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# New Navigation Satellite System Based on Intermediate Circular Orbits

G. Perrotta* and S. Di Girolamo†
*Alenia, 00131 Rome, Italy*

**In the framework of the Global Navigation Satellite System, European industries are identifying and studying new satellite constellations able to cope with required navigation performance for terrestrial, maritime, air, and space users. Alenia Aerospazio has identified many new satellite constellations. (Some of them are constituted by low Earth orbits or intermediate circular orbits for global coverage; others consider satellites in high elliptical orbits or geosynchronous orbits for regional coverage.) All of them have been compared in terms of navigation performance, e.g., accuracy, availability, continuity, and integrity. The best one is a constellation of 27 satellites located in intermediate circular orbits at a common altitude of 10,389 km and a common inclination of 57 deg. This constellation has been identified by the Walker method to find a space system able to guarantee a global and continuous coverage with low positioning dilution of precision values (always less than 4) and with a coverage level equal to 6, i.e., from each point of the Earth surface it is always possible to see at least six of the satellites. After both the payload design and the budget have been identified and analyzed, the satellite platform has been designed, obtaining, in this way, mass, power, and propellant budgets. The launch strategy and the orbit acquisition phase have been defined.**

## Introduction

THE increasing interest in the definition of a civil global satellite navigation system has resulted in the identification of new satellite constellations. The existing systems, i.e., the Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS), are military and do not fulfill all navigation performance requirements: accuracy, integrity, availability, and continuity of the service. The Global Navigation Satellite System (GNSS1), in the current definition, is an integration between the existing satellite systems and a set of geostationary satellites, i.e., the INMARSAT III satellites plus additional ones yet to be defined and launched, as far as the space segment is concerned. To cope with both accuracy and integrity requirements, an improved ground segment will be provided. In this respect, according to the dimension of area covered by the relevant service there will be a wide area augmentation system (WAAS) or a local area augmentation system (LAAS), mainly differing by the way integrity information and ionospheric and differential corrections are relayed to the users. The European Geostationary Navigation Overlay Service (EGNOS) is the one envisaged for the European Civil Aviation Conference (ECAC) area.

The main disadvantages of the GNSS1 system are the following.

1) GNSS1 is devised to overcome the limitations of the military GPS system, i.e., selective availability and antispoofing.

2) The system is a hybrid integration of different space and ground components.

3) Navigation signals reception difficulties exist.

4) The accuracy level is not always satisfied in the aircraft final landing phases.

Although the accuracy currently achieved with GPS is enough for marine navigation in open water and for aircraft navigation in en-route oceanic phases, for many other applications further improvements in accuracy are needed to cover more stringent requirements imposed by other applications and to allow significant savings and an increase of safety levels. GNSS1 will be able to cope only with some of those stemming from navigation of ships on internal waterways, of aircraft during approach and landing, or of trains and road vehicles in heavy traffic situations for which, in some cases, real-time accuracy of 1 m or less is required.

GNSS2 is a medium-to-long-term European program involving a new civil navigation system. GNSS2 will have to provide not only a better accuracy but also an autonomous integrity service: new-generation satellite navigation receivers are able to determine the faulty navigation satellite and to isolate the failure by means of receiver autonomous integrity monitoring (RAIM). This function can be accomplished when at least six navigation satellites are in simultaneous visibility from the user. The reliability of the system will be increased, and the navigation service will be provided continuously, also when one or two navigation satellites will be in failure status.

## Satellite Constellations Identification

In a number of practical applications of satellites, including communications, navigation, and various types of surveillance, it is desirable to use a system of several satellites in orbit simultaneously so that the coverage provided by the system as a whole is substantially greater than that available from any single satellite. When a navigation service is required, the coverage can be worldwide and/or regional, and the minimum number of simultaneous satellites visible from any point of the service area must be greater than or equal to 4 due to positioning measurement requirements. In particular, for the GNSS, the stringent requirements on integrity and continuity of the service have led to an increase in the minimum number of contemporary visible nav-satellites up to 6, i.e., coverage level = 6, over all of the Earth's surface, i.e., global coverage.

Another basic requirement is to have small dilution of precision (DOP) values, e.g., positioning dilution of position (PDOP) less than 4.

The GPS system, which is constituted by 24 satellites at a common altitude of 20,000 km, fulfills the preceding requirements; however, as already has been said, the GPS system presents drawbacks, such as selective availability, given its military nature. Consequently, the idea is to find another constellation of satellites with 1) a civil users nature from the beginning of its development phase; 2) small satellites ($< 500$ kg); and 3) performances similar to that of GPS.

To satisfy the second point, we have preferred to consider satellites located in orbits lower with respect to the GPS altitude of 20,000 km, e.g., to minimize the propellant consumption for transfer orbit maneuvers.

Because of the high coverage level, e.g., 6, the first solution would seem to be the adoption of geostationary satellites, but unfortunately GEOs alone do not allow a navigation service due to bad geometrical conditions. Besides, geostationary satellites do not allow a service

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*Advanced Studies and Projects Scientist, Divisione Spazio, Via Saccomuro 24.

†Navigation System Engineer, Divisione Spazio, Via Saccomuro 24.

in high-latitude zones. In this study the following different orbits have been investigated[1–4]: geosynchronous orbit (GSO), intermediate circular orbit (ICO), high elliptical orbit (HEO), and low Earth orbit (LEO).

To identify constellations of satellites in circular orbits, i.e., GSO, ICO, and LEO, the Walker method[5–10] has been used, whereas for HEO constellations the generalized rule for advanced constellation evaluation or GRACE method[11] has been applied.

The Walker method is based on the best choice of the delta patterns, i.e., the constellations in which the total number of satellites are in equal-period circular orbits, evenly spaced, and all at the same inclination to a reference plane, with a uniform distribution of the satellites among and within the orbital planes. In choosing pattern characteristics, the primary objective is to minimize the total number of satellites. As a secondary objective, it is assumed that the mimimum distance between closed satellites should be as large as possible to improve the system geometry and consequently to reduce the DOP values.

The GRACE[11] method, developed by Alenia Aerospazio, consists of a set of iterative evaluations and requires input data that regard the mission and the characteristics of the orbit constellations that must be found and analyzed.

An algorithm identifies a set of candidate constellations that potentially may fulfill the requirements. The constellations are checked with respect to the mission performance requirements through the use of a mesh of check points over the Earth.

For navigation applications, with a coverage level greater than 4, the GRACE method also implements the PDOP calculations to verify the fitness of the system geometry.

Each constellation is identified by a code, called the GRACE code:

$$T/S/F/K$$

where

$T$ = total number of spacecraft
$S$ = number of different Earth subtracks
$F$ = index that defines the relative orbit phase between spacecraft put in different subtracks
$K$ = index that can be equal to 1, 2, or 3 if the apogee orbit point is, respectively, always over the northern or southern hemisphere or alternately

Using the preceding methods and a coverage level 6 with a mask angle of 5 deg, the constellations shown in Table 1 have been identified. The main system performances for each of them have been evaluated and compared[12] in terms of accuracy, availability, continuity, and integrity. The work done can be summarized by the following sentence: each identified constellation presents satisfactory performances. Starting from the preceding performances results the differences between one constellation and the other are not so big. However, the constellation with GSO or HEO orbits can offer only a regional service, whereas the others, obtained with LEO and ICO

**Table 1 Identified satellite constellations**

| Constellation | Coverage | Total number of satellites | Orbit planes | Altitude, km | Inclination, deg |
|---|---|---|---|---|---|
| GSO1 | Global | 18 GSO | 9 | 35,786 | 65 |
| GSO2 | Global | 18 GSO | 6 | 35,786 | 53 |
| GSO3 | Global | 20 GSO | 4 | 35,786 | 59 |
| GSO4 | Global | 20 GSO | 5 | 35,786 | 65 |
| ICO1 | Global | 21 ICO | 7 | 20,183 | 63 |
| ICO2 | Global | 24 ICO | 3 | 20,183 | 54 |
| ICO3 | Global | 24 ICO | 8 | 20,183 | 60 |
| ICO4 | Global | 24 ICO | 4 | 20,183 | 57 |
| ICO5 | Global | 27 ICO | 3 | 10,389 | 54 |
| ICO6 | Global | 27 ICO | 9 | 10,389 | 57 |
| LEO1 | Global | 70 LEO | 5 | 2,700 | 54 |
| LEO2 | Global | 72 ICO | 9 | 2,700 | 57 |
| GSOR | Regional | 12 GSO | 4 | 35,786 | 80 |
| HEOGEO | Regional | 6HEO + 3GEO | 6; 3 | semiaxis = 42,164 | 63; 0 |

orbits, can provide a global coverage. ICO and LEO constellations also present costs reduction in terms of launch acquisition. In this paper we have selected and further analyzed an ICO constellation because, in this case, the number of required satellites is reduced (with respect to the LEO constellations).

The selected constellation, which will be referenced from here on, has the following main characteristics: 1) total satellite number = 27, 2) orbit planes = 9, 3) satellite per plane = 3, 4) altitude = 10,389 km, and 5) inclination = 57 deg.

## Accuracy

The geometrical configurations of a GNSS system have a strong impact on the user positioning determination. The PDOP values give the information on the quality of the geometry: The lower the PDOP values are, the more precise the accuracy is.

The concept of PDOP comes from the analysis of the basic system of equations for the navigation solution.[13,14] This is a system of nonlinear equations that can be numerically solved, i.e., by the Newton–Raphson method, obtaining the user position and the range biases; this method is called the geometrical solution.

Figures 1 and 2 refer to the identified ICO constellation. Figure 1 shows both the percentile and the cumulative probability of the visible GNSS satellites from any point of the Earth's surface. Figure 2 represents the PDOP, the horizontal dilution of precision (HDOP),

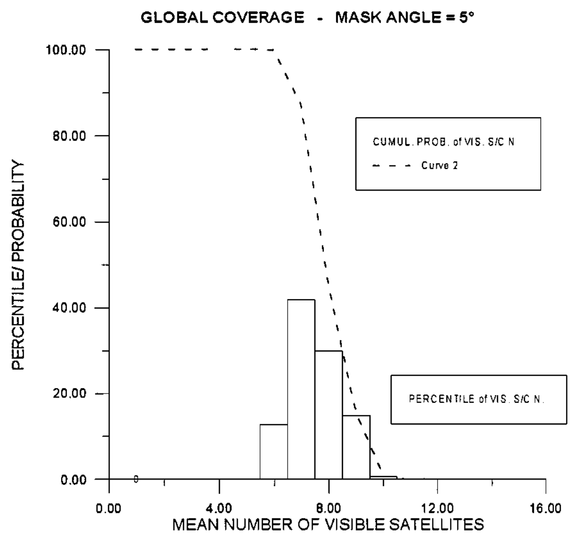


**Fig. 1 GNSS visible spacecraft: percentile and probability for the ICO constellation.**

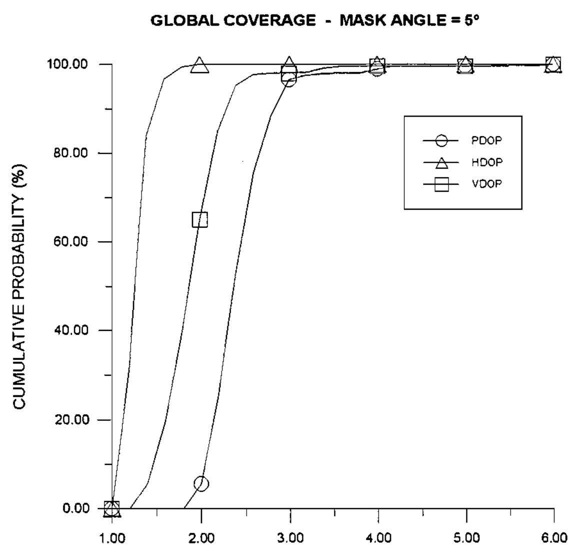


**Fig. 2 Cumulative DOP probability for the identified ICO constellation.**

and the vertical dilution of precision (VDOP) cumulative probability; it can be seen that all the DOP quantities always assume values lower than 4.

If the user is a satellite in an LEO orbit, then the localization can be done on the basis of the Kalman filtering technique (because the satellite motion can be very well modeled), which allows one to sensibly improve the navigation accuracy performance. The Kalman filter solution is based on the results obtained by modeling 1) the user motion and the relative perturbations (like the Earth gravity model and the Jacchia model for the atmospheric drag), 2) the navigation satellite's motion, 3) the measurements available from the navigation constellations and the relative error sources (like ionospheric propagation and user and navigation satellite clock bias error, etc.), and 4) the receiver and the navigation processor, which implements a Kalman filter.

In particular, the Kalman filter processes four pseudorange and pseudorange-rate measurements (obtained from the signals coming from the navigation satellites selected by a criterion based on the concept of minimum PDOP) at each integration step. Table 2 shows the Kalman filter algorithm adopted in this context.

For the Kalman filter analysis, we will use as the reference user a satellite with the following circular orbit characteristics: inclination = 97.26 deg, altitude = 500 km (period = 1.6 h), and right ascension of ascending node (RAAN) = 0 deg. Figure 3 shows the position errors for the identified ICO constellation.

**Table 2 Kalman filter algorithm**

| Step | Description |
|---|---|
| 1) $x_i = f(x_{i-1}, t_{i-1}, \mathrm{DT})$ | State vector integration |
| 2) $F = \mathrm{d}f/\mathrm{d}x_{i-1}$ | Transition matrix update |
| 3) $C = FCF' + S$ | Error covariance matrix propagation |
| Do 15 $i = 1, m$ | |
| 4) Fetch $y_i^*$ | Actual measurement fetching |
| 5) $y_i = h_i(x_i, t_i)$ | $i$th measurement estimation |
| 6) $H = \mathrm{d}h_i/\mathrm{d}x_i$ | Observation matrix |
| 7) $A = CH'$ | Temporary matrix $A(n \times 1)$ |
| 8) $DR_i$ = computation | Underweighting factor |
| 9) $V = HA + R_i + Dr_i$ | $i$th residual covariance |
| 10) $r = y_i^* - y_i$ | $i$th residual |
| 11) If ($r^2 > 16$ V) go to step 15 | Residual edit |
| 12) $W = A/V$ | Gain matrix $(n \times 1)$ |
| 13) $x_i = x_i + Wr$ | $x_i$ updating |
| 14) $C = C - WA'$ | Error covariance updating[a] |
| 15) Continue | |
| 16) Go to step 1 | |

[a]Using matrix symmetry.

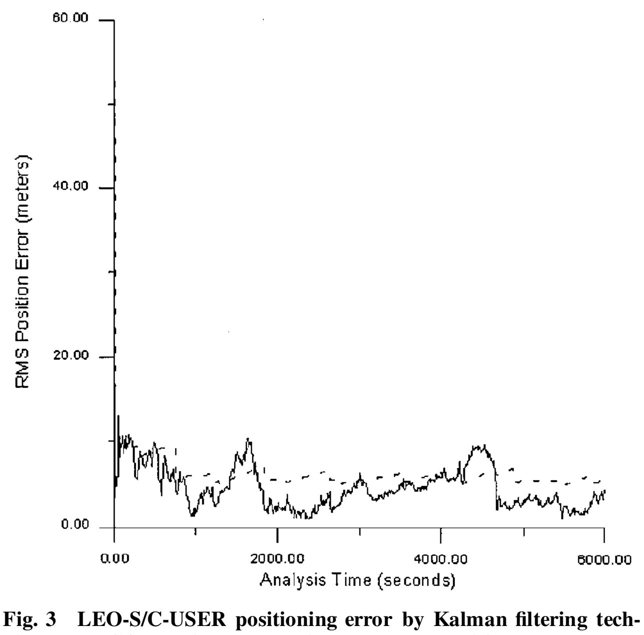


**Fig. 3 LEO-S/C-USER positioning error by Kalman filtering technique and ICO satellite constellation: ——, rms position error, and – – –, position error estimated by the filter.**

## Availability

The availability of a navigation system is the percentage of time that the service of the system can be used,[15–18] dealing with three different nonavailability causes: 1) coverage outages, 2) system failures, and 3) system maintenance. This formulation takes into account the probability $p_i$ to get $i$ unavailable satellites within the $T$ satellites in the constellation and the mean constellation value ($CV_i$, according to the required accuracy/integrity) that is obtained with $i$ unavailable satellites. The constellation value is defined as the fraction of the Earth's surface, averaged over time, where a characteristic of the constellation does not exceed a certain number (for example PDOP < 6).

The mean availability is then

$$A = \sum_{i=0}^{T-1} p_i CV_i$$

(as $p_i$ decreases rapidly, the sum can generally be performed only for low values of $i$).

From this point of view, a constellation availability can be improved by acting on 1) the payload design and launch replenishment scenario [mean time between failure and mean time to repair for short- and long-term failures ($\mathrm{MTBF_{ST}}$, $\mathrm{MTTR_{ST}}$, $\mathrm{MTBF_{LT}}$, and $\mathrm{MTTR_{LT}}$)], 2) the satellites orbit [implying mean time between maneuvers ($\mathrm{MTBF_M}$)] and maneuvers time, and 3) the constellation (robustness of the constellation to satellite failure). Results are derived from the following assumptions[11–13]: $\mathrm{MTBF_{ST}} = 7300$ h, $\mathrm{MTTR_{ST}} = 36$ h, $\mathrm{MTBF_{LT}} = 124$ months, $\mathrm{MTTR_{LT}} = 1$ month.

The availability values for the selected constellation are listed in Table 3; they have been computed considering zero, one, and two possible failures. For one-failure analysis, $T$ simulations are needed. For two-failure analysis, $T \times (T - 1)/2$ simulations are needed.

The average value between all simulations has been derived.

## Continuity

The continuity[15–18] of a navigation system is its capability to constantly provide a user with nominal navigation services throughout a route. Continuity is very similar to availability, even if continuity differs from availability in that continuity is defined as the probability of an occurrence causing loss of service, whereas availability is defined as the percentage of time the service is not available.

Continuity depends on short-term reliability, with problems occurring from the space segment (short-term failure probability) and the user segment (shadowing, multipath, user maneuvers).

The formulation takes into account the probability $P_t$ that a satellite becomes unusable during a given period of time $t$ (whether it comes from the satellite failure or from the user segment):

$$P_t \cong \left[\frac{1}{\mathrm{MTBF_{ST}}} + \frac{1}{\mathrm{MTBF_{LT}}} + \frac{1}{\mathrm{MTBF_M}}\right]$$

With the same notations as for availability, the mean probability of loss of continuity over time $t$ is given by

$$C = P_t \sum_{i}^{T-1} p_i (T - i)(CV_i - CV_{i+1})$$

In our calculations, $t$ has been set equal to 1 h to have a continuous service during the en-route and prelandings phases, whereas during the landing phase reduced $t$ values would be needed.

The continuity values for the selected constellation are listed in Table 3.

## Integrity

Integrity is defined as "that quality which relates to the trust[18,19] which can be placed in the correctness of the information supplied by the facility."[17] The definition of the integrity parameter,[18,19] although correct, presents the main drawback to be purely qualitative; the parameter it refers to is not measurable. Thus the following definition is preferred: "The integrity of a navigation system is the ability of the system to provide timely warnings to users when the system should not be used for navigation" (see Ref. 13). Integrity can be

**Table 3 Navigation performances of the identified ICO satellite constellation**

| 27 ICO spacecraft | $H = 10{,}389$ km | | | | $T = 6$ h | | | |
|---|---|---|---|---|---|---|---|---|
| No. of failures | Probability | HDOP < 3 | Probability | HDOP < 2.2 | VDOP < 3 | Integrity | VDOP < 4 | Integrity |
| 0 | 0.6771 | 1 | 0.6771 | 1 | 0.9952 | 6 | 0.9952 | 6 |
| 1 | 0.2383 | 0.9991 | 0.2383 | 0.9969 | 0.9881 | 5.18 | 0.9881 | 5.18 |
| 2 | 0.0647 | 0.9967 | 0.0647 | 0.9885 | 0.9715 | 4.7 | 0.9715 | 4.7 |
| Total | Availability | 99.96% | | 99.85% | 99.20% | | 99.20% | |
| | Continuity | 0.999949 | | | 0.999962 | | 0.999982 | 0.999962 |

defined also as a percentage of time wherein the system properly apprises the pilot of its true mission performance (for aircraft users). Integrity includes all of the following processes: 1) the detection and isolation (if possible) of a malfunction (wrong signal transmission), 2) the decision to set an alarm, and 3) the (selective) dissemination of this alarm to users.

Ground-based monitoring techniques [ground integrity control (GIC), ground integrity monitoring (GIM), etc.] employ local area integrity monitoring stations and/or a network of distributed monitor stations (wide area) in order to be able to monitor all active navigation satellites in view. To assess the correctness of the satellite signals, the monitor stations first measure their pseudorange to each satellite in view. The difference between the measured and computed ranges serves as the basis test quantity for the integrity performance information.

More than four satellites in view enables the user to autonomously evaluate the service integrity level by using one of the following methods: 1) receiver autonomous integrity monitoring (RAIM) (five satellites in view are needed) and 2) aircraft aided integrity monitoring (AAIM) by inertial sensors (six satellites in view are needed).

The criterion to evaluate the integrity used here is the following: the integrity analyses include an Earth surface grid; the selected satellite constellation is deprived of one and two satellites per analysis, considering the possibility that one or two satellites are in failure or are not available for navigation. All possible satellite constellations obtained from the selected one depriving one or two satellites each time are analysed. The average number of visible satellites obtained considering all the preceding analyses, all nodes of the Earth grid, and all the analyses steps is defined as the integrity system parameter. It has to be mentioned that, after having computed the integrity values, then also the geometry of the system has been analyzed to verify if the DOP values are greater than a fixed value.

The integrity values for the selected constellation are listed in Table 3. They have been computed as the minimum visible satellites number pondered over time, space, and failure events configuration.

## Launch and Orbit Acquisition Strategy

The selected satellite launcher is ARIANE 5. The parking orbit has a perigee altitude equal to 560 km, an apogee altitude equal to 10,389 km, e.g., equal to the final altitude, and an orbit inclination equal to 57 deg. The total number of launches foreseen is nine, e.g., equal to the total number of orbit planes.

The total delta velocity required for the apogee burns is 1.13 km/s. Considering that the launch satellite mass is about 490 kg, the required propellant (for a bipropellant chemical thruster with specific impulse of 280 s) is about 170 kg. The transfer orbit duration will be less than 70 h, considering that the total thrust duration for apogee thrust is less than 5 h.

## Satellite Design

In addition to the navigation service, the selected satellite constellation will be able to provide automatic dependent surveillance (ADS) services, thereby fulfilling the International Civil Aviation Organization (ICAO) recommendations. Thus a payload architecture, covering both navigation and ADS service requirements, has been identified. Each satellite will be provided with 1) a forward channel for navigation service, 2) 300 bidirectional voice channels (4.8 kbps each), 3) 5000 surveillance channels (50 bps each), 4) two L band transmission (Tx) antennas that provide the coverage for ADS and navigation services, 5) one spot beam coverage reception (Rx) antenna for ADS service (separated Tx and Rx functions have been assumed to reduce output losses and passive Inter Modulation Products' (IMP's) effects), and 6) one Ku band Tx and Rx antenna used to receive and transmit the signals from and to the ground.

The major characteristics of the spacecraft are summarized as follows: mass at launch: <500 kg, solar array power: <750 W end of life (EOL), payload mass: 85 kg, payload power: 400 W, launcher: Ariane 5, and life time: 10 years.

The spacecraft is being designed in a modular scheme. The satellite is three-axes inertial attitude stabilized. The attitude determination is derived from Earth sensor, sun sensor, magnetometer, and star tracker data, which are managed by the central processor. The attitude control is obtained both in a passive, i.e., gravity gradient, and an active way, i.e., magnetic coils.

The transfer orbit maneuvers are made by a bipropellant chemical propulsion system, whereas two ion electric thrusters are used for orbit-keeping maneuvers.

High-efficiency GaAs solar array design is foreseen. The structure houses 170-kg propellant tanks in a central cylinder designed with graphite/epoxy materials.

Passive and active control techniques are used to maintain the temperatures of the spacecraft equipment within allowable operating ranges. Heat pipes are used to better distribute the thermal energy.

## Conclusions

A new satellite constellation based on an intermediate circular orbit at a common altitude of 10,389 km has been found. The space segment has been investigated, its performances in terms of a future navigation service has been examined. This system allows a global and continuous navigation service. The system allow a continuous visibility over a global service area with a coverage level of 6, verifying good DOP performances, i.e., HDOP and VDOP less than 4 for at least 99.5%.

The system can be realized under one of the following hypotheses: 1) with GPS-like technologies or 2) with new criteria, e.g., new frequency band, new band occupation, new signal structure, better clocks accuracy, etc.

A Kalman filtering technique has been used to evaluate the accuracy for an LEO satellite user: Typically 10-m, three-dimensional position error can be achieved by the selected constellation, if the first hypothesis is used, whereas better accuracy can be achieved if the second hypothesis is considered.

The aircraft users have very demanding navigation requirements, especially during the landing phase. The studied satellite system is also able to fulfill the aircraft navigation requirements, at least until the phase prelanding, whereas as regards categories CAT-1, CAT-2, and CAT-3, the aid of a ground support, able to implement the differential navigation technique, is needed. Particularly, as regards CAT-1, the required navigation performances can be achieved without ground support, either by using an on-board navigation instrumentation, such as accelerometers, gyros, and altimeters, or by adopting new navigation technologies, e.g., hypothesis 2.

Analyses in terms of availability, continuity, and integrity have been carried on, giving the following performance: 1) HDOP $< 3$ and VDOP $< 4$ for about 99.5%, taking into account up to two failures, 2) continuity $> 0.99996$, and 3) integrity $> 4.7$, i.e., when two failures are considered. The launch strategy and the orbit acquisition phase have been defined.

After both payload design and budget have been identified and analyzed, the satellite platform has been designed, obtaining mass, power, and propellant budgets. A spacecraft launch mass of less than

500 kg has been found. The required peak satellite radio frequency power is less than 400 W.

The expected system costs are very low because the spacecraft belongs to a small satellite category and because of the reduced launch costs, e.g., the final orbit altitude is 10,389 km, and multisatellite launches have been taken into account.

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A. C. Tribble
*Associate Editor*