Assured PNT Challenges for Current Nav Technologies

Michael L. Carroll

November 11, 2024



What is Assured PNT?

Assured Position, Navigation, and Timing (A-PNT):

- Assured Position, Navigation, and Timing (A-PNT):
 - Provides reliable PNT information, even in GPS-degraded or denied environments

- Assured Position, Navigation, and Timing (A-PNT):
 - Provides reliable PNT information, even in GPS-degraded or denied environments
 - Critical for applications requiring high-precision and resilience, such as military, aviation, and critical infrastructure

- Assured Position, Navigation, and Timing (A-PNT):
 - Provides reliable PNT information, even in GPS-degraded or denied environments
 - Critical for applications requiring high-precision and resilience, such as military, aviation, and critical infrastructure
- Main Goals of A-PNT

What is Assured PNT?

Assured Position, Navigation, and Timing (A-PNT):

- Provides reliable PNT information, even in GPS-degraded or denied environments
- Critical for applications requiring high-precision and resilience, such as military, aviation, and critical infrastructure

Main Goals of A-PNT

 Ensuring accuracy and integrity of position, navigation, and timing data

What is Assured PNT?

Assured Position, Navigation, and Timing (A-PNT):

- Provides reliable PNT information, even in GPS-degraded or denied environments
- Critical for applications requiring high-precision and resilience, such as military, aviation, and critical infrastructure

Main Goals of A-PNT

- Ensuring accuracy and integrity of position, navigation, and timing data
- Providing robustness against jamming, spoofing, and interference

What is Assured PNT?

Assured Position, Navigation, and Timing (A-PNT):

- Provides reliable PNT information, even in GPS-degraded or denied environments
- Critical for applications requiring high-precision and resilience, such as military, aviation, and critical infrastructure

Main Goals of A-PNT

- Ensuring accuracy and integrity of position, navigation, and timing data
- Providing robustness against jamming, spoofing, and interference
- Mitigating risks of depending on GPS

Technologies Critical to A-PNT

Global Navigation Satellite Systems (GNSS):

- Global Navigation Satellite Systems (GNSS):
 - Primary source of PNT data, with anti-jamming and anti-spoofing techniques (e.g., M-Code and SAASM for secure military applications)

- Global Navigation Satellite Systems (GNSS):
 - Primary source of PNT data, with anti-jamming and anti-spoofing techniques (e.g., M-Code and SAASM for secure military applications)
- Inertial Navigation Systems (INS):

- Global Navigation Satellite Systems (GNSS):
 - Primary source of PNT data, with anti-jamming and anti-spoofing techniques (e.g., M-Code and SAASM for secure military applications)
- Inertial Navigation Systems (INS):
 - Provides self-contained PNT information with accelerometers and gyroscopes, allowing operation in GPS-denied environments

- Global Navigation Satellite Systems (GNSS):
 - Primary source of PNT data, with anti-jamming and anti-spoofing techniques (e.g., M-Code and SAASM for secure military applications)
- Inertial Navigation Systems (INS):
 - Provides self-contained PNT information with accelerometers and gyroscopes, allowing operation in GPS-denied environments
- Alternative PNT Sources:

Technologies Critical to A-PNT

Global Navigation Satellite Systems (GNSS):

 Primary source of PNT data, with anti-jamming and anti-spoofing techniques (e.g., M-Code and SAASM for secure military applications)

Inertial Navigation Systems (INS):

 Provides self-contained PNT information with accelerometers and gyroscopes, allowing operation in GPS-denied environments

Alternative PNT Sources:

 Terrestrial-based signals (e.g., radio, cellular networks) and signals from Low Earth Orbit (LEO) satellites

- Global Navigation Satellite Systems (GNSS):
 - Primary source of PNT data, with anti-jamming and anti-spoofing techniques (e.g., M-Code and SAASM for secure military applications)
- Inertial Navigation Systems (INS):
 - Provides self-contained PNT information with accelerometers and gyroscopes, allowing operation in GPS-denied environments
- Alternative PNT Sources:
 - Terrestrial-based signals (e.g., radio, cellular networks) and signals from Low Earth Orbit (LEO) satellites
- Precision Timing Sources:

Technologies Critical to A-PNT

Global Navigation Satellite Systems (GNSS):

 Primary source of PNT data, with anti-jamming and anti-spoofing techniques (e.g., M-Code and SAASM for secure military applications)

Inertial Navigation Systems (INS):

 Provides self-contained PNT information with accelerometers and gyroscopes, allowing operation in GPS-denied environments

Alternative PNT Sources:

 Terrestrial-based signals (e.g., radio, cellular networks) and signals from Low Earth Orbit (LEO) satellites

Precision Timing Sources:

 Atomic clocks and GPS-disciplined oscillators to ensure reliable timing



Technologies Critical to A-PNT

Global Navigation Satellite Systems (GNSS):

 Primary source of PNT data, with anti-jamming and anti-spoofing techniques (e.g., M-Code and SAASM for secure military applications)

Inertial Navigation Systems (INS):

 Provides self-contained PNT information with accelerometers and gyroscopes, allowing operation in GPS-denied environments

Alternative PNT Sources:

 Terrestrial-based signals (e.g., radio, cellular networks) and signals from Low Earth Orbit (LEO) satellites

Precision Timing Sources:

 Atomic clocks and GPS-disciplined oscillators to ensure reliable timing

Spoofing and Adversarial Threats

Spoofing and Adversarial Threats

■ Purpose of M-Code:

Spoofing and Adversarial Threats

- Purpose of M-Code:
 - Developed by the U.S. Department of Defense (DoD) for enhanced security in military GPS

Spoofing and Adversarial Threats

Purpose of M-Code:

- Developed by the U.S. Department of Defense (DoD) for enhanced security in military GPS
- Provides stronger encryption, anti-jamming, and anti-spoofing features compared to earlier GPS signals

Spoofing and Adversarial Threats

Purpose of M-Code:

- Developed by the U.S. Department of Defense (DoD) for enhanced security in military GPS
- Provides stronger encryption, anti-jamming, and anti-spoofing features compared to earlier GPS signals
- Current Status:

Spoofing and Adversarial Threats

Purpose of M-Code:

- Developed by the U.S. Department of Defense (DoD) for enhanced security in military GPS
- Provides stronger encryption, anti-jamming, and anti-spoofing features compared to earlier GPS signals

Current Status:

 No publicly available evidence that adversaries have successfully spoofed M-Code signals



Spoofing and Adversarial Threats

Purpose of M-Code:

- Developed by the U.S. Department of Defense (DoD) for enhanced security in military GPS
- Provides stronger encryption, anti-jamming, and anti-spoofing features compared to earlier GPS signals

Current Status:

- No publicly available evidence that adversaries have successfully spoofed M-Code signals
- M-Code's design makes spoofing significantly more challenging than with civilian signals

Spoofing and Adversarial Threats

Purpose of M-Code:

- Developed by the U.S. Department of Defense (DoD) for enhanced security in military GPS
- Provides stronger encryption, anti-jamming, and anti-spoofing features compared to earlier GPS signals

Current Status:

- No publicly available evidence that adversaries have successfully spoofed M-Code signals
- M-Code's design makes spoofing significantly more challenging than with civilian signals
- DoD Countermeasures:

Spoofing and Adversarial Threats

Purpose of M-Code:

- Developed by the U.S. Department of Defense (DoD) for enhanced security in military GPS
- Provides stronger encryption, anti-jamming, and anti-spoofing features compared to earlier GPS signals

Current Status:

- No publicly available evidence that adversaries have successfully spoofed M-Code signals
- M-Code's design makes spoofing significantly more challenging than with civilian signals

DoD Countermeasures:

 Ongoing assessment and improvements in GPS security to counter emerging threats

Spoofing and Adversarial Threats

■ Purpose of M-Code:

- Developed by the U.S. Department of Defense (DoD) for enhanced security in military GPS
- Provides stronger encryption, anti-jamming, and anti-spoofing features compared to earlier GPS signals

Current Status:

- No publicly available evidence that adversaries have successfully spoofed M-Code signals
- M-Code's design makes spoofing significantly more challenging than with civilian signals

DoD Countermeasures:

- Ongoing assessment and improvements in GPS security to counter emerging threats
- Continued vigilance as part of broader efforts to secure military navigation and timing

Spoofing and Adversarial Threats

■ Purpose of M-Code:

- Developed by the U.S. Department of Defense (DoD) for enhanced security in military GPS
- Provides stronger encryption, anti-jamming, and anti-spoofing features compared to earlier GPS signals

Current Status:

- No publicly available evidence that adversaries have successfully spoofed M-Code signals
- M-Code's design makes spoofing significantly more challenging than with civilian signals

DoD Countermeasures:

- Ongoing assessment and improvements in GPS security to counter emerging threats
- Continued vigilance as part of broader efforts to secure military navigation and timing

Key Features Enhancing M-Code Resilience

Key Features Enhancing M-Code Resilience

Higher Power Signal:

Key Features Enhancing M-Code Resilience

Higher Power Signal:

 M-Code is broadcast at a higher power level than civilian GPS signals, making it harder to overwhelm with jamming signals

Key Features Enhancing M-Code Resilience

- Higher Power Signal:
 - M-Code is broadcast at a higher power level than civilian GPS signals, making it harder to overwhelm with jamming signals
- Advanced Modulation Techniques:

Key Features Enhancing M-Code Resilience

Higher Power Signal:

 M-Code is broadcast at a higher power level than civilian GPS signals, making it harder to overwhelm with jamming signals

Advanced Modulation Techniques:

 Uses Binary Offset Carrier (BOC) modulation, which improves signal separation and reduces interference



Key Features Enhancing M-Code Resilience

- Higher Power Signal:
 - M-Code is broadcast at a higher power level than civilian GPS signals, making it harder to overwhelm with jamming signals
- Advanced Modulation Techniques:
 - Uses Binary Offset Carrier (BOC) modulation, which improves signal separation and reduces interference
- Narrower Beam Forming:

Key Features Enhancing M-Code Resilience

Higher Power Signal:

 M-Code is broadcast at a higher power level than civilian GPS signals, making it harder to overwhelm with jamming signals

Advanced Modulation Techniques:

 Uses Binary Offset Carrier (BOC) modulation, which improves signal separation and reduces interference

Narrower Beam Forming:

 Directed beam shaping on modern GPS III satellites focuses signals for military users, increasing jamming resistance

Key Features Enhancing M-Code Resilience

Higher Power Signal:

 M-Code is broadcast at a higher power level than civilian GPS signals, making it harder to overwhelm with jamming signals

Advanced Modulation Techniques:

 Uses Binary Offset Carrier (BOC) modulation, which improves signal separation and reduces interference

Narrower Beam Forming:

- Directed beam shaping on modern GPS III satellites focuses signals for military users, increasing jamming resistance
- Enhanced Encryption and Anti-Spoofing:

Key Features Enhancing M-Code Resilience

Higher Power Signal:

 M-Code is broadcast at a higher power level than civilian GPS signals, making it harder to overwhelm with jamming signals

Advanced Modulation Techniques:

 Uses Binary Offset Carrier (BOC) modulation, which improves signal separation and reduces interference

Narrower Beam Forming:

 Directed beam shaping on modern GPS III satellites focuses signals for military users, increasing jamming resistance

■ Enhanced Encryption and Anti-Spoofing:

 Strong encryption and authentication make M-Code signals harder for adversaries to disrupt or imitate



Key Features Enhancing M-Code Resilience

Higher Power Signal:

 M-Code is broadcast at a higher power level than civilian GPS signals, making it harder to overwhelm with jamming signals

Advanced Modulation Techniques:

 Uses Binary Offset Carrier (BOC) modulation, which improves signal separation and reduces interference

Narrower Beam Forming:

 Directed beam shaping on modern GPS III satellites focuses signals for military users, increasing jamming resistance

■ Enhanced Encryption and Anti-Spoofing:

 Strong encryption and authentication make M-Code signals harder for adversaries to disrupt or imitate

Strategies for Resilience and Accuracy

Strategies for Resilience and Accuracy

Sensor Fusion Algorithms:

Strategies for Resilience and Accuracy

Sensor Fusion Algorithms:

 Integrate data from multiple sources (GNSS, INS, timing devices) to create a reliable composite solution

Strategies for Resilience and Accuracy

Sensor Fusion Algorithms:

- Integrate data from multiple sources (GNSS, INS, timing devices) to create a reliable composite solution
- Kalman filters and machine learning models are commonly used

Strategies for Resilience and Accuracy

- Sensor Fusion Algorithms:
 - Integrate data from multiple sources (GNSS, INS, timing devices) to create a reliable composite solution
 - Kalman filters and machine learning models are commonly used
- Robust Signal Authentication:

Strategies for Resilience and Accuracy

Sensor Fusion Algorithms:

- Integrate data from multiple sources (GNSS, INS, timing devices) to create a reliable composite solution
- Kalman filters and machine learning models are commonly used

Robust Signal Authentication:

 Techniques to verify signal integrity and authenticity, essential for detecting spoofing and interference

Strategies for Resilience and Accuracy

- Sensor Fusion Algorithms:
 - Integrate data from multiple sources (GNSS, INS, timing devices) to create a reliable composite solution
 - Kalman filters and machine learning models are commonly used
- Robust Signal Authentication:
 - Techniques to verify signal integrity and authenticity, essential for detecting spoofing and interference
- System Redundancy:

Strategies for Resilience and Accuracy

Sensor Fusion Algorithms:

- Integrate data from multiple sources (GNSS, INS, timing devices) to create a reliable composite solution
- Kalman filters and machine learning models are commonly used

Robust Signal Authentication:

 Techniques to verify signal integrity and authenticity, essential for detecting spoofing and interference

System Redundancy:

 Use of alternative PNT sources to maintain accuracy in contested or challenging environments

Strategies for Resilience and Accuracy

Sensor Fusion Algorithms:

- Integrate data from multiple sources (GNSS, INS, timing devices) to create a reliable composite solution
- Kalman filters and machine learning models are commonly used

Robust Signal Authentication:

- Techniques to verify signal integrity and authenticity, essential for detecting spoofing and interference
- System Redundancy:
 - Use of alternative PNT sources to maintain accuracy in contested or challenging environments
- Intermittent GPS Synchronization:

Strategies for Resilience and Accuracy

Sensor Fusion Algorithms:

- Integrate data from multiple sources (GNSS, INS, timing devices) to create a reliable composite solution
- Kalman filters and machine learning models are commonly used

Robust Signal Authentication:

 Techniques to verify signal integrity and authenticity, essential for detecting spoofing and interference

System Redundancy:

 Use of alternative PNT sources to maintain accuracy in contested or challenging environments

Intermittent GPS Synchronization:

 Periodic GPS updates improve INS drift performance and timing accuracy



Strategies for Resilience and Accuracy

Sensor Fusion Algorithms:

- Integrate data from multiple sources (GNSS, INS, timing devices) to create a reliable composite solution
- Kalman filters and machine learning models are commonly used

Robust Signal Authentication:

 Techniques to verify signal integrity and authenticity, essential for detecting spoofing and interference

System Redundancy:

 Use of alternative PNT sources to maintain accuracy in contested or challenging environments

Intermittent GPS Synchronization:

 Periodic GPS updates improve INS drift performance and timing accuracy

System Components

Assured Position, Navigation, and Timing (A-PNT) System Components

Primary Navigation Sources

System Components

Primary Navigation Sources

 GNSS (e.g., GPS), supplemented with anti-jamming technology

System Components

- Primary Navigation Sources
 - GNSS (e.g., GPS), supplemented with anti-jamming technology
- Alternative PNT Sources

System Components

Primary Navigation Sources

- GNSS (e.g., GPS), supplemented with anti-jamming technology
- Alternative PNT Sources
 - Terrestrial radio, cellular, and other satellite constellations

System Components

- Primary Navigation Sources
 - GNSS (e.g., GPS), supplemented with anti-jamming technology
- Alternative PNT Sources
 - Terrestrial radio, cellular, and other satellite constellations
- IMUs and Precise Clocks

System Components

Primary Navigation Sources

- GNSS (e.g., GPS), supplemented with anti-jamming technology
- Alternative PNT Sources
 - Terrestrial radio, cellular, and other satellite constellations
- IMUs and Precise Clocks
 - INS data for position and orientation in GPS-denied conditions

System Components

- Primary Navigation Sources
 - GNSS (e.g., GPS), supplemented with anti-jamming technology
- Alternative PNT Sources
 - Terrestrial radio, cellular, and other satellite constellations
- IMUs and Precise Clocks
 - INS data for position and orientation in GPS-denied conditions

■ State Vector $x = [P_x, P_y, P_z, V_x, V_y, V_z, Orientation, Accel Bias, Gyro Bias, Clock Bias$

- State Vector $\mathbf{x} = [P_x, P_y, P_z, V_x, V_y, V_z, \text{Orientation}, \text{Accel Bias}, \text{Gyro Bias}, \text{Clock Bias}]$
- Position and Velocity

- State Vector $x = [P_x, P_y, P_z, V_x, V_y, V_z, Orientation, Accel Bias, Gyro Bias, Clock Bias$
- Position and Velocity
- Attitude and Orientation

- State Vector $\mathbf{x} = [P_x, P_y, P_z, V_x, V_y, V_z, \text{Orientation}, \text{Accel Bias}, \text{Gyro Bias}, \text{Clock Bias}]$
- Position and Velocity
- Attitude and Orientation
- Accelerometer and Gyroscope Biases

- State Vector $x = [P_x, P_y, P_z, V_x, V_y, V_z, Orientation, Accel Bias, Gyro Bias, Clock Bias$
- Position and Velocity
- Attitude and Orientation
- Accelerometer and Gyroscope Biases
- Clock Bias and Drift

- State Vector $x = [P_x, P_y, P_z, V_x, V_y, V_z, Orientation, Accel Bias, Gyro Bias, Clock Bias$
- Position and Velocity
- Attitude and Orientation
- Accelerometer and Gyroscope Biases
- Clock Bias and Drift

Overview

■ What is IGS?

What is IGS?

 IGS is a global collaborative network led by NASA's Jet Propulsion Laboratory (JPL)

What is IGS?

- IGS is a global collaborative network led by NASA's Jet Propulsion Laboratory (JPL)
- Provides highly accurate GNSS data and products, supporting research, navigation, and Earth observation

What is IGS?

- IGS is a global collaborative network led by NASA's Jet Propulsion Laboratory (JPL)
- Provides highly accurate GNSS data and products, supporting research, navigation, and Earth observation
- Support by 500+ Tracking Stations and Dozens of Analysis Centers

Overview

What is IGS?

- IGS is a global collaborative network led by NASA's Jet Propulsion Laboratory (JPL)
- Provides highly accurate GNSS data and products, supporting research, navigation, and Earth observation
- Support by 500+ Tracking Stations and Dozens of Analysis Centers
- GNSS Systems Supported:

Additional Navaids: The International GNSS Service (IGS)

Overview

What is IGS?

- IGS is a global collaborative network led by NASA's Jet Propulsion Laboratory (JPL)
- Provides highly accurate GNSS data and products, supporting research, navigation, and Earth observation
- Support by 500+ Tracking Stations and Dozens of Analysis Centers

GNSS Systems Supported:

■ IGS includes data from multiple GNSS systems: GPS, GLONASS, Galileo, BeiDou, and QZSS

Additional Navaids: The International GNSS Service (IGS)

Overview

What is IGS?

- IGS is a global collaborative network led by NASA's Jet Propulsion Laboratory (JPL)
- Provides highly accurate GNSS data and products, supporting research, navigation, and Earth observation
- Support by 500+ Tracking Stations and Dozens of Analysis Centers

GNSS Systems Supported:

- IGS includes data from multiple GNSS systems: GPS, GLONASS, Galileo, BeiDou, and QZSS
- Enables multi-constellation support, increasing resilience when GPS signals are unavailable

Additional Navaids: The International GNSS Service (IGS)

Overview

■ What is IGS?

- IGS is a global collaborative network led by NASA's Jet Propulsion Laboratory (JPL)
- Provides highly accurate GNSS data and products, supporting research, navigation, and Earth observation
- Support by 500+ Tracking Stations and Dozens of Analysis Centers

GNSS Systems Supported:

- IGS includes data from multiple GNSS systems: GPS, GLONASS, Galileo, BeiDou, and QZSS
- Enables multi-constellation support, increasing resilience when GPS signals are unavailable

Applications in Navigation and PNT Systems

Precise GNSS Satellite Orbits:

- Precise GNSS Satellite Orbits:
 - Provides satellite position data with centimeter-level accuracy

- Precise GNSS Satellite Orbits:
 - Provides satellite position data with centimeter-level accuracy
- Satellite Clock Corrections:

- Precise GNSS Satellite Orbits:
 - Provides satellite position data with centimeter-level accuracy
- Satellite Clock Corrections:
 - Offers high-accuracy clock corrections, improving timing accuracy across systems

- Precise GNSS Satellite Orbits:
 - Provides satellite position data with centimeter-level accuracy
- Satellite Clock Corrections:
 - Offers high-accuracy clock corrections, improving timing accuracy across systems
- Earth Rotation Parameters (ERP):



- Precise GNSS Satellite Orbits:
 - Provides satellite position data with centimeter-level accuracy
- Satellite Clock Corrections:
 - Offers high-accuracy clock corrections, improving timing accuracy across systems
- Earth Rotation Parameters (ERP):
 - Supports high-precision geospatial applications by modeling Earth's rotational variations

- Precise GNSS Satellite Orbits:
 - Provides satellite position data with centimeter-level accuracy
- Satellite Clock Corrections:
 - Offers high-accuracy clock corrections, improving timing accuracy across systems
- Earth Rotation Parameters (ERP):
 - Supports high-precision geospatial applications by modeling Earth's rotational variations
- Ionospheric and Tropospheric Data:

- Precise GNSS Satellite Orbits:
 - Provides satellite position data with centimeter-level accuracy
- Satellite Clock Corrections:
 - Offers high-accuracy clock corrections, improving timing accuracy across systems
- Earth Rotation Parameters (ERP):
 - Supports high-precision geospatial applications by modeling Earth's rotational variations
- Ionospheric and Tropospheric Data:
 - Models atmospheric effects on GNSS signals, enabling better correction and positioning accuracy

- Precise GNSS Satellite Orbits:
 - Provides satellite position data with centimeter-level accuracy
- Satellite Clock Corrections:
 - Offers high-accuracy clock corrections, improving timing accuracy across systems
- Earth Rotation Parameters (ERP):
 - Supports high-precision geospatial applications by modeling Earth's rotational variations
- Ionospheric and Tropospheric Data:
 - Models atmospheric effects on GNSS signals, enabling better correction and positioning accuracy

Role of IGS in GPS-Denied Scenarios

Role of IGS in GPS-Denied Scenarios

Multi-Constellation GNSS Data:

Role of IGS in GPS-Denied Scenarios

Multi-Constellation GNSS Data:

 IGS provides real-time GNSS data from systems like GLONASS and Galileo, which can supplement GPS-denied times

Role of IGS in GPS-Denied Scenarios

- Multi-Constellation GNSS Data:
 - IGS provides real-time GNSS data from systems like GLONASS and Galileo, which can supplement GPS-denied times
- Leveraging Precise Clock Corrections:

Role of IGS in GPS-Denied Scenarios

Multi-Constellation GNSS Data:

 IGS provides real-time GNSS data from systems like GLONASS and Galileo, which can supplement GPS-denied times

Leveraging Precise Clock Corrections:

 Accurate timing corrections from IGS improve clock drift estimates, supporting INS and gyro-based dead reckoning



Role of IGS in GPS-Denied Scenarios

- Multi-Constellation GNSS Data:
 - IGS provides real-time GNSS data from systems like GLONASS and Galileo, which can supplement GPS-denied times
- Leveraging Precise Clock Corrections:
 - Accurate timing corrections from IGS improve clock drift estimates, supporting INS and gyro-based dead reckoning
- Ionospheric Models for Error Mitigation:

Role of IGS in GPS-Denied Scenarios

Multi-Constellation GNSS Data:

 IGS provides real-time GNSS data from systems like GLONASS and Galileo, which can supplement GPS-denied times

Leveraging Precise Clock Corrections:

 Accurate timing corrections from IGS improve clock drift estimates, supporting INS and gyro-based dead reckoning

Ionospheric Models for Error Mitigation:

 IGS's atmospheric data can be used to refine position estimates, reducing gyro error propagation

Role of IGS in GPS-Denied Scenarios

- Multi-Constellation GNSS Data:
 - IGS provides real-time GNSS data from systems like GLONASS and Galileo, which can supplement GPS-denied times
- Leveraging Precise Clock Corrections:
 - Accurate timing corrections from IGS improve clock drift estimates, supporting INS and gyro-based dead reckoning
- Ionospheric Models for Error Mitigation:
 - IGS's atmospheric data can be used to refine position estimates, reducing gyro error propagation
- Earth Rotation Parameters (ERP):

Role of IGS in GPS-Denied Scenarios

Multi-Constellation GNSS Data:

 IGS provides real-time GNSS data from systems like GLONASS and Galileo, which can supplement GPS-denied times

Leveraging Precise Clock Corrections:

 Accurate timing corrections from IGS improve clock drift estimates, supporting INS and gyro-based dead reckoning

Ionospheric Models for Error Mitigation:

 IGS's atmospheric data can be used to refine position estimates, reducing gyro error propagation

Earth Rotation Parameters (ERP):

 ERPs help maintain geodetic accuracy, which stabilizes navigation in the absence of direct GNSS signals



Role of IGS in GPS-Denied Scenarios

Multi-Constellation GNSS Data:

 IGS provides real-time GNSS data from systems like GLONASS and Galileo, which can supplement GPS-denied times

Leveraging Precise Clock Corrections:

 Accurate timing corrections from IGS improve clock drift estimates, supporting INS and gyro-based dead reckoning

Ionospheric Models for Error Mitigation:

 IGS's atmospheric data can be used to refine position estimates, reducing gyro error propagation

■ Earth Rotation Parameters (ERP):

■ ERPs help maintain geodetic accuracy, which stabilizes navigation in the absence of direct GNSS signals

Enhancing PNT Robustness with IGS Data

Increased Redundancy through Multi-GNSS Data:

- Increased Redundancy through Multi-GNSS Data:
 - Enables fallback to alternative GNSS systems (e.g., GLONASS, Galileo), maintaining PNT resilience

- Increased Redundancy through Multi-GNSS Data:
 - Enables fallback to alternative GNSS systems (e.g., GLONASS, Galileo), maintaining PNT resilience
- Reduced Dependence on Single GNSS System:

- Increased Redundancy through Multi-GNSS Data:
 - Enables fallback to alternative GNSS systems (e.g., GLONASS, Galileo), maintaining PNT resilience
- Reduced Dependence on Single GNSS System:
 - IGS provides products compatible with multiple constellations, lowering the impact of GPS outages

- Increased Redundancy through Multi-GNSS Data:
 - Enables fallback to alternative GNSS systems (e.g., GLONASS, Galileo), maintaining PNT resilience
- Reduced Dependence on Single GNSS System:
 - IGS provides products compatible with multiple constellations, lowering the impact of GPS outages
- Supports Continuous Navigation:

- Increased Redundancy through Multi-GNSS Data:
 - Enables fallback to alternative GNSS systems (e.g., GLONASS, Galileo), maintaining PNT resilience
- Reduced Dependence on Single GNSS System:
 - IGS provides products compatible with multiple constellations, lowering the impact of GPS outages
- Supports Continuous Navigation:
 - By integrating IGS products, INS and gyro systems maintain bounded errors and reliable navigation



- Increased Redundancy through Multi-GNSS Data:
 - Enables fallback to alternative GNSS systems (e.g., GLONASS, Galileo), maintaining PNT resilience
- Reduced Dependence on Single GNSS System:
 - IGS provides products compatible with multiple constellations, lowering the impact of GPS outages
- Supports Continuous Navigation:
 - By integrating IGS products, INS and gyro systems maintain bounded errors and reliable navigation



Delayed GPS OCX and MGUE Programs:

- Delayed GPS OCX and MGUE Programs:
 - GPS OCX (Next Generation Operational Control System):

Critical for improved anti-jamming and anti-spoofing capabilities, but delayed deployment affects A-PNT timelines

- Delayed GPS OCX and MGUE Programs:
 - GPS OCX (Next Generation Operational Control System):
 - Critical for improved anti-jamming and anti-spoofing capabilities, but delayed deployment affects A-PNT timelines
 - GPS MGUE (Military GPS User Equipment):
 Essential for integrating M-Code, which is designed to enhance signal security; delays impact military readiness for secure PNT

- Delayed GPS OCX and MGUE Programs:
 - GPS OCX (Next Generation Operational Control System):
 - Critical for improved anti-jamming and anti-spoofing capabilities, but delayed deployment affects A-PNT timelines
 - GPS MGUE (Military GPS User Equipment):
 Essential for integrating M-Code, which is designed to enhance signal security; delays impact military readiness for secure PNT
- Increased Costs Due to Extended Timelines:

- Delayed GPS OCX and MGUE Programs:
 - GPS OCX (Next Generation Operational Control System):
 - Critical for improved anti-jamming and anti-spoofing capabilities, but delayed deployment affects A-PNT timelines
 - GPS MGUE (Military GPS User Equipment):
 Essential for integrating M-Code, which is designed to enhance signal security; delays impact military readiness for secure PNT
- Increased Costs Due to Extended Timelines:
 - Project delays require additional funding to maintain and upgrade legacy systems as a stopgap solution

- Delayed GPS OCX and MGUE Programs:
 - GPS OCX (Next Generation Operational Control System):
 - Critical for improved anti-jamming and anti-spoofing capabilities, but delayed deployment affects A-PNT timelines
 - GPS MGUE (Military GPS User Equipment):
 Essential for integrating M-Code, which is designed to enhance signal security; delays impact military readiness for secure PNT
- Increased Costs Due to Extended Timelines:
 - Project delays require additional funding to maintain and upgrade legacy systems as a stopgap solution
- Dependency on Supplemental PNT Solutions:

- Delayed GPS OCX and MGUE Programs:
 - GPS OCX (Next Generation Operational Control System):
 - Critical for improved anti-jamming and anti-spoofing capabilities, but delayed deployment affects A-PNT timelines
 - GPS MGUE (Military GPS User Equipment):
 Essential for integrating M-Code, which is designed to enhance signal security; delays impact military readiness for secure PNT
- Increased Costs Due to Extended Timelines:
 - Project delays require additional funding to maintain and upgrade legacy systems as a stopgap solution
- Dependency on Supplemental PNT Solutions:
 - Delays in OCX and MGUE push agencies to invest in alternative PNT solutions (e.g., terrestrial or LEO-based systems), increasing overall costs

- Delayed GPS OCX and MGUE Programs:
 - GPS OCX (Next Generation Operational Control System):
 - Critical for improved anti-jamming and anti-spoofing capabilities, but delayed deployment affects A-PNT timelines
 - GPS MGUE (Military GPS User Equipment):
 Essential for integrating M-Code, which is designed to enhance signal security; delays impact military readiness for secure PNT
- Increased Costs Due to Extended Timelines:
 - Project delays require additional funding to maintain and upgrade legacy systems as a stopgap solution
- Dependency on Supplemental PNT Solutions:
 - Delays in OCX and MGUE push agencies to invest in alternative PNT solutions (e.g., terrestrial or LEO-based systems), increasing overall costs

Adapting to Delays and Rising Costs

Balancing Investment in Legacy Systems and Modernization:

- Balancing Investment in Legacy Systems and Modernization:
 - Funding needed to sustain legacy GPS systems until OCX and MGUE are operational, adding to budget strain

- Balancing Investment in Legacy Systems and Modernization:
 - Funding needed to sustain legacy GPS systems until OCX and MGUE are operational, adding to budget strain
 - Resources diverted to address immediate operational gaps rather than long-term A-PNT advancements

- Balancing Investment in Legacy Systems and Modernization:
 - Funding needed to sustain legacy GPS systems until OCX and MGUE are operational, adding to budget strain
 - Resources diverted to address immediate operational gaps rather than long-term A-PNT advancements
- Investment in Alternative A-PNT Technologies:

- Balancing Investment in Legacy Systems and Modernization:
 - Funding needed to sustain legacy GPS systems until OCX and MGUE are operational, adding to budget strain
 - Resources diverted to address immediate operational gaps rather than long-term A-PNT advancements
- Investment in Alternative A-PNT Technologies:
 - Increased allocation for non-GPS-dependent solutions (e.g., IMUs, precision timing, and LEO constellations) adds to the budget but enhances resilience

- Balancing Investment in Legacy Systems and Modernization:
 - Funding needed to sustain legacy GPS systems until OCX and MGUE are operational, adding to budget strain
 - Resources diverted to address immediate operational gaps rather than long-term A-PNT advancements
- Investment in Alternative A-PNT Technologies:
 - Increased allocation for non-GPS-dependent solutions (e.g., IMUs, precision timing, and LEO constellations) adds to the budget but enhances resilience
- Cost of Integrating New Technologies:

Adapting to Delays and Rising Costs

Balancing Investment in Legacy Systems and Modernization:

- Funding needed to sustain legacy GPS systems until OCX and MGUE are operational, adding to budget strain
- Resources diverted to address immediate operational gaps rather than long-term A-PNT advancements

Investment in Alternative A-PNT Technologies:

- Increased allocation for non-GPS-dependent solutions (e.g., IMUs, precision timing, and LEO constellations) adds to the budget but enhances resilience
- Cost of Integrating New Technologies:
 - Integrating supplemental technologies with existing infrastructure can be complex and costly



Adapting to Delays and Rising Costs

Balancing Investment in Legacy Systems and Modernization:

- Funding needed to sustain legacy GPS systems until OCX and MGUE are operational, adding to budget strain
- Resources diverted to address immediate operational gaps rather than long-term A-PNT advancements

Investment in Alternative A-PNT Technologies:

- Increased allocation for non-GPS-dependent solutions (e.g., IMUs, precision timing, and LEO constellations) adds to the budget but enhances resilience
- Cost of Integrating New Technologies:
 - Integrating supplemental technologies with existing infrastructure can be complex and costly
 - Ensuring interoperability between legacy and new systems is resource-intensive



Adapting to Delays and Rising Costs

Balancing Investment in Legacy Systems and Modernization:

- Funding needed to sustain legacy GPS systems until OCX and MGUE are operational, adding to budget strain
- Resources diverted to address immediate operational gaps rather than long-term A-PNT advancements

Investment in Alternative A-PNT Technologies:

- Increased allocation for non-GPS-dependent solutions (e.g., IMUs, precision timing, and LEO constellations) adds to the budget but enhances resilience
- Cost of Integrating New Technologies:
 - Integrating supplemental technologies with existing infrastructure can be complex and costly
 - Ensuring interoperability between legacy and new systems is resource-intensive



Overview

Optical Gyroscopes

Overview

Optical Gyroscopes

■ Fiber-Optic Gyroscopes (FOGs)
Achieve accuracy of 0.1 to 0.0001 degrees per hour

Overview

Optical Gyroscopes

- Fiber-Optic Gyroscopes (FOGs)
 Achieve accuracy of 0.1 to 0.0001 degrees per hour
- Optical Resonator Gyroscopes (ORGs)
 Random drift values as low as 0.06 degrees per hour

- Optical Gyroscopes
 - Fiber-Optic Gyroscopes (FOGs)
 Achieve accuracy of 0.1 to 0.0001 degrees per hour
 - Optical Resonator Gyroscopes (ORGs)
 Random drift values as low as 0.06 degrees per hour
- Micro-Electro-Mechanical Systems (MEMS) Gyroscopes

- Optical Gyroscopes
 - Fiber-Optic Gyroscopes (FOGs)
 Achieve accuracy of 0.1 to 0.0001 degrees per hour
 - Optical Resonator Gyroscopes (ORGs)
 Random drift values as low as 0.06 degrees per hour
- Micro-Electro-Mechanical Systems (MEMS) Gyroscopes
 - Miniaturization advances enable high-precision navigation-grade applications

- Optical Gyroscopes
 - Fiber-Optic Gyroscopes (FOGs)
 Achieve accuracy of 0.1 to 0.0001 degrees per hour
 - Optical Resonator Gyroscopes (ORGs)
 Random drift values as low as 0.06 degrees per hour
- Micro-Electro-Mechanical Systems (MEMS) Gyroscopes
 - Miniaturization advances enable high-precision navigation-grade applications
- Quantum Gyroscopes

Overview

Optical Gyroscopes

- Fiber-Optic Gyroscopes (FOGs)
 Achieve accuracy of 0.1 to 0.0001 degrees per hour
- Optical Resonator Gyroscopes (ORGs)
 Random drift values as low as 0.06 degrees per hour

■ Micro-Electro-Mechanical Systems (MEMS) Gyroscopes

- Miniaturization advances enable high-precision navigation-grade applications
- Quantum Gyroscopes
 - Using double-mode surface-acoustic-wave cavities to surpass standard quantum limits

Overview

Optical Gyroscopes

- Fiber-Optic Gyroscopes (FOGs)
 Achieve accuracy of 0.1 to 0.0001 degrees per hour
- Optical Resonator Gyroscopes (ORGs)
 Random drift values as low as 0.06 degrees per hour

Micro-Electro-Mechanical Systems (MEMS) Gyroscopes

- Miniaturization advances enable high-precision navigation-grade applications
- Quantum Gyroscopes
 - Using double-mode surface-acoustic-wave cavities to surpass standard quantum limits
- Applications

Expanding to medical, sensing, imaging, and critical navigation

Overview

Optical Gyroscopes

- Fiber-Optic Gyroscopes (FOGs)
 Achieve accuracy of 0.1 to 0.0001 degrees per hour
- Optical Resonator Gyroscopes (ORGs)
 Random drift values as low as 0.06 degrees per hour

■ Micro-Electro-Mechanical Systems (MEMS) Gyroscopes

- Miniaturization advances enable high-precision navigation-grade applications
- Quantum Gyroscopes
 - Using double-mode surface-acoustic-wave cavities to surpass standard quantum limits
- Applications

Expanding to medical, sensing, imaging, and critical navigation

Navigation-Grade Gyroscope Performance Criteria

■ Bias Instability (Drift Rate)

Navigation-Grade Gyroscope Performance Criteria

- Bias Instability (Drift Rate)
 - Drift rates around 0.01 to 1 degree per hour

Navigation-Grade Gyroscope Performance Criteria

- Bias Instability (Drift Rate)
 - Drift rates around 0.01 to 1 degree per hour
- Scale Factor Accuracy

- Bias Instability (Drift Rate)
 - Drift rates around 0.01 to 1 degree per hour
- Scale Factor Accuracy
 - Accuracy within 50 ppm

- Bias Instability (Drift Rate)
 - Drift rates around 0.01 to 1 degree per hour
- Scale Factor Accuracy
 - Accuracy within 50 ppm
- Noise Performance (Angle Random Walk)

- Bias Instability (Drift Rate)
 - Drift rates around 0.01 to 1 degree per hour
- Scale Factor Accuracy
 - Accuracy within 50 ppm
- Noise Performance (Angle Random Walk)
 - Below 0.01 degrees per $\sqrt{\text{hour}}$

- Bias Instability (Drift Rate)
 - Drift rates around 0.01 to 1 degree per hour
- Scale Factor Accuracy
 - Accuracy within 50 ppm
- Noise Performance (Angle Random Walk)
 - Below 0.01 degrees per $\sqrt{\text{hour}}$
- Thermal Stability and Bandwidth

- Bias Instability (Drift Rate)
 - Drift rates around 0.01 to 1 degree per hour
- Scale Factor Accuracy
 - Accuracy within 50 ppm
- Noise Performance (Angle Random Walk)
 - Below 0.01 degrees per $\sqrt{\text{hour}}$
- Thermal Stability and Bandwidth
 - Consistent performance under varying temperatures and dynamic changes

- Bias Instability (Drift Rate)
 - Drift rates around 0.01 to 1 degree per hour
- Scale Factor Accuracy
 - Accuracy within 50 ppm
- Noise Performance (Angle Random Walk)
 - Below 0.01 degrees per $\sqrt{\text{hour}}$
- Thermal Stability and Bandwidth
 - Consistent performance under varying temperatures and dynamic changes



MEMS Gyroscopes with Navigation-Grade Performance Examples

MEMS Gyroscopes with Navigation-Grade Performance Examples

■ CEA-Leti's Nano-Resistive Sensing Gyroscope

- CEA-Leti's Nano-Resistive Sensing Gyroscope
 - \blacksquare Bias instability of 0.02°/h and angular random walk (ARW) of 0.004°/ \sqrt{h}

- CEA-Leti's Nano-Resistive Sensing Gyroscope
 - Bias instability of $0.02^{\circ}/h$ and angular random walk (ARW) of $0.004^{\circ}/\sqrt{h}$
- Safran's Si-MEMS Gyroscope

- CEA-Leti's Nano-Resistive Sensing Gyroscope
 - Bias instability of $0.02^{\circ}/h$ and angular random walk (ARW) of $0.004^{\circ}/\sqrt{h}$
- Safran's Si-MEMS Gyroscope
 - High-precision with optimization for CSWAP requirements

- CEA-Leti's Nano-Resistive Sensing Gyroscope
 - Bias instability of $0.02^{\circ}/h$ and angular random walk (ARW) of $0.004^{\circ}/\sqrt{h}$
- Safran's Si-MEMS Gyroscope
 - High-precision with optimization for CSWAP requirements
- EMCORE's Quartz MEMS IMU

- CEA-Leti's Nano-Resistive Sensing Gyroscope
 - Bias instability of $0.02^{\circ}/h$ and angular random walk (ARW) of $0.004^{\circ}/\sqrt{h}$
- Safran's Si-MEMS Gyroscope
 - High-precision with optimization for CSWAP requirements
- EMCORE's Quartz MEMS IMU
 - Angle random walk į $0.006^{\circ}/\sqrt{h}$, bias stability of $0.2^{\circ}/h$ over temperature

- CEA-Leti's Nano-Resistive Sensing Gyroscope
 - Bias instability of $0.02^{\circ}/h$ and angular random walk (ARW) of $0.004^{\circ}/\sqrt{h}$
- Safran's Si-MEMS Gyroscope
 - High-precision with optimization for CSWAP requirements
- EMCORE's Quartz MEMS IMU
 - Angle random walk | $0.006^{\circ}/\sqrt{h}$, bias stability of $0.2^{\circ}/h$ over temperature



Importance without GPS

Reducing Drift Accumulation

- Reducing Drift Accumulation
 - Synchronizes timing, reducing drift over time

- Reducing Drift Accumulation
 - Synchronizes timing, reducing drift over time
- Improving Dead Reckoning Accuracy

- Reducing Drift Accumulation
 - Synchronizes timing, reducing drift over time
- Improving Dead Reckoning Accuracy
 - Enables consistent time-stamping of measurements

- Reducing Drift Accumulation
 - Synchronizes timing, reducing drift over time
- Improving Dead Reckoning Accuracy
 - Enables consistent time-stamping of measurements
- Supporting Sensor Fusion Algorithms

- Reducing Drift Accumulation
 - Synchronizes timing, reducing drift over time
- Improving Dead Reckoning Accuracy
 - Enables consistent time-stamping of measurements
- Supporting Sensor Fusion Algorithms
 - Accurate timing of multi-sensor data, improving algorithm performance

- Reducing Drift Accumulation
 - Synchronizes timing, reducing drift over time
- Improving Dead Reckoning Accuracy
 - Enables consistent time-stamping of measurements
- Supporting Sensor Fusion Algorithms
 - Accurate timing of multi-sensor data, improving algorithm performance
- Supporting Assisted Inertial Navigation Systems (AINS)

- Reducing Drift Accumulation
 - Synchronizes timing, reducing drift over time
- Improving Dead Reckoning Accuracy
 - Enables consistent time-stamping of measurements
- Supporting Sensor Fusion Algorithms
 - Accurate timing of multi-sensor data, improving algorithm performance
- Supporting Assisted Inertial Navigation Systems (AINS)
 - Assists in periodic GPS syncing for extended stability

- Reducing Drift Accumulation
 - Synchronizes timing, reducing drift over time
- Improving Dead Reckoning Accuracy
 - Enables consistent time-stamping of measurements
- Supporting Sensor Fusion Algorithms
 - Accurate timing of multi-sensor data, improving algorithm performance
- Supporting Assisted Inertial Navigation Systems (AINS)
 - Assists in periodic GPS syncing for extended stability

Overview and History

Founded in 1984

- Founded in 1984
- Specializes in fiber optic, MEMS, and ring laser gyro technology

- Founded in 1984
- Specializes in fiber optic, MEMS, and ring laser gyro technology
- Applications in aerospace, defense, and industrial markets

- Founded in 1984
- Specializes in fiber optic, MEMS, and ring laser gyro technology
- Applications in aerospace, defense, and industrial markets

Timing Solutions for PNT

GPS-Disciplined Time and Frequency Systems

- GPS-Disciplined Time and Frequency Systems
 - M-Code and SAASM GPS receivers for secure applications

- GPS-Disciplined Time and Frequency Systems
 - M-Code and SAASM GPS receivers for secure applications
- High-Precision Oscillators



- GPS-Disciplined Time and Frequency Systems
 - M-Code and SAASM GPS receivers for secure applications
- High-Precision Oscillators
 - Uses Rubidium Atomic Clocks for precise timing

- GPS-Disciplined Time and Frequency Systems
 - M-Code and SAASM GPS receivers for secure applications
- High-Precision Oscillators
 - Uses Rubidium Atomic Clocks for precise timing
- Certified for Defense Applications

- GPS-Disciplined Time and Frequency Systems
 - M-Code and SAASM GPS receivers for secure applications
- High-Precision Oscillators
 - Uses Rubidium Atomic Clocks for precise timing
- Certified for Defense Applications
 - Approved Host Application Equipment integrator

Timing Solutions for PNT

- GPS-Disciplined Time and Frequency Systems
 - M-Code and SAASM GPS receivers for secure applications
- High-Precision Oscillators
 - Uses Rubidium Atomic Clocks for precise timing
- Certified for Defense Applications
 - Approved Host Application Equipment integrator
