SA includes all of the environmental, positional, and time conditions (past, present, and projected future) that affect the capabilities of the warfighter. Combat stress levels are inversely proportional to SA. Lack of SA will lead to adverse military decisions at all levels of command. CID plays a major role in achieving the capability to build and maintain a coherent tactical picture as discussed in the Section 16 overview and in Fig. 16.6-1. CID is the capability to differentiate potential targets—mobile and fixed, over large areas with corresponding long distances—as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release.

The technologies include those needed for positive, timely, and reliable identification of friends, foes, and neutrals; classification of foes by class, type, and nationality; and interoperability required among the U.S. military and allied nations. The challenges are enormous, particularly in three specific areas: (1) a cooperative/noncooperative sensor systems; (2) a command, control, and communications (C3) systems—in particular, digital datalinks and radios, each of which contributes a portion to the CID solution; and (3) artificial intelligence tools that will fuse sensor and information. As such, CID is viewed as a capability, not a single system or technology. A "system-of-systems" approach is required. This subsection will consolidate the critical technologies addressed in the other sections/subsections [Section 10 (Information Technology), Section 11 (Lasers and Optics), and Section 18 (Sensors)], as well as explore other technologies that will provide increasingly superior performance of SA/CID capabilities.

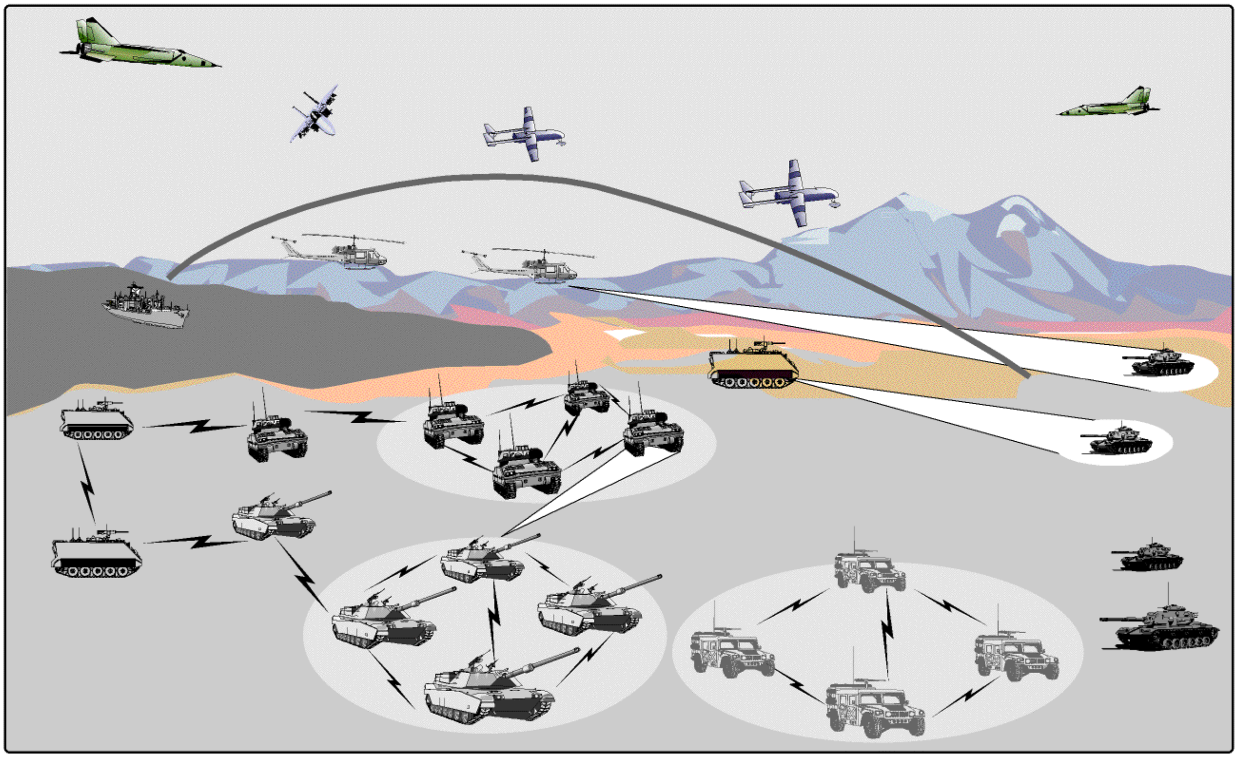

Figure 16.6-1. Concept Combat Identification

This subsection will discuss three classes of technologies:

- *Sensors.* The target is characterized either noncooperatively (e.g., jet-engine modulation, high-range resolution radar, or electronic support measures) or cooperatively [e.g., MK XII (IFF) system or Battlefield Combat Identification System (BCIS)].
- *C3 (particularly digital datalinks and radios).* The target declares (either periodically or when queried) its identification and position in a reference frame that the "shooter" can correlate with its own weapon and sensor system (e.g., Link 16).
- *Artificial Intelligence Tools*. Vast amounts of data will need to be processed, correlated, stored, and displayed in real-time to be useful to a warfighter. AI tools include expert systems, intelligent agents, decision aides, modeling and simulation, and virtual reality.

Currently, the cooperative tri-Service Mark XII RF/IFF system (circa 1970s) is the Q&A technology to identify friendly forces. Non-responses are considered unknown. Visual identification is used for neutral identification and foe identification in the air-to-surface and surface-to-surface areas, respectively. There is no long-range positive identification capability on the ground.

Limitations in sensor resolution—coupled with variations in target aspect, state, countermeasures, and the battlespace signal propagation environment—complicate the job of target labeling.

Cooperative identification sensor systems, which only identify friends, have the advantage of being less of a technical challenge; however, they require all friendly potential targets to be equipped with the same corresponding identification equipment. This limitation will require more combined use of both cooperative and non-cooperative sensor systems.

Overhead CID technology sensor improvements that can interpret imaging and nonimaging sensor data to reliably identify the target ID in near real time are necessary. Communication improvements in secured data dissemination of SA multimedia information down to the lowest mobile echelon is required. The unprecedented amount of raw information produced by modern sensor systems and the effectiveness of C3 systems can overwhelm the capability of human operators and decision makers, requiring the need for a reliable automated decision aide tool. CID can be highly useful only when it is fully integrated with both C3 and weapon systems. CID requires effective and timely synchronization of communications systems with data from real-time surveillance, target tracking, and intelligence systems.

Affordability and exploitability are major barriers to having universal CID capability:

- Affordability. The cost of CID suites that are properly integrated with the weapon sight (both cooperative and noncooperative) are usually prohibitive if they are not form, fit, function and interchangeable (F3I) with an existing sensor or system. Additional functionality in the form of communications, SA, or sensing is helpful in making CID more affordable. The affordability of a system will also vary significantly depending on the environment in which it is considered. Aviation/maritime systems are generally more expensive than ground–based systems. As a result, solutions that are programmatically "affordable" for aircraft/maritime platforms are often prohibitively expensive for combat vehicles.

If the identification is determined by an off-board sensor, there is the added necessity to pass, correlate, and provide the warfighter the required information in a timely fashion. This requirement to correlate an identification label with a sensor return in the "weapon sight" is a key discriminator and a source of significant cost for the systems. Technology that eases the integration overhead of a CID-related system or reduces its component cost is required.

- **Signature Exploitability.** Noncooperative techniques of identification are most attractive to warfighters because of their ability to generate labels for foe, friend, and neutral contacts and because they can provide additional identification information on adversaries (e.g., platform type, class, nationality). For air/ maritime targets, the current capabilities of these systems are limited in range, aspect, and timeliness of reporting. The result is that the indications from this class of systems are frequently in the "unknown" or "not available" state. For combat vehicles, the signal environment is such that reliable identification at maximum weapon range remains a significant technical challenge. Limitations in sensor resolution—coupled with variations in target aspect, state, countermeasures, and the battlespace signal propagation environment—complicate the job of target labeling.

Other issues are reliability and security. Unless the system is 100-percent reliable, possibilities exist for fratricide in combat. Antennas and other external devices (the BCIS uses an externally mounted transponder) may be blown off during combat, rendering the system useless. Another problem is security. If an enemy can read, jam, or duplicate the incoming or outgoing signals, the system's effectiveness becomes severely degraded. If the signals are not of an LPI nature, an enemy is likely to be able to localize emission sources and target them. It is also reasonable to expect that some of our systems will fall into enemy hands; therefore, our system must be reprogrammable. A different type of active system does not require interrogations but periodically transmits required information such as identity and status in the blind. This information "strobing" would have to be spectrally unique to prevent detection, but could simplify the overall system and allow one-half of the ID equation to remain passive. RFID tagging technology has great potential. This bar code system with a brain and voice can provide security in "secure" areas when the RFID tag is attached to the warfighter.

In the next 3–5 years, RFID technology using secure, encrypted, millimeter waveform in the 33- to 40-GHz Ka-band will remain the primary NATO IFF capability to identify friendly forces in the battlespace for the foreseeable future. Advances in RFID technology will result in improved performance, cost reduction, and size reduction. Figure 16.6-2 shows the architecture interface concept for future U.S. Army combat identification systems to improve air-to-surface and surface-to-surface capabilities.

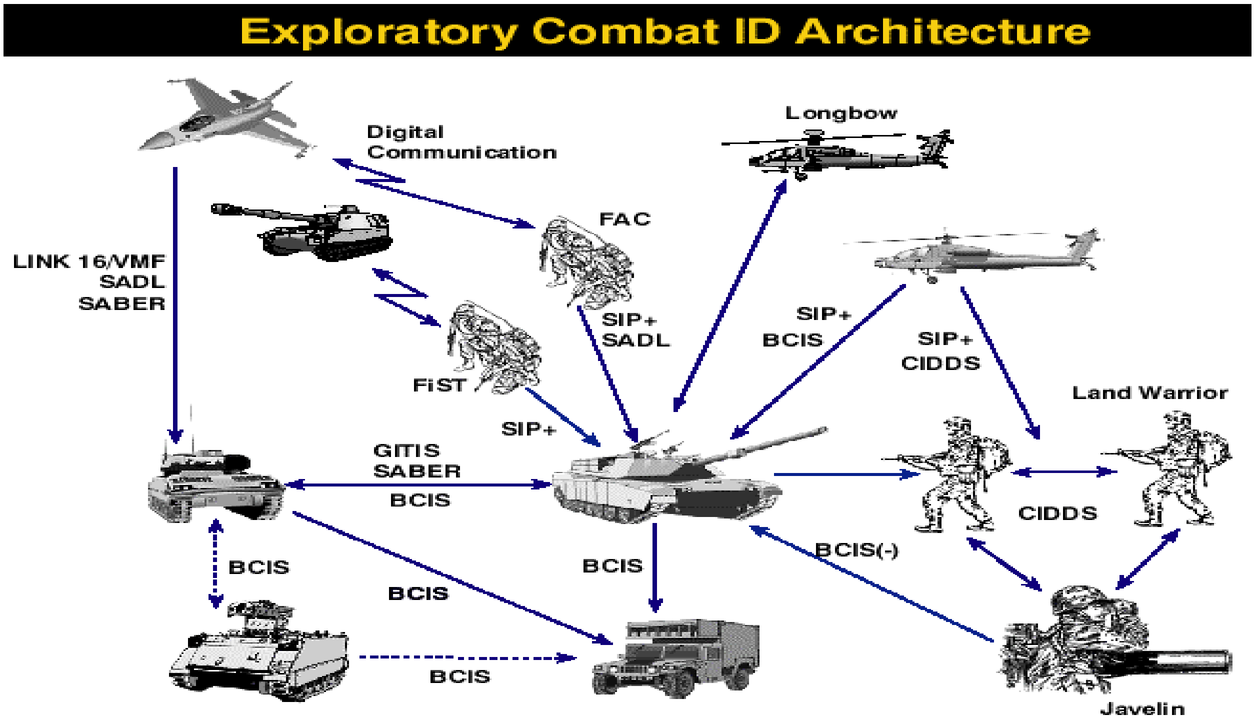

Figure 16.6-2. U.S. Army's Combat Identification Concept

LIST OF TECHNOLOGY DATA SHEETS
16.6. SITUATIONAL AWARENESS AND COMBAT IDENTIFICATION

Identification Friend or Foe, Millimeter-Wave (mmW) Technology.......... 16-59
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<u>Note</u>: For other related sensor technologies, see Sections 11 and 18. For other communication and information technologies, see Section 10.

DATA SHEET 16.6. IDENTIFICATION FRIEND OR FOE, MILLIMETER-WAVE (mmW) TECHNOLOGY

Developing Critical Technology Parameter	In the next 3–5 years: Ground-to-ground identification ranges 5–25 km day or night, clear sky, rain, or dust. Air-to-ground identification ranges 100–200 miles. Identification time: <1 second. Probability of correct ID 90–97 percent.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	The Battlefield Identification System Environment and Performance Simulator (BISEPS) system has been developed in support of MMW/BCIS performance evaluation. BISEPS computes the probability of correct identification and measures net latency.
Unique Software	The various technologies that will reduce fratricide must be integrated into an overall architecture. Can be configured to send, receive, and display secure, digital information with other similarly equipped units on the battlefield.
Major Commercial Applications	Air traffic control, vehicle identification, railcar stacking, and location.
Affordability	Integration and interoperability are major cost drivers.

BACKGROUND

This technology provides positive identification of friendly platforms and dismounted soldiers from both ground and air weapons platforms and dismounted soldiers. System includes interrogators and transponders combined for shooters and transponders only for nonshooters.

DATA SHEET 16.6. DATA FUSION/ARTIFICIAL INTELLIGENCE/ DECISION AIDS TECHNOLOGY

Developing Critical Technology Parameter	Fuses information from a wide variety of sources to bring the confidence factor of the target identity to near 100 percent.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms for tracking a large number of targets in a cluttered environment.
Major Commercial Applications	Manufacturing quality control, internal medicine, financial market analysis, information retrieval. Multimedia medical database. Waste management.
Affordability	Integration and interoperability are major cost drivers.

BACKGROUND

Complex problem solving in warfighting typically requires the problem solver to access and combine data from multiple sources and to develop a dynamic assessment of an evolving situation. Data fusion focuses on providing the distributed tools and systems infrastructure to fuse data from multiple network sources. These data are combined with other knowledge and planning tools to make and evaluate several alternative plans.

Current methods of data fusion are:

- Extended Kalman filtering
- Model-based approaches
- Wavelet decomposition
- Artificial neural networks
- Fuzzy logic.

The *Quadrennial Defense Review* identifies the key to future success for U.S. forces as being an integrated "system of systems," linking intelligence collection and assessment, C2, weapons systems, and support elements to achieve battlespace awareness. Achieving this will require vast amounts of data, necessitating automatic decision-making tools.

Methods developed in the field of AI include the following:

- Common-sense reasoning
- Nonmonotonic logic
- Circumspection
- Algorithms used in neural networks
- Extensions to Bayesian calculi.

Most ATR development, being based on analysis of single image frames and segmented target regions, is currently limited to the pattern recognition subset of recognition theory. More generalized ATR processing would take advantage of multiple geo-registered information sources and temporally displace data in order to dynamically reason about situations. A future is feasible where sensors and information will be ubiquitous.

DATA SHEET 16.6. AUTOMATIC TARGET RECOGNITION (ATR) ALGORITHMS

Developing Critical Technology Parameter	In next 5–10 years: Model-based or neural-network-based reasoning integrated with pattern recognition promises reliable target detection with low false alarms (0.01 false alarms/km^2).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms for tracking a large number of targets in a cluttered environment.
Major Commercial Applications	Tracking high-value vehicle and rail cargo. Robotics. Medical analysis.
Affordability	Integration of ATR and sensor data is a key affordability issue, which can reduce warfighter workload and stress levels.

BACKGROUND

ATR algorithm technology provides a noncooperative, real-time capability to detect and identify objects. This capability, when integrated with other cooperative identification systems, provides a very high probability of detection and identification of friend, foe, and neutral targets. The development of both data-driven and model-based approaches using single and multiple sensors are two means to achieve this capability.

ATR data-base development includes target signature modeling and scene synthesis efforts that support ATR algorithms for single/multisensor electro-optics and radar systems. Signature modeling is critical to rapid target identification. Synthetic data also provides a practical means of exploring complex, multi-sensor ATR designs. Scene syntheses provide high-fidelity models for distributed, interactive simulations to assess new ATR technologies.

DATA SHEET 16.6. WIDE-AREA IMAGING AND SURVEILLANCE SENSORS

Developing Critical Technology Parameter	In next 5–10 years. Imaging sensors will be able to detect targets in shallow hide and camouflage or foliage. Interferometric synthetic aperture radar (IFSAR) sensors will provide rapid production of current and high-resolution terrain data over wide-ranging areas from airborne and spaced-based platforms. Laser radars will produce high-resolution DTED maps (see subsection 16.3). Resolution: 1 m at 500 km.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Integrating ATR algorithms and POSITIME systems with sensors.
Major Commercial Applications	Tracking high-value commercial vehicle and rail cargo.
Affordability	Mostly unique military hardware and software that will still rely primarily on government investment. Integration and interoperability are major cost drivers.

BACKGROUND

This technology will provide target identification over a wide area of the battlefield, both day and night, and in all weather conditions. Key technologies will focus on the penetration of camouflage and foliage. A new third-generation thermal imaging (TI) camera operating in a 3–5 μm waveband can provide high sensitivity in the detection and tracking of high-temperature target emissions.

Target identification can be achieved using sound waves. Time-delay spectrometry can be employed as a way of isolating a desired reflected signal from other reflections. This dramatically increases the SNR when a neural-network-based classification system is used. Propagation of sound in the atmosphere is governed by a number of interacting physical mechanisms, including geometrical spreading, molecular absorption, reflection from a porous ground, curved ray paths due to refraction, diffraction by ground topography, and scattering by turbulence. Accurate predictions of sound signatures from a distant source must somehow account for all of these phenomena simultaneously. Although this goal is still beyond current capabilities, developments in computational tools for predicting sound propagation through the atmosphere have increased dramatically during recent years. The computational techniques now include analytical solutions for propagation above porous ground, analytical solutions for selected atmospheric profiles, ray-tracing techniques which include interaction with the ground and meteorological conditions, and more sophisticated numerical solutions to the wave equation.

The conversion of interferometric synthetic aperture radar (IFSAR) to obtain highly accurate elevation data is possible using innovative algorithms. Near real-time elevation data determination is also possible using fast correlating stereo and high multiple electro-optical images. Laser radars can be used for the production of high-resolution DTED (see subsection 16.3).

DATA SHEET 16.6. SYNTHETIC APERATURE RADAR (SAR) AND INVERSE SAR (ISAR) SENSORS

Developing Critical Technology Parameter	Next 5–10 years: Recognizing targets under variable sensor and deployment conditions, coping with sensor squint, depression and aspect angles, target articulation, configuration, shadow obscuration, terrain layover, and camouflage. Target mapping in color. Mapping resolution less than 1 ft in both azimuth and slant range. Mapping swath: 10 nmi. Altitude range: 0.2–13.1 km.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Use of model-driven ATR for both SAR and ISAR sensors.
Major Commercial Applications	Imaging technologies are used in medical imaging, law enforcement, robotics, transportation sensing, and multimedia. Precision mapping and images.
Affordability	Combining technologies for both stationary and moving targets is a cost driver, but a high operational payback. Integration and interoperability are major cost drivers.

BACKGROUND

One of the primary goals of SAR is to develop integrated approaches for recognizing targets under variable sensor and deployment conditions, coping with sensor squint, depression and aspect angles, target articulation, configuration, shadow, obscuration, terrain layover, and camouflage. In the near time frame, it is expected to recognize 20 different high-value tactical and strategic targets under all sensor and deployment conditions.

DATA SHEET 16.6. INFRARED SENSORS/DEVICES

Developing Critical Technology Parameter	Next 5–10 years: This technology will provide a day/night target detection, classification, and dissemination capability at stand-off ranges. Can identify noncooperative, small-radar-cross-section aircraft, ground vehicles, and ships at extended ranges. Range expected to increase 3–5× from current capabilities.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Target classification systems is required.
Major Commercial Applications	Law enforcement agency use for interdiction, boarding, and surveillance. Automatic highway systems.
Affordability	Complexity of classification signature data base and integration are major cost drivers. Integration and interoperability are major cost drivers.

DATA SHEET 16.6. LASER RADAR SENSORS/DEVICES

Developing Critical Technology Parameter	In next 5–10 years: Three-dimensional laser radar with tunable laser radar for target detection and identification of obscured targets. Wavelength: 1.5 µm–3.5 µm. Ground-to-ground: measure the shape of objects at distances of 1 km or more. Can display the shape and directional velocity of moving targets. Range data is measured to an accuracy of 0.005 m. Air to ground: determine target location with accuracy of 0.3 m from 40,000 ft.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Integrates GPS, ATR software, and satellite communications.
Major Commercial Applications	Vehicle detection and classification as part of intelligent highway systems; automation of agricultural equipment and precise measurement of distances.
Affordability	Integration and interoperability are major cost drivers.

DATA SHEET 16.6. TAGGING TECHNOLOGY

Developing Critical Technology Parameter	In next 5–10 years: A micro-silicon chip, no bigger than a coffee grind and a micro-miniaturized antenna will provide a very low-cost ID for installation on any type of material. Tag remains passive until scanned by device (i.e., radio, laser) without having to get near the tag or even have line of sight to it. Transmission can use low probability of intercept algorithms. Scanner can change or add information on the chip.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Replacement for bar codes. Tracking mail, luggage, production parts and spare parts, identification and location.
Affordability	Leveraging commercial technology will minimize cost.

BACKGROUND

Tags can be used actively or passively to provide vehicles and personnel tracking on which those tags have been implanted, overtly or covertly. The tags can be implanted in equipment upon manufacturing, into raw materials at growth or mining, or onto vehicles, and equipment later (i.e., decals). The location or activity could be scanned from ground or overhead (i.e., UAV or satellite) radio or laser scanners.