COMPUTER-AIDED DESIGN SYSTEMS

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PECULIARITIES OF FUTURE AIR NAVIGATION SYSTEM BASED ON INERTIAL NAVIGATION SYSTEMS/GLOBAL POSITIONING SYSTEM

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Using an inertial navigation system and Global Positioning System together is preferable to using any of them separately. Derived benefits depend on the level of combining information. Inertial navigation systems/Global Positioning System integration architectures are defined as separate, loosely and tightly coupled, deeply integrated configurations.

Keywords: inertial navigation systems, Global Positioning System, integration.

Introduction. Present-day navigation systems should meet the demands of accuracy, integrity, availability and continuity of navigation.

Many inertial navigation systems can be replaced with less accurate inertial systems if Global Positioning System (GPS) was permanently available to update the inertial system to limit its error growth.

International Civil Aviation Organization (ICAO) Committee on future navigational systems (FANS – Future Air Navigation System) made a decision on the obligatory use of satellite navigation systems in combination with inertial navigation systems (INS) [1].

Providing given levels of accuracy and marked quality reliability indexes envisages special requirements to modern and perspective systems of navigation.

The measure of integrity is the probability of system operation characteristics recovery detection (especially accuracy) for certain limits and information about it at the specified time.

Availability is determined by the probability of reliable and accurate information reception by a consumer at the specified time. Continuity is characterized by the probability of providing a consumer with reliable information at the specified time. Credibility is defined as the ability of navigational system to support the available probability of its characteristics in necessary limits at the specified time in some region/ providing necessary level of those indexes is often a more complicated problem than providing necessary accuracy of navigation measurements.

Table 1 summarizes features and shortcomings of INS and GPS.

Table 1

Features of INS and GPS

	Attributes	**Shortcomings**
GPS	Self-initializing Errors are bounded	Low data rate Lower attitude accuracy Susceptible to interference (intentional and unintentional) Expensive infrastructure
INS	High data rate Both translational and rotational information Self-contained (not susceptible to jamming)	Unbounded errors Requires knowledge of gravity field Requires initial conditions High per unit cost

The goal of INS/GPS integration, besides providing the redundancy of two systems, is to take advantage of the synergy outlined as follows:

1) The conventional approach to aiding the receiver's carrier and code tracking loops with inertial sensor information allows us to reduce the effective bandwidth of these loops, even during severe vehicle maneuvers, thereby improving the ability of the receiver to track the signals in a noisy environment such as caused by a jammer. The more accurate the inertial information is, the narrower is the bandwidth of the loops that can be designed. In jamming environment, this allows the vehicle to approach a jammer-protected target more closely before losing GPS tracking [2]. A "deeply-integrated" approach to aiding will be shown to be even more robust. Outside the jamming environment, INS data provides high bandwidth accurate navigation and information control and allows a long series of GPS measurements to play a role in the recursive navigation solution. They also provide an accurate navigation solution in situations where "GPS only" navigation would be subject to "natural" short-term outages caused by signal blockage and antenna shading.

The inertial system provides the only navigation information when the GPS signal is not available.

The inertial position and velocity information can reduce the search time required to reacquire the GPS signals after an outage and to enable direct code reacquisition in the jamming environment.

2) Low-noise inertial sensors can have their bias errors calibrated during the mission by using GPS measurements in an integrated navigation filter that combines inertial system and GPS measurements to derive further benefits. The accuracy achieved by the combined INS/GPS system should exceed the specified accuracy of GPS alone.

Features of complex inertial-satellite systems. Due to different physical nature and different principles of the navigation algorithms INC and satellite navigation system (SNS) well complement each other. Their common use allows, on the one hand, limiting the increase of INC errors and, on the other hand, to decrease the noise components of SNS errors, to increase the rate of information output to airborne consumers, to substantially raise the level of noise immunity [1].

Table 2 presents data that characterize the characteristics of complex inertial-satellite systems as compared to separate traditional airborne systems. This information convincingly testifies the prospects of SNS and INS complication.

Table 2

Factors	Degree of improvement
Accuracy	Increase on 30 % and more
Mass	Diminution on 30–70 %
Volume	Diminution on 50-60 %
Power consumption	Diminution on 25-50 %
Reliability	Increase twice
Degree of redundancy	Increase on 50 % and more

Recent progress in INS/GPS technology has accelerated the potential use of these integrated systems, while awareness concerning GPS vulnerabilities to interference has also been increased. Accuracy in broadcasting GPS signals will provide 1 meter INS/GPS accuracy. This high accuracy will be extensively used. At the same time the lower-costed inertial components will be developed and they will also have the improved accuracy. Highly integrated A/J architectures for INS/GPS systems will become common, replacing avionics architectures based on functional black boxes where receivers and inertial systems are treated as stand-alone systems.

The degree of inertial-satellite system integration in composition of integrated flight and navigation system up to recent time allowed the use of complex data processing only on the stage of navigation task solution. However, continuous increase of demands for SNS navigation consumer equipment and also considerable expansion of the solved task set induces more acute need of inertial-satellite system complication at the stage of primary data processing, i. e. at the stage of radio-navigation data processing. This is a principally new integration degree that conduces to the appearance of the inertial-satellite systems of integrated type. The system complication at the level of primary data processing permits: to reduce the time of measuring device signal search; to decrease or fully eliminate the probability of inadvertent capture signals by the servo loop system; to decrease the probability of tracking stall for the corresponding parameters of radio signals; to increase the characteristics of accuracy and noise immunity of radio technical indicators in the mode of tracking; to eliminate or to decrease the methodical errors of indicators; for high-dynamic consumers to compensate the influence of object motion for indicator operation.

Deep structural and functional combination of GLONASS and GPS receivers on the level of primary radio signals processing, forming the integrated navigation equipment on the basis of corresponding task solution synthesis is required to obtain the maximal positive effect from their complication. It is recommended to extend the integrated SNS GLONASS/GPS with INS for air maneuverable objects at the level of secondary data processing, with additional use of INS output information about acceleration in tracking loop for code and Doppler shift of carrier frequency, i. e. at the level of primary data processing.

Such extension of information allows to:

– change coordinates, increase altitude, velocity and time accuracy of the consumer;

– clarify orientation angles (heading, roll, pitch);

– estimate and clarify navigation transmitters calibration parameters, such as gyro drifts, scale factors, accelerometer shifts and so on;

– provide the continuity of navigational data at all stages of motion including temporal inoperability of SNS receiver in cases of disturbance influence or forceful maneuvers of the aircraft;

– improve navigation support integrity characteristics, i. e. ability at integrated information processing of autonomous equipment (especially INS) and SNS;

– data-processing the autonomous indications (especially INS) and SNS to supply the solution of airborne autonomous control integrity task (CAIM-Craft Autonomous Integrity Management) in addition to integrity that is realized on the receiver SNS (RAIM).

INS/GPS integration architectures. INS/GPS integration architectures are defined as separate, loosely and tightly coupled, deeply integrated configurations (fig. 1 – 4) [3].

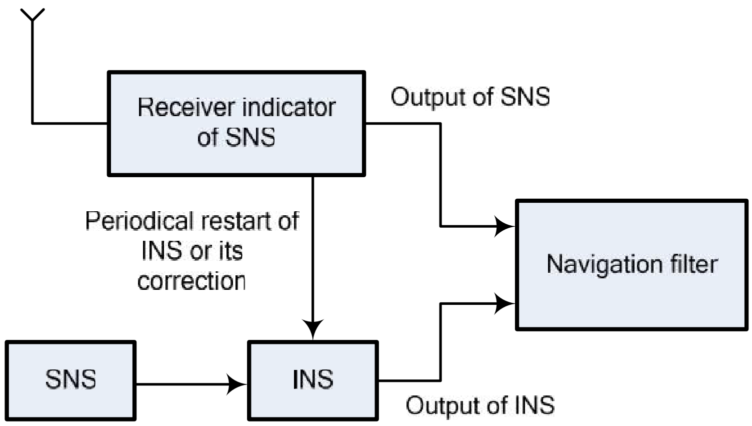

Fig. 1. Separate GPS and INS systems with a possible INS restart: SNS – satellite navigation system; INS – inertial navigation system

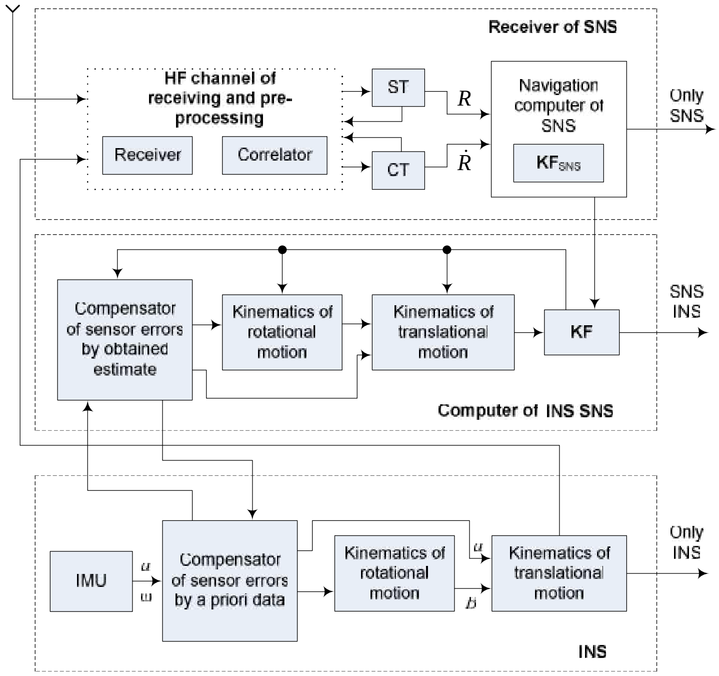

Fig. 2. A loosely coupled INS/GPS navigation system: HF – high frequency; KF – Kalman filter; ST – shift tracking; CT – code tracking; IMU – Inertial Measurement Unit

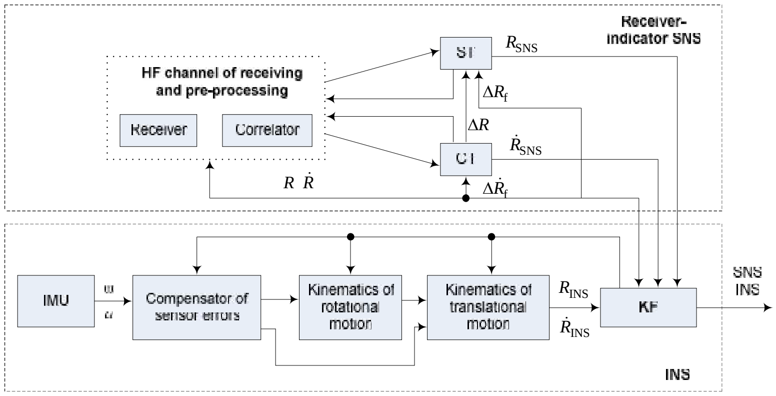

Fig. 3. A tightly coupled INS/GPS navigation system offering only one combined solution

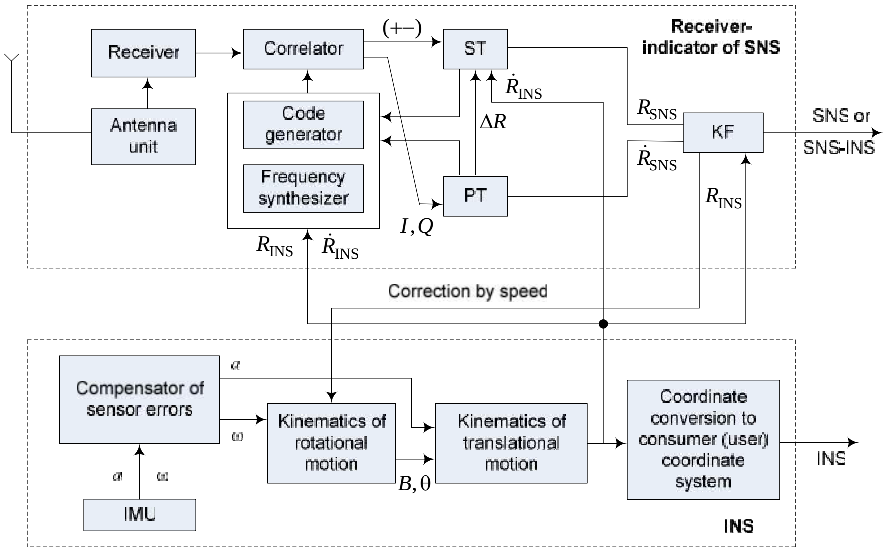

Fig. 4. INS/GPS deep integration: PT – phase tracking

Table 3 summarizes the benefits that have been gained by coupling GPS with INS. The benefits are cumulative. That is, the benefits for each level also include those for the previous level.

Table 3

Cumulative benefits of increasingly tight coupling

Coupling Level	Benefits
Uncoupled/reset INS to GPS (Sum of system attributes)	Position, velocity, acceleration, attitude, and attitude rate information Redundant systems A drift-free GPS A high-bandwidth INS
Loosely coupled	More rapid GPS acquisition In-flight calibration and alignment Better inertial instrument calibration and alignment Better attitude estimates Longer operation after jamming
Tightly coupled	Better navigation performance Better instrument calibration Reliable tracking under high dynamics Reduced tracking loop bandwidth (jamming resistance) Optimum use of however many SVs available
Deeply integrated	Advantages the single filter removes the problem of the “cascade” filters switching, compactness requirements reduction of power consumption. Disadvantages the state vector contains up to 40 components, that is why the filter is difficult to realize; necessity of development of the special sensors.

In the deeply integrated architecture the problem is formulated directly as an estimation problem in which the optimum (minimum-variance) solution for each component of the multidimensional navigation state vector is searched.

By formulating the problem in this manner, the navigation algorithms are derived directly from the assumed dynamical models, measurement models, and noise models. The solutions that are obtained are not based on the usual notions of tracking loops and operational modes (e. g., State 3, State 5, etc.). Rather, the solution employs a nonlinear filter that operates efficiently at all jammer/signal (J/S) levels and is a significant departure from traditional extended Kalman filter designs. The navigator includes adaptive algorithms for estimating post-correlation signal and noise power using the full correlator bank. Filter gains continuously are adapted to changes in the J/S environment, and the error covariance propagation is driven directly by measurements to enhance robustness under high jamming conditions.

The “deep integration” architecture for combining INS and GPS may allow (fig. 5) for tracking the GPS satellites up to 70 – 75 dB J/S, an improvement of 15 to 20 dB above conventional *P*(*Y*) code tracking of 54 to 57 dB [4]. If future increases of 20 dB in broadcast satellite power using the *M*-code spot beam (*M* spot) are also achieved, nearly 40 dB of additional performance margin would be achieved, a jammer of nearly 100 kW will be required to break a lock at 10 km. Furthermore, a new receiver technology with advanced algorithms and space-time adaptive or nulling antenna technologies might also be incorporated into the system, further increasing its A/J capability significantly.

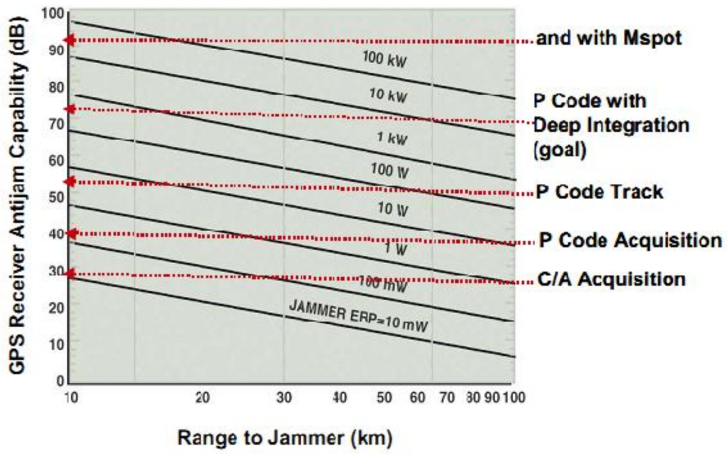

Fig. 5. Possible A/J capabilities

After analyzing and observing simulation results, the following cautious assertions can be made:

1) When GPS is available, its measurements dominate in navigation performance. The steady-state navigation error will be reduced by inertial aiding, which allows GPS measurement noise to be "averaged out." Improvement of steady-state error with improving inertial quality is not dramatic.

2) Tight coupling is superior to loose coupling for maintaining lock in a jamming environment, but the gain is hard to quantify, except for improvement in the signal-to-noise ratio.

3) Better inertial instruments gain more from in-flight alignment and perform better after GPS is lost.

This is because poorer instruments in general have larger proportions of uncalibrated noise.

4) For short time intervals after GPS loss, coupling architectures can make a difference to performance (because they affect calibration and alignment quality).

5) In the long run, basic IMU quality will dominate navigation accuracy due to instrument noise and loss of calibration accuracy.

Finally, we can admit that there is a dramatic difference in jammed performance if Doppler ground-speed measurements are available.

Unification of Integrated Inertial-Satellite Navigation Systems. The variety of inertial-satellite navigation systems requires the methods of unification row construction to lower the costs of their creation. The methodology of ISNS unification row includes the following stages:

– systematization – selection of typical aviation objects (modernization or perspective) for which construction of ISNS unification row is offered;

– classification – forming principal requirements for ISNS table for selected typical objects (by accuracy, reliability, time of readiness, boundary power-consumption, boundary volume, boundary mass, maximum time of continuous operation);

– typification – generation of ISNS variants (which differ by inertial sensors of primary information, SNS receivers and integration structure), that satisfy the requirements mentioned above;

– characterizing – expert estimation of basic characteristics including integrated ISNS initial variants costs;

– special unitization – choosing minimum ISNS unification row using additional cost criterion.

Conclusions. If the integration level between two systems increases, the benefits also generally increase. The comparison of deeply integrated approach and closely coupled one indicates that deeply integrated approach is likely to be more employed in future.

References

1. *Захарін Ф. М.* Алгоритмічне забезпечення інерціально-супутникових систем навігації / Ф. М. Захарін, В. М. Синєглазов, М. К. Філяшкін. К.: НАУ-Друк, 2011. – 316 с. [*Zakharin F. M.* Algorithms of inertial-navigation satellite systems / F. M. Zakharin, V. M. Sineglazov, M. K. Filyashkin. K.: NAU-DRUK, 2011. – 316 p.]
2. Schmidt, G. and Phillips, R., INS/GPS Integration Architectures, NATO RTO Lecture Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology, September 2011.
3. Schmidt, G. and Phillips, R., INS/GPS Integration Architecture Performance Comparisons, NATO RTO Lecture Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology, September 2011.
4. Schmidt, G. and Phillips, R., INS/GPS Technology Trends, NATO RTO Lecture Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology, September 2011.

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Перспективи розвитку інтегрованих инерциально-супутникових систем навігації повітряних суден цивільної авіації

Показано переваги спільного використання інерційних і супутникових навігаційних систем порівнянно з роздільним. Отримані вигоди залежать від рівня комплексування інформації. Наведено архітектури навігаційних систем різного ступеня інтеграції.

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Перспективы развития интегрированных инерциально-спутниковых систем навигации воздушных судов гражданской авиации

Показаны преимущества совместного использования инерциальных и спутниковых навигационных систем по сравнению с раздельным. Полученные выгоды зависят от уровня комплексирования информации. Приведены архитектуры навигационных систем разной степени интеграции.