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NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION
BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO AGARDograph 300

Flight Test Techniques Series – Volume 18

Flight Testing of Radio Navigation Systems

(les Essais en vol des systèmes de radionavigation)

This AGARDograph has been sponsored by the SCI-055 Task Group, the Flight Test Technology Team of the Systems Concepts and Integration Panel (SCI) of RTO.

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Edited by
H. Bothe
H.-J. Hotop

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Flight Testing of Radio Navigation Systems

(RTO AG-300 Vol. 18)

Executive Summary

This AGARDograph describes the basic principles and the flight test procedures that are currently in use for testing conventional and advanced radio navigation systems and ground stations. Along with the well known conventional enroute navigation systems, like VOR, DME and TACAN, the more recent GPS navigation techniques and the test methods are discussed. Also, terminal area navigation systems like ILS, and MLS are covered.

Testing of these systems is presented including the description of test methods and procedures which flight test engineers would benefiting from when writing the appropriate flight test programs and which also could be briefed to on-board test crews when assigned to fly their test missions for newly developed and installed ground systems. The flight test methods section is also dealing with the flight inspection techniques for radio navigation sites that are in operational use today. Special attention is drawn to the more general radio frequency problems like multipath and on-board antennas of the navigation systems. The inspection techniques periodically check if the current data are within the requirements, i.e. if accuracy, reliability, coverage, availability and quality of the signals correspond to the standards applicable for operational sites and ground stations. Some of these standards are summarised and presented in tables of the report and reference is given to documents containing more detailed information on that subject matter.

The requirements for the equipment and instrumentation systems of inspection aircraft are also discussed including recommendations for the user. Various flight inspection techniques are described using semi- and fully automatic methods developed in the U.S. and in Europe where the Netherlands, France, U.K. and Germany operate their own national flight inspection aircraft and facilities.

A large list of useful reference documents is added to the report. These can be helpful to the reader looking for appropriate details if the full background should be needed for the information contained in this AGARDograph.

les Essais en vol des systèmes de radionavigation

(RTO AG-300 Vol. 18)

Synthèse

Cette AGARDographie présente les principes et les procédures d'essais en vol actuellement utilisés pour les essais de stations au sol et de systèmes de radionavigation classiques et avancés. Les techniques récentes de navigation GPS et les méthodes d'essais sont examinées, ainsi que les systèmes classiques de navigation en route, tels que le VOR, le DME ou le TACAN. Les systèmes de navigation en zone terminale, tels que ILS et MLS sont également couverts.

Les essais de ces systèmes sont présentés avec la description des méthodes et procédures dont les ingénieurs d'essais en vol pourraient s'inspirer lors de l'établissement de leurs programmes et qui pourraient également être communiquées sous forme de briefings aux équipages d'essais devant réaliser des missions comportant des essais de systèmes au sol récemment développés et installés. Les chapitres sur les méthodes d'essais en vol traitent également des techniques d'inspection en vol pour des sites de radionavigation qui sont opérationnels aujourd'hui. Il est aussi demandé d'accorder une attention particulière aux problèmes plus courants des radiofréquences tels que la propagation par trajets multiples et les antennes embarquées des systèmes de navigation. Les techniques d'inspection prévoient la vérification périodique de la conformité des données aux spécifications, c'est à dire la conformité de la précision, la fiabilité, la couverture et la qualité des signaux aux normes applicables aux sites opérationnels et aux stations au sol. Certaines de ces normes sont résumées et présentées dans les tableaux joints au rapport avec renvoi à des documents présentant des informations plus détaillées.

Les cahiers des charges des équipements et des systèmes d'instrumentation des aéronefs à contrôler sont également examinés, avec des recommandations à l'intention des utilisateurs. Différentes techniques d'inspection en vol sont décrites, y compris les méthodes automatiques et semi-automatiques développées aux Etats-Unis et en Europe, où les Pays-Bas, la France, et l'Allemagne exploitent leurs propres installations nationales d'inspection en vol.

Une liste détaillée de documents de référence est jointe au rapport. Ces documents intéresseront le lecteur souhaitant s'informer sur le contexte global des informations contenues dans cette AGARDographie.

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Preface

During the last 40 years a number of different radio navigation systems have been introduced to civil as well as to military aviation. The progress in space and microwave technologies recently has allowed new systems with higher accuracy and reliability. These systems are developed as navigational aids for enroute and terminal navigation as well as for guidance and control during final approach and landing of an aircraft. The complexity of the systems requires extensive flight testing during the system development. Moreover, the approval of the ground facilities for use by civil and military aircraft is dependent on flight tests of every new installation. Once a radio navigation station is cleared for service, the accuracy is supervised by additional flight tests at well-defined time intervals. The considerable amount of flight test hours spent every year for the flight testing of all radio navigation stations in service and the complexity of the task requires planning of the flight test program by the flight test engineer in the most efficient manner.

Flight Testing of Radio Navigation Systems

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20099 Hamburg, Germany

1. INTRODUCTION

The primary goal of this volume is to acquaint flight-test and instrumentation engineers with the flight testing of radio systems for aeronautical navigation. In this connection first the systems under consideration are outlined in principle. Here much room is given to the Global Positioning System GPS because of its growing importance. Multiple aeronautical GPS applications like long range, short range and terminal area navigation as well as taxi and ramp guidance on the airports are still under further development. Following this a shorter description of the conventional enroute and terminal area navigation systems is given. The adverse effects of radio wave propagation, like multipath, the flight test engineer should be aware of lead up to the instrumentation systems and their application to the different flight test methods. A description of the flight inspection procedures being in use in the United States and in Europe will be found as well as a survey of and requirements on the engaged aircraft. The flight inspection of radio navigation stations in these countries is under continuous development regarding technical improvements and cost. During the process of coming into being of this volume the civil and military flight inspection organizations have been combined country by country with the exception of France.

2. GPS-NAVIGATION

The Global Positioning System (GPS-NAVSTAR) is a globally usable navigation system based on satellites. The satellites are built and launched by the United States. GPS consist of three parts: the space-, the control- and the user segment. Figure 2.1 illustrates these three parts. The space segment includes the 21 (or more precise 24) satellites that are required on six special orbits called Kepler paths. These paths are called "normal orbits". This means that each satellite moves on an orbital ellipse with the focal point at the center of the earth. Generally this is a path fixed in space. These paths have an inclination angle of about 55 degree to the equator and the difference between the orbits is 60 degrees. Figure 2.2 shows the orbits of the GPS-satellites. The height of the orbits, that is, the vertical distance to the earth surface of these paths is about 20 000 km. These orbital conditions produce a rotation time of nearly 12 hours. For GPS navigation, a minimum of 18 satellites is enough for full coverage of the earth, with each location receiving at least three to four satellites all the time. A spare set of three satellites in addition is normally sufficient, but for reliability and to avoid areas of degraded navigation capability, 24 satellites are needed.

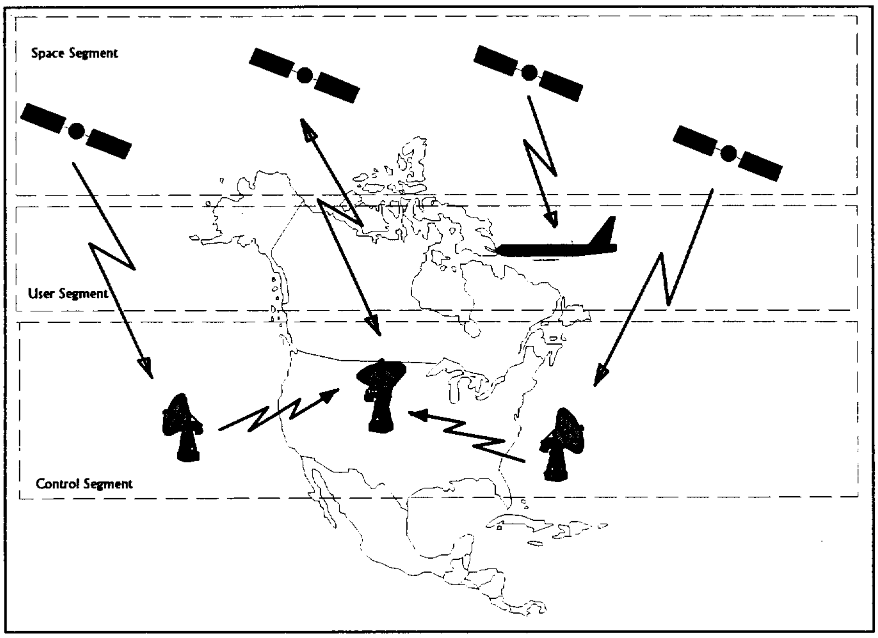


Figure 2.1: The space-, control and user segment of the GPS. [1,86]

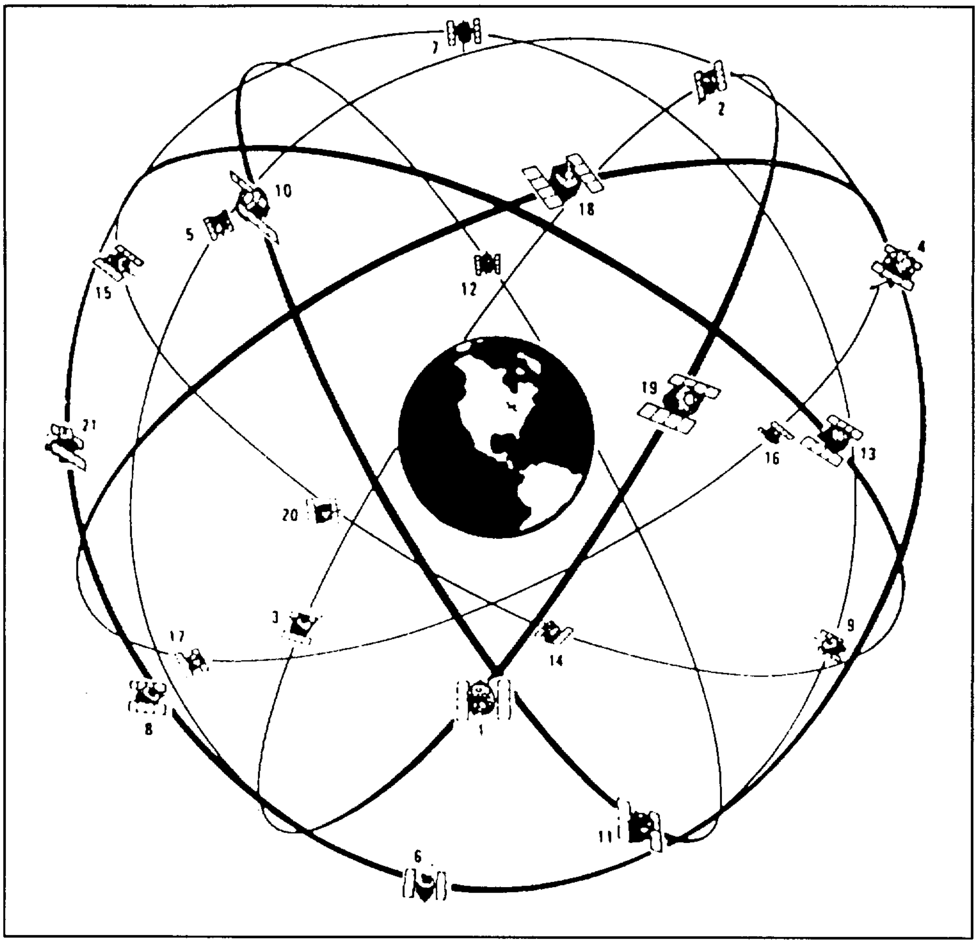
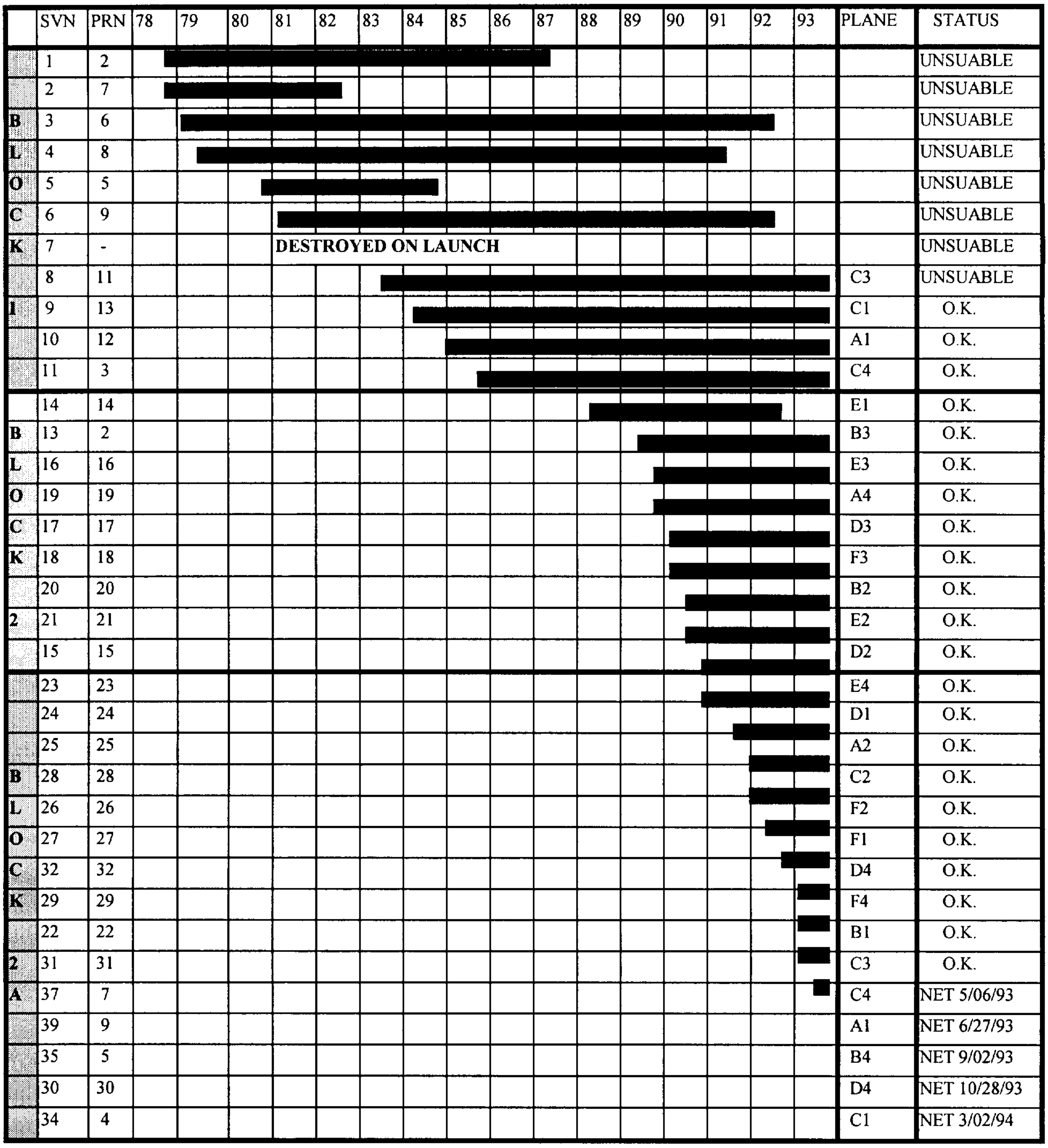


Figure 2.2: GPS satellites and their orbits. [86]

In 1978 the first two satellites were launched, but nowadays they are unusable. Table 2.1 gives a summary of all satellites and their constellation status for the GPS-NAVSTAR-system between 1978 and 1994. For the whole GPS-system the United States planned 24 satellites. The different orbits of the satellites are marked by the letters A to F in the table and on each orbit four satellites rotate around the world. As of the end of 1993, all satellites are in space. This is the reason that a lot of GPS-navigation-systems and GPS-added-navigation systems were planned since 1980. The first tests were made in 1989 to see if the number of satellites was sufficient for flight- and vehicle tests with a minimum of four satellites on the horizon for some hours a day. So the GPS navigation accuracy for different activities on ground, sea, and air wasn't globally tested yet even today. Ship navigation has used GPS for several years, as has geodesy for high accuracy survey. For aircraft navigation, all GPS satellites are required--especially as it is particularly concerned with the third dimension (height). A first global GPS study in 1999 shows that 24 GPS satellites without augmentation cannot meet the requirements for an airspace system. [16] In 1999 the number of GPS operating satellites are 27 which means 24 satellites for the basic configuration (6 orbits with 4 satellites each) and 3 spare satellites. The next possible expansion can be 30 GPS satellites on 6 orbits which is discussed in the literature to meet the requirements for airspace systems. [16]

The control segment displayed in figure 2.1 is the ground operating system surveying and controlling the satellites. The Consolidated Satellite Operations Center (CSOC) is located at the Falcon Air Force station near Colorado Springs, Colorado. Some other monitoring stations receive data from the GPS satellites and track them. All data are transmitted to the main ground station CSOC and here an update of the position data for the satellites is calculated. At this station, the accuracy of the navigation data evaluated from the GPS signals can be determined and two different accuracy codes are transmitted to the satellites. As expected, the additional work of these ground stations is the service and control for the satellites.

The functional idea of the GPS is normally very simple. The satellites transmit signals that are received on board the navigating vehicle and this is called the user segment. The actual position will be calculated by the difference in time that it takes to transmit signals from each of the



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O	5	5			■	■	■	■	■											UNSUABLE
C	6	9				■	■	■	■	■	■	■	■	■	■	■	■			UNSUABLE
K	7	-				DESTROYED ON LAUNCH														UNSUABLE
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	10	12								■	■	■	■	■	■	■	■	■	A1	O.K.
	11	3								■	■	■	■	■	■	■	■	■	C4	O.K.
	14	14											■	■	■	■	■		E1	O.K.
B	13	2												■	■	■	■	■	B3	O.K.
L	16	16												■	■	■	■	■	E3	O.K.
O	19	19												■	■	■	■	■	A4	O.K.
C	17	17													■	■	■	■	D3	O.K.
K	18	18													■	■	■	■	F3	O.K.
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	23	23													■	■	■	■	E4	O.K.
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	25	25														■	■	■	A2	O.K.
B	28	28															■	■	C2	O.K.
L	26	26															■	■	F2	O.K.
O	27	27															■	■	F1	O.K.
C	32	32															■	■	D4	O.K.
K	29	29																■	F4	O.K.
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	39	9																	A1	NET 6/27/93
	35	5																	B4	NET 9/02/93
	30	30																	D4	NET 10/28/93
	34	4																	C1	NET 3/02/94

Table 2.1: GPS NAVSTAR constellation through 1993. [104]

observed satellites. Each satellite transmits the signals on two different frequencies: L1= 1575.42 MHz and L2 = 1227.60 MHz. Two different precisions are available: the "precise positioning service" (pps), usable only for military sources; and the "standard positioning service" (sps) usable for the general aviation. The position is calculated out of the "pseudo random noise" (prn) added to the carrier frequency. For the different accuracies, the length of the period is different. For the c/a code (course/acquisition code) corresponding to the sps, the repeatability is 1 ms while the p- and y-codes corresponding to the pps have a repeatability of seven days. In addition to the phase difference, one needs the actual position of the received satellite and a time synchronisation for the data. In this case, binary data with a rate of 50 bits per second on the carrier signal are transmitted. Ephemeris data for the position calculation of the satellites, the system time, and status information are transmitted to the vehicle receiver. For sps-users, errors are added to the position information of the satellites; so only pps-users are able to correct these errors by the selective availability (s/a)-code. Part of the status information indicates to the user whether the s/a-code is turn on or off.

The GPS receiver on the ground or on-board an aircraft consists of three separate parts: the antenna, the antenna electronics unit, and the GPS receiver processor. The antenna control unit significantly improves the ECM performance of the GPS system by automatically creating nulls in the radiation reception pattern directed towards the jamming source. The antenna has to be located at the top of the aircraft where satellites near the horizon can also be received. On the receiver processor card, normally a Kalman filter algorithm is implemented to get the position- and velocity-information out of the minimum of four received satellites. If the system detects only three satellites, the height can not be calculated and the accuracy decreases. The reasons for losing satellite connection are different. Perhaps the aircraft makes a turn and the antenna can not detect all satellites--such as some satellites standing near the zenith of the antenna (in which case no vertical position can be calculated), or the signals of some satellites are being interfered with. So the first algorithm of the receiver processor is to detect the number of satellites on the horizon normally between 30 and 60 degrees and to choose a minimum of four satellites for navigation purposes.

The measuring principle for the GPS receiver is to detect the signals from the satellites and measure the time difference--or more precisely the time delay. All satellites transmit their synchronized signals at exactly the same time. But the time base for the receiver can not be synchronized with that of one of the satellites, so the measured time delay includes errors of the time base. The range calculated out of these measurements is called "pseudo range" and has to be recalculated to get highly accurate receiver position information. In this case the receiver detects four pseudo ranges--one from each of four satellites. By the transmission of the binary data, the position of the transmitting satellite is also known. Figure 2.3 demonstrates the situation for three satellites. For each range the position vector of the aircraft can be calculated out of the pseudo range R_i for the i-th satellite as follows:

$$R_i = \sqrt{(x - y_{S_i})^2 + (y - y_{S_i})^2 + (z - z_{S_i})^2} * c * t \qquad (1)$$

with $\begin{pmatrix} x \\ y \\ z \end{pmatrix}$ position of the aircraft, $\begin{pmatrix} x_{S_i} \\ y_{S_i} \\ z_{S_i} \end{pmatrix}$ position of the satellite S_i and t the time error

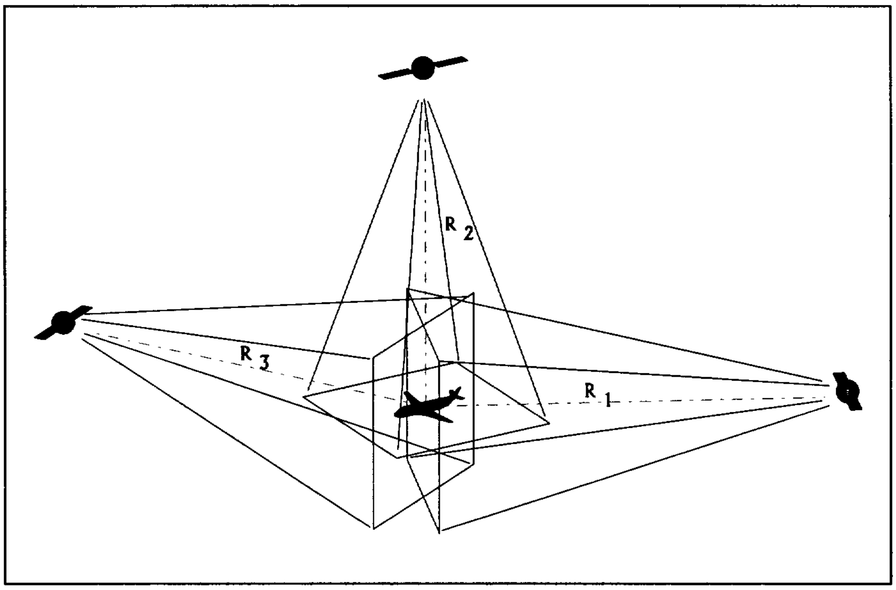


Figure 2.3: GPS receiver situation for three satellites using the pseudo range measurement.

This example uses three satellites, which implies three equations of pseudo ranges for the four unknown values x, y, z, t. Therefore, four satellites are needed to calculate the four unknown values. The time error can be calculated with an accuracy of 170 nsec. The calculation work is done by Kalman filter techniques. Additionally, the errors of the Doppler effect can be eliminated by using Kalman filters.

All GPS receivers on the market have an output called DOP (dilution of precision) which gives a measurement of the quality for the position calculation. The pseudo range R_i^s can be measured by the above equation, using s = 1 to 4 satellites and (to prevent stochastic influence) i = 1 measurements. The stochastic and pseudo range errors are summarized in the DOP. That is a simple function of the diagonal elements of the covariance matrix of the evaluated parameters. If σ_0 denotes the standard deviation of the pseudo range and σ is the deviation of the calculated data--for example the vertical position--the DOP factor is defined as: $\sigma = \mathrm{DOP} \cdot \sigma_0$. In other words, this value is the relation between the possible maximum error and the individual error, where the possible maximum error is the uncertainty of the pseudo range measurements. Different DOP factors are evaluated:

$$\mathrm{VDOP} = \sigma_h \qquad \text{vertical DOP}$$

$$\mathrm{HDOP} = \sqrt{\sigma_N^2 + \sigma_E^2} \qquad \text{horizontal DOP}$$

$$\mathrm{PDOP} = \sqrt{\sigma_N^2 + \sigma_E^2 + \sigma_D^2} \qquad \text{position DOP}$$

$$\mathrm{TDOP} = \sigma_t \qquad \text{time DOP}$$

$$\mathrm{GDOP} = \sqrt{\sigma_N^2 + \sigma_E^2 + \sigma_D^2 + \sigma_t^2} \qquad \text{geometric DOP}$$

The DOP criteria can also be used to find the best four satellites out of the geometric constellation--if more than four satellites are available. The average value of HDOP and VDOP is about 2 for the best possible constellation of four satellites. Besides this error estimation, some of the GPS receivers have a so-called FOM (figure of merit) which informs the user of how many satellites are received and what accuracy of the position information can be reached. The following table 2.2 lined out the FOM status for the GPS receiver of SEL-ALCATEL named GLOBOS AN 2000. The information is helpful for the user and other systems using the GPS data.

Position	FOM	Remarks
invalid	9	No satellites tracked
"	8	At least 1 satellite tracked, but internal clock not yet correct.
"	7	At least 1 satellite tracked with corrected internal clock
"	6	At least 2 satellites tracked with corrected internal clock; Ephemeris data decoded and valid.
"	5	The position calculation has started, but is still unstable.
valid	4	The position (2-D) is calculated with 3 satellites, but has not yet reached the final accuracy.
"	3	The position (2-D) is calculated with 3 satellites; position calculation is supported by RF-carrier phase.
"	2	The position (3-D) is calculated with 4 or more satellites but has not yet reached the final accuracy.
"	1	The position (3-D) is calculated with 4 or more satellites; position calculation is supported by RF-carrier phase.

Table 2.2: FOM status of the SEL-ALCATEL GPS receiver. [86]

A lot of corrections can be made in the GPS receivers to improve the accuracy. For example, a troposphere and ionosphere model has to be implemented and to get high precision navigation data the orbital relaxation has to be regarded. Although the dual frequency observations and water vapour radiometer measurement are effective in reducing the limitation caused by the propagation media, the orbital error must still be dealt with. This is only a short description of all kind of errors which one has to look for. A lot of these errors can be eliminated by simple equations. As an example, figure 2.4 shows the "single satellite in a plane example." Assume that two receivers are located at position A and B in the figure and each of them has the capability of measuring the phase of a satellite signal relative to its local frequency standard. For this example we assume no clock error and the distance between the two receivers is small relative to the distance to the satellite. If there exists a small perturbation Δd of the distance between A and B, the corresponding phase difference of the received wavelength λ is

$$\Delta\phi_{(\text{without noise})} = \frac{\Delta d}{\lambda} \cos((\theta(t))) \tag{2}$$

which is measured in cycles. The wavelength for the GPS problem is about 20 cm. If the distance between A and B is known, the problem is to estimate the deviation from the nominal value based on the difference between the calculated and measured phase lags. Together with the measurement noise, Equation (2) becomes

$$\Delta\phi = \frac{\Delta d}{\lambda} \cos((\theta(t))) + \phi_{(\text{measurement noise})} \tag{3}$$

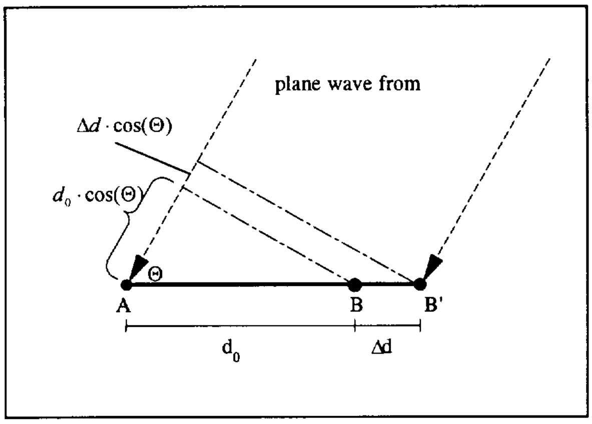


Figure 2.4: Single satellite geometry. [13]

This correction of the phase for each satellite can be calculated by Kalman filter techniques. Together with all the other corrections, highly accurate GPS navigation can be calculated.

Another main problem of the GPS technology is the measurement of the height. Because the distance between the satellites and the receiver antenna of an aircraft is very large, the measured angle differences in the vertical channel are very small. For the cross-track navigation, it is important to receive satellites in different azimuth directions and to be high enough over the horizon. But there is no demand on elevation of these satellites. For the vertical channel, having satellites of different elevations is important for the calculation. Otherwise there will not be sufficient triangulation from the satellites to measure the height. Lower satellites spread in azimuth yields a better horizontal position measurement, whereas some higher satellites are needed in order to measure the height. This implies the demand to give priority to the satellites with an elevation between 30 and 60 degrees over the horizon. Additionally, if there are more than four satellites available to receive, the ones with the highest difference in elevation have to be selected for calculating the height with a higher accuracy.

All position output data are calculated in the world geodetic system 1984 (WGS 84) coordinate frame. To use and perhaps support other systems with the GPS data, it is very important to know exactly the coordinate frame because errors less than 10 m for the GPS position can grow up to miles if the co-ordinate frames differ. As is well known, the earth is not a ball but an ellipsoid. The difference between the great axes is about 21 km and the main difference between national and international co-ordinate frames is the position of the ellipsoid gravity and mass center. For example, the variation between the European data 50 (ED-50) coordinate frame and the WGS-84 is 18 m and in Cartesian components Δx = -86 m, Δy = -111 m and Δz = -124 m. Coordinate transformations are known which convert the position and velocity information from one to the other coordinate frame.

The accuracy of the GPS position differs with the code that can be received. While with the pps-code the position accuracy can reach tenths of centimeters, the sps-code gives position information with an accuracy more than 10 meters. For in-flight receivers one can summarize the accuracy for the different codes as follows:

pps-code	≈ 3 m
sps-code with s/a-mode off	≈ 10 m
sps-code with s/a-mode on	≈ 30 m
sps-code with DGPS	< 3 m (see section 2.3)
pps-code with DGPS	< 0,3 m (with carrier phase).

The accuracy itself is also dependent on the receiver technology. If only the position is calculated out of the four ranges of the satellites and no error correction is done for the Doppler effect, the accuracy is smaller.

2.1 GPS supported INS Navigation

The so-called pure GPS-navigation calculates a highly accurate position and velocity. But for flight guidance and flight control of an aircraft, additional signals are important. For example, one needs the rotation rates and the angles for all axes as well as several accelerations of the aircraft. The hardware of such a system is called inertial reference system (IRS). Systems that supply all this information and in addition calculate the navigation information are the inertial navigation systems (INS) or, with less accuracy, the attitude heading reference systems (AHRS). In the following table 2.3, the different accuracies for the GPS and INS are marked out.

parameter	accuracy	
	INS	GPS
position, long-term	low	high
position, short-term	high	low
velocity, long-term	low	high
velocity, short term	high	low
attitude, heading	high	none
body rates	high	none
acceleration	high	none
ready time 1)	seconds	minutes
real time (UTC)	none	high

1) without the initial alignment

Table 2.3: Accuracy comparison between GPS and INS.

If one disregards initial INS 'alignment', then ephemeris acquisition should be disregarded also. In that event, ready times of INS and GPS become equivalent.

As shown in table 2.3, combining GPS and INS functions will result in high accuracy and fast ready time for all data under all conditions. While the INS-navigation systems are very expensive, the combination of an AHRS with reduced accuracy together with a GPS provides high performance at lower cost. The AHRS consists of a less accurate IRS combined with a heading reference (flux valve or magnetometer) and supported by radio navigation systems. Since the difference between AHRS and INS is only the accuracy, in the following explanation the name INS is used as a synonym for both.

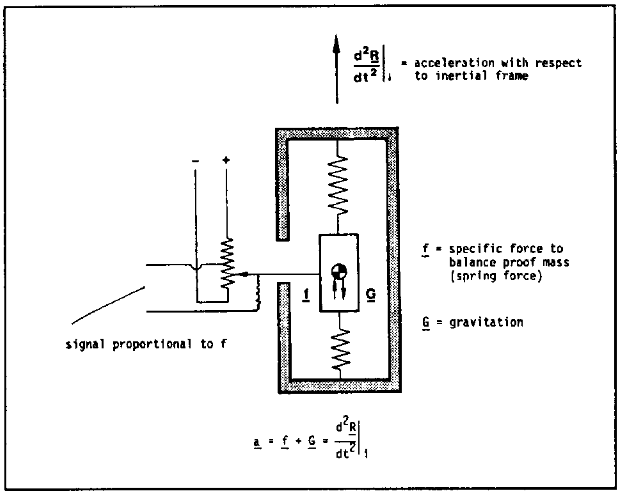


Figure 2.5: Principle of a simple accelerometer. [92]

2.1.1 Short description of the inertial navigation

An inertial navigation system contains two principal parts of hardware components: accelerometers and gyros. These instruments measure the translational and rotational motions of the body. An accelerometer in its simplest form (figure 2.5) is a mass balanced on two spring forces and can be used to measure the translational motion of a body in only one direction. The problems of manufacturing such a sensor have been solved and a lot of high performance accelerometers with bias errors of less than 10^{-5} g have been built. To measure the translational motion of a body in the three-dimensional coordinate frame, a so-called acceleration-triad is needed with three accelerometers sensing along orthogonal axes. The main problem with the accelerometer aircraft installation is the influence of the earth gravitational field. The triad should always be orthogonal to the earth coordinate frame, which means aligning one axis parallel to the gravity vector ($\vec{g}$). As the earth is rotating, the effects of coriolis and of centrifugal acceleration are measured by the accelerometers also.

In the $\vec{z}$-axis, pointing to the earth center, these effects of earth and transport rate are negligible because the accelerometer senses mainly the $\vec{g}$-vector of $9.81\ m/s^2$. With the $\vec{g}$-vector, the accelerometer triad is aligned orthogonal to the earth coordinate frame. Therefore, on the ground and before starting, the maximum acceleration direction is measured and the z-axis of the accelerometer cross is moved in the direction of the maximum acceleration. Otherwise, if the triad is fixed, the evaluated data of the $\vec{g}$-vector in all three directions of the accelerometer cross are stored in the navigation computer and can provide the elements of the corresponding transformation matrix.

The interesting data for navigation purposes are normally the position and the velocity. With the laws of Newton, it is well known that the acceleration is equal to the first derivative of the velocity and the second derivative of the position. On the ground, after the acceleration cross is aligned, this situation is uncomplicated. But if the aircraft is moving, other sensors must provide the angles between the measured signals in the aircraft (body) coordinate frame and the navigation coordinate frame. Therefore, a navigation system requires three gyros in addition to the accelerometers. Let us assume that the data of the gyros are present, then the accelerometer data have to be transformed from the aircraft coordinate frame to the earth coordinate frame by a transformation matrix $\mathbf{C}_{(n,b)}$ (b=body to n=geographical):

$$\mathbf{C}_{(n,b)} = \begin{pmatrix} \cos\theta\cos\psi & \cos\theta\ \sin\psi & -\sin\theta \\ \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi & \sin\phi\cos\theta \end{pmatrix} \tag{4}$$

with the roll angle Θ, the pitch angle ϕ, and the azimuth or heading ψ. For example, to transform the velocity vector from the aircraft body coordinate frame into the geographical frame, the following equation has to be evaluated: $\vec{v}_n = \mathbf{C}_{(n,b)}\ \vec{v}_b$. The transformation from the geographical into the body coordinate frame can be done by: $\vec{v}_b = \mathbf{C}^T_{(n,b)}\ \vec{v}_n = \mathbf{C}_{(b,n)}\ \vec{v}_n$. The upper index T indicates the transposed matrix (the transformation matrices are orthogonal and therefore the inverse matrix is equal to its transposed).

To calculate the velocity, the accelerometer data has to be integrated by additionally compensating the $\vec{g}$-vector as well as the coriolis- and centrifugal accelerations of the earth. Additionally, the velocity has to be transformed into the geographical coordinate frame. The position vector in the earth geographical frame is evaluated by integrating the velocity vector components.

The other measurement components of an inertial navigation system are the gyros. A lot of different gyro types are available--for example mechanical gyros, optical rate sensors, etc. A mechanical gyro is basically a rotor whose axis is fixed in a gimbals element (see figure 2.6). The main problem with a gyro is its drift due to factorization errors such as unbalance, anisoelasticity, motor hunting, etc. (Stieler and Winter, 1982 [92]; Wrigley et. al., 1969 [107]). With the aim of minimizing sensor errors, the gyros are built for special applications and the accuracy is mainly specified by the drift factor per hour. For navigation purposes, gyros are needed with a drift less than $0.1^{\circ}/h$ for attitude and heading reference systems and less than $0.01^{\circ}/h$ for real navigation systems.

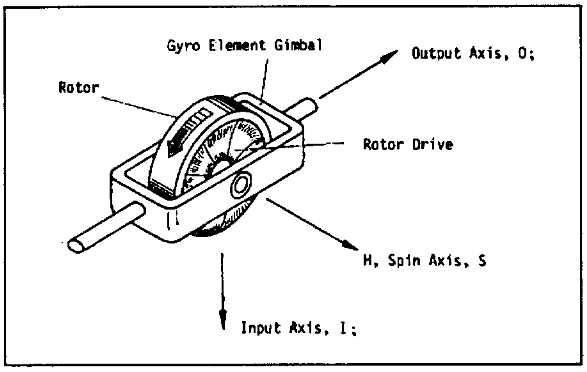


Figure 2.6: Principles of a gyro. [92]

Optical gyros are divided into two different types: the laser gyros and the fiber gyros. The physical principle of both gyros is based on the "Sagnac" effect. For the laser gyro, two light beams travel in opposite directions in a closed loop and are influenced by the rotation around the axis normal to the optical ring. Figure 2.7 shows the Honeywell laser gyro for inertial navigation systems. The drift error of such a laser gyro for navigation purposes must be less than $0.01^{\circ}/h$, although normally the gyros produce $0.001^{\circ}/h$. The fiber gyro works on the same principle as the laser gyro except that the light beams are inside a fiber circuit which is wrapped around a coil. The production of a fiber gyro is cheaper than a laser gyro. However, for highly accurate rotation measurements fiber sensors are not applicable.

Two main types of inertial navigation systems exist: the platform and the strapdown systems. For the platform system, the three accelerometers and gyros are mounted on a stabilized platform with three gimbals. If a rotation around one axis is sensed by a gyro, the signal is measured by the pick-off and transmitted to the associated gimbals servo motor. The platform with the gyros and accelerometers on it keeps itself oriented to the inertial space. The advantage of the platform system is a nearly total isolation from the vibrations of the aircraft, because

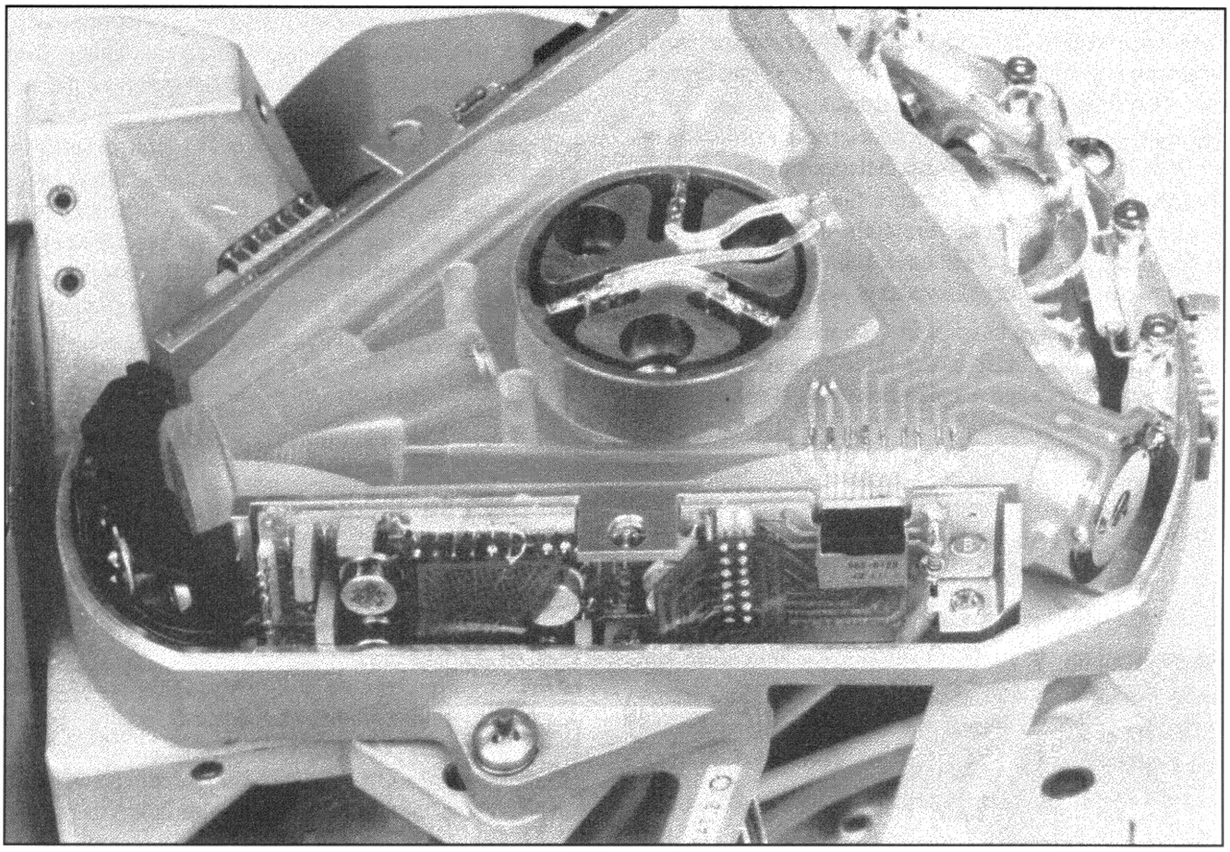


Figure 2.7: The Honeywell Laser Gyro. [78, 43]

the gyros only sense small rotation rates. However, a sophisticated mechanisation is necessary for the factorisation of the gimbals platform. For the strapdown system technology, the gyros and accelerometers are hard-mounted parallel to the aircraft's body axis. The hardware gimbals platform mechanisation has to be transferred into an analysis or set of equations, which must be evaluated in a computer. The main problems for these systems are an extremely wide scale region for the measured rotation rate and a detection of all the vibrations of the aircraft. Only the laser gyros survey such a wide region of rotation rate with the required high accuracy. The accelerometers cause no problem. Due to the gyros and mechanisation errors, the position accuracy of an inertial navigation system depends on time and is normally 1-2 NM/h (nautical miles per hour). This means, for example, that for a 10-hour flight across the Atlantic, the position error at the arrival airport is about 10 to 20 NM.

The errors of inertial navigation systems can be evaluated using the physical mechanisation description of the systems. The error model for the horizontal channels in the form of a differential vector-matrix-equation is as follows:

$$\dot{\vec{x}} = \mathbf{F}\cdot\vec{x} = \left(\begin{array}{c} \dot{\varepsilon}_N \\ \dot{\varepsilon}_E \\ \dot{\varepsilon}_D \\ \hline \delta\dot{v}_N \\ \delta\dot{v}_E \\ \hline \delta\dot{S}_N \\ \delta\dot{S}_E \\ \hline \dot{D}_N \\ \dot{D}_E \\ \dot{D}_D \end{array}\right) = \left[\begin{array}{ccc|cc|cc|c} 0 & -\varsigma & \frac{v_N}{E} & 0 & \frac{1}{E} & \alpha & 0 & \\ \varsigma & 0 & \eta & -\frac{1}{E} & 0 & 0 & 0 & I \\ -\frac{v_N}{E} & -\eta & 0 & 0 & -\gamma & -\kappa & 0 & \\ \hline 0 & -a_D & a_E & \frac{v_D}{E} & -2\zeta & -\xi & 0 & 0 \\ a_D & 0 & -a_N & \alpha+\zeta & \rho & \tau & 0 & 0 \\ \hline & 0 & & \frac{1}{E} & 0 & 0 & 0 & 0 \\ & 0 & & 0 & \frac{1}{E\cos\varphi} & 0 & 0 & 0 \\ \hline & 0 & & \multicolumn{2}{c|}{0} & \multicolumn{2}{c|}{0} & 0 \end{array}\right] \cdot \left(\begin{array}{c} \varepsilon_N \\ \varepsilon_E \\ \varepsilon_D \\ \hline \delta v_N \\ \delta v_E \\ \hline \delta S_N \\ \delta S_E \\ \hline \mathrm{D}_N \\ \mathrm{D}_E \\ \mathrm{D}_D \end{array}\right) \tag{5}$$

with : $\alpha = \omega_0 \sin\varphi$, $\beta = \omega_0 \cos\varphi$, $\varsigma = \alpha + v_E\,\gamma$, $\gamma = \frac{\tan\varphi}{E}$, $\kappa = \beta + \frac{v_E}{E\cos^2\varphi}$,

$\eta = \beta + \frac{v_E}{E}$, $\rho = v_N\,\gamma + \frac{v_D}{E}$, $\xi = 2\,v_E\,\beta - \frac{v_E^2}{E\cos^2\varphi}$, $\tau = \frac{\xi\,v_N}{v_E} - 2\,v_D\,\alpha$.

To evaluate the errors of the inertial navigation system, supporting information is needed to get the error equation: $\Delta\vec{v} = \vec{v}_{INS} - \vec{v}_{support}$. These differences, together with the above error equation for the INS, are input for a Kalman filter algorithm. As is known, such an algorithm works as follows: If no support information is present, the so-called prediction formulas have to be evaluated:

Prediction :

$$\begin{aligned} \hat{\vec{x}}_{k+1}(-) &= \Phi(k+1\,;\,k)\;\hat{\vec{x}}_k(+) \\ \mathbf{P}_{k+1}(-) &= \Phi(k+1\,;\,k)\,\mathbf{P}_{k+1}(-)\,\Phi^T(k+1\,;\,k) + \mathbf{Q}_k \end{aligned} \tag{6}$$

and if a supporting information in form of the vector $\vec{z}$ can be used, the so-called update algorithm has to be calculated:

Update :

$$\begin{aligned} \hat{\vec{x}}_k(+) &= \hat{\vec{x}}_k(-) + \mathbf{K}_k\left[\vec{z}_k - \mathbf{H}_k\;\hat{\vec{x}}_k(-)\right] \\ \mathbf{P}_k(+) &= \left[\mathbf{I} - \mathbf{K}_k\;\mathbf{H}_k\right]\mathbf{P}_k(-) \\ \mathbf{K}_k &= \mathbf{P}_k(-)\,\mathbf{H}_k^T\left[\mathbf{H}_k\;\mathbf{P}_k(-)\;\mathbf{H}_k^T + \mathbf{R}_k\right]^{-1} \end{aligned} \tag{7}$$

In these equations, the matrix $\Phi(k+1\,;\,k)$ is the evaluation of the differential equation of the error modeling. Normally this equation changes into a difference equation if one assumes that the changes in the continuous functions are very small between a small time interval [kT , (k+1)T] (T is the scan-rate, normally less than 0.1s). With these settings, the result of the differential equation becomes: $\dot{\vec{x}} = \mathbf{F}\;\vec{x} \;\Rightarrow\; \vec{x}_{k+1} = e^{F(t-t_0)}\;\vec{x}_k$, and using the Taylor series presentation for the e-function, it follows:

$\vec{x}_{k+1} = \Phi(t\,;\,t_0)\,\vec{x}_k$ with $\Phi(t\,;\,t_0) \approx \mathbf{I} + \mathbf{F}\,\Delta t$ as the transition matrix . The other matrices in the two formulas of the Kalman filter are called the measurement vector $\vec{z}$, the measurement matrix **H**, the error estimation vector $\hat{\vec{v}}$, the covariance matrix **P**, and the Kalman gain matrix **K**.

These are the conditions for calculating high accuracy INS navigation. Naturally the accuracy is dependent on the accuracy of the support information as well as which kind of inertial navigation system is used. Nevertheless, this part should only show how supporting INS with radio navigation works and that all equations and algorithm are present. Improvements for smaller evaluation time and numeric stability are made continuously, but the procedure for supporting INS navigation systems described above will be used in a lot of systems.

Summing-up, the accuracy of the pure INS is dependent on the errors of its accelerometers and gyros. For short time measurements--within minutes--the accuracy of the accelerometer and gyro measurements imply very high accuracy navigation, but for long term utilization the errors grow. As an example, the following table 2.4 shows the errors of the calculated velocity and position errors depending only on an accelerometer error of 10^{-5}g:

Otherwise, these errors depend on the gyro errors too; therefore, the errors can rise or fall as the transformation matrix influences the calculation of the specific value. Naturally, for the vertical channel these errors are not acceptable and a barometric sensor supports the INS navigation. As described above, the INS systems on the market have an accuracy of 1 NM/h 1-σ for the horizontal navigation. For increasing this accuracy, support information from high accuracy long term--but position based--systems like the radio navigation systems are used to increase the pure INS errors.

time	accelerometer error	velocity error	position error
1 minute	10^{-4} m/s^2	$6\cdot10^{-3}$	$3.6\cdot10^{-1} = 0.36$ m
½ hour	10^{-4} m/s^2	$1.8\cdot10^{-1} = 0.18$	648 m
1 hour	10^{-4} m/s^2	$3.6\cdot10^{-1} = 0.36$	1296 m $\approx$ 1.3 km

Table 2.4: Demonstration of the accumulation of INS errors.

2.1.2 Combining inertial navigation and GPS

The first question to answer before evaluating a support-algorithm for the INS is: in which coordinate frame does this calculation take place? The INS navigates in the geographical coordinate frame while the GPS works in the WGS-84 coordinate system. The conventional support of INS-systems is evaluated in the geographical coordinate frame. Therefore, all supporting information has to be transformed to this coordinate frame by a special transformation matrix. Otherwise it is possible to reformulate the differential error equation for the INS into WGS-84 and evaluate all errors of the INS in this coordinate frame. At the end of the algorithm, all data has to be transformed into the geographical coordinate frame. This is normally the better way to evaluate high accuracy navigation information. With the calculation, the position accuracy grows and can be used to increase the accuracy of all other data calculated by the INS system, like euler angles, angle rates, body accelerations, etc. If these data are more accurate, then the electronic flight guidance system can work more accurately and effectively.

The signals of the GPS system, like the position $\vec{x}_{GPS}$, can be used as input data for the measurement vector $\vec{z}_k = \vec{x}_{INS} - \vec{x}_{GPS}$ of the Kalman filter algorithm. The matrix $\mathbf{R}_k$ describes the accuracy of the GPS measurement. So, as the GPS data are available around the world all the time with a high accuracy, the INS system can be supported very well. This can perhaps reduce the cost of the INS because the precision for the production of accelerometers, and especially the gyros, may decrease. However, the loss of precision in the measurement units must be regarded when implementing the software and when implementing algorithms for high precision support evaluation of the data.

2.2 Differential GPS (DGPS)

Because GPS has the two different codes (sps and pps) and the accuracy of the codes can be degraded by the ground stations, alternate procedures and developments are discussed. Besides, the accuracy of the pure GPS navigation is not sufficient for high accuracy landing procedures such as CAT III. Otherwise a GPS receiver is cheap enough to be installed in a general aviation aircraft and this is the reason to expect GPS to be used as a high accuracy radio navigation system for instrument landing procedures.

The problem for the GPS receiver onboard an aircraft is the absence of a reference, or a non-moving position, for a time period. Therefore, the errors in the satellite positions cannot be corrected. In addition, the time error and Doppler effect are calculated with less accuracy. If a ground GPS station receives the same satellites as the receiver onboard and is able to transmit from the ground to the aircraft, the errors of the satellite positions can evaluated and transmitted to the GPS onboard. Figure 2.8 show such a configuration.

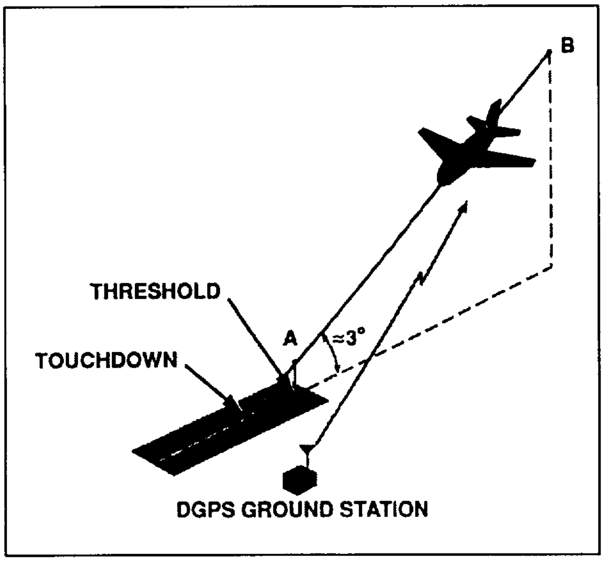


Figure 2.8: ILS look-alike DGPS system. [41]

The ground station is equipped with a GPS receiver and a computer that calculates the range for all received satellite data. The position of the ground station is known; therefore, the errors in the satellite position or the range measurements can be corrected. In this case, the ground station position is transformed into the WGS-84 coordinate frame and an exact range to the satellite can be calculated. A comparison with the measured range produces the error range compensation for the GPS receiver onboard the aircraft. With these corrections, the sps code data can achieve accuracies of less than 5 m. This is not enough for CAT III landing procedures, but significantly improves the accuracy of an sps code system. These first systems are built only for test procedures to show that the DGPS idea works.

2.3 Local Area DGPS

While the DGPS is already tested in several countries, the Local Area DGPS (LADGPS) is in the development phase and therefore is considered a future system. But the idea is similar to the DGPS that is specially developed for the aerodrome area. To get enroute the same accuracy for the GPS navigation, DGPS ground stations are planned (at known geographical coordinates) to transmit in the coverage area a GPS-like signal to the aircraft. With the pseudo-range corrections, the receiver onboard the aircraft can evaluate high accuracy navigation data. While the DGPS stations are normally located at international or great national airports, this LADGPS can be additionally used for several local airports which are not equipped with ILS, or in the future to be used *instead* of ILS for CAT I precision approaches.

Different studies about the configuration of a GPS Local Area Augmentation System (GPS/LAAS) are described. The system is based on a 30 satellite GPS constellation or a 24 satellite GPS constellation with four geostationary satellites (GPS/WAAS). Ground transmitters act like additional GPS satellites and reduce the GPS errors to improve the accuracy and to achieve a high availability. Three categories of GPS/LAAS ground stations were considered in parallel to the approach categories. The difference between category I and II are the antennas--commonly in use ground antennas or multipath limiting antennas--. Category III includes antennas that improve multipath performance and double the number of GPS receivers used in the upgraded station. The requirement for the GPS/LAAS configuration meets 0.9999 availability under different conditions.

2.4 Wide Area DGPS

This Wide Area Differential DGPS (WADGPS) is an eventual goal for a differential GPS that transmits the pseudo-range corrections for all satellites. Therefore, a number of ground DGPS stations must be planned to receive the GPS signals and transmit the errors to the aircraft. The corrections must be received at each aircraft position in the world, so the data must be transmitted via two geostationary satellite such as INMARSAT II/III. But all the questions about transmitting channels, data frames, availability, service, and costs have not yet been discussed and answered. Figure 2.9 demonstrates a WADGPS installation for the United States. A lot of ground GPS stations receive the same signals as the aircraft. A wide area master station collects all data and evaluates the errors and corrections while the ground earth station transmits these signals via a communication satellite to the aircraft.

First results for such a Wide Area GPS are coming out from the Wide Area Augmentation System (WAAS) planned by the FAA together with the University of Ohio. This system shall provide initial operational capability in a first phase starting in 1998. The second phase of the project, planned for 2001, adds additional ground sites and redundancy to provide increased system availability. The main intention for such a system is to collect all data about the GPS and geostationary communication satellites and combine with the ground station data to form the WAAS. In addition to the ground reference stations, a master station collects all data and, via communication satellites, transmits to the user the differential corrections, ionospheric delay information, and GPS/WAAS accuracy. It also verifies residual error bounds for each monitored satellite. The central data processing sites also generate navigation messages and other information helpful to the user.

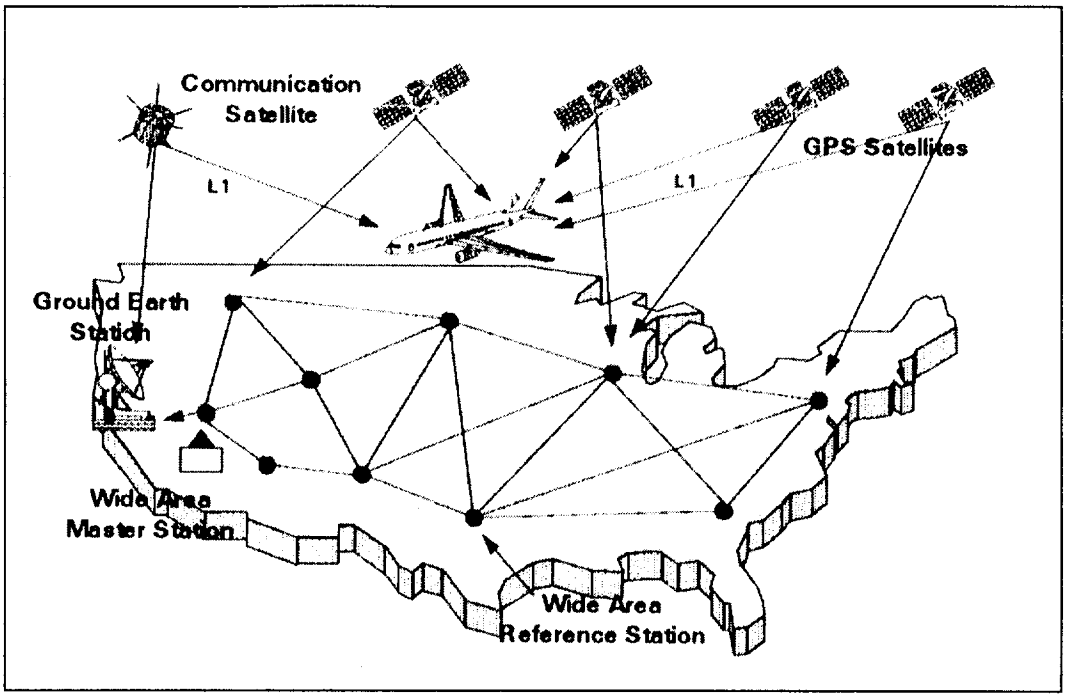


Figure 2.9: Wide area augmentation system based on DGPS. [91]

In contrast to the LADGPS, a WADGPS has more than one ground station and therefore more differences between the receivers, satellites and epochs can be measured. This implies a better correlation of the GPS phase signal as well as the clock error. Other errors such as ephemeris errors and hardware delays or influences by multipath, atmosphere, shadowing, etc. can be reduced too.

The other reason to install a WADGPS as opposed to LADGPS is the communication between aircraft and ground station. Using WADGPS, the differential and error signals of the satellites and the GPS measurements are transmitted via geostationary communication satellites, thus reducing the cost.

An assessment study find out that a GPS/WAAS configuration with 24 GPS satellites and four geostationary communication satellites (GEOS) can satisfy all requirements for Category I approach. This GPS/WAAS configuration consists of a geostationary uplink site, a wide-area reference site, a wide-area master site and a special WAAS avionics onboard the aircraft. In principle, a lot of error sources and risks could be modeled in such a WAAS configuration. For Category I approaches under different assumptions about the error modeling and elimination a WAAS configuration met 0.999 availability. These results are based on assessment studies and the current WAAS GEOS implementation is unclear. [16]

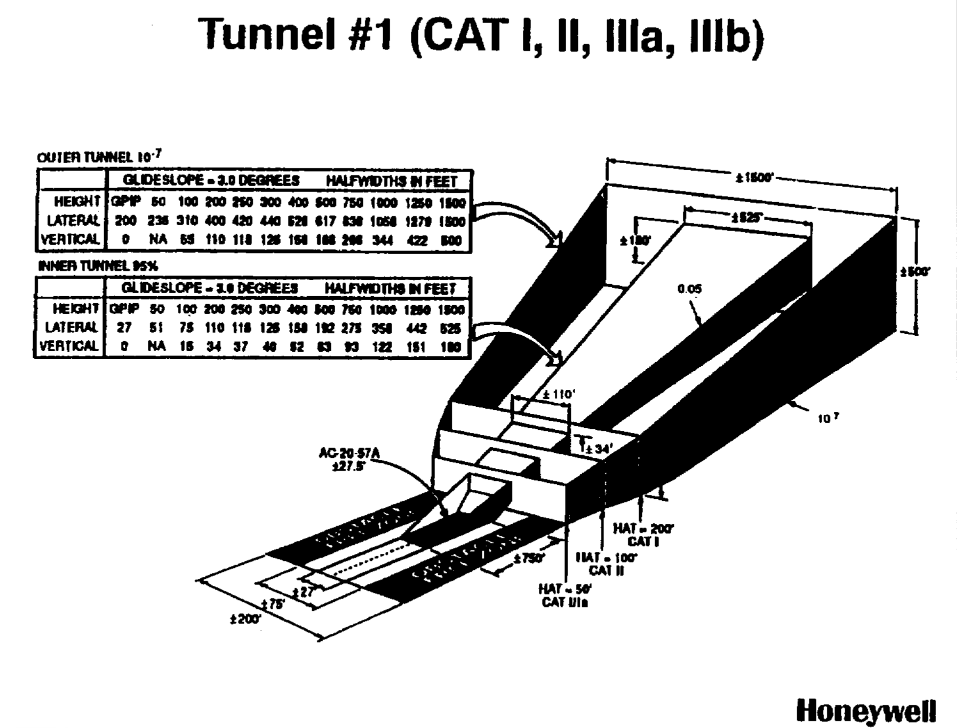
In addition to the WAAS implementation, other issues must be dealt with: the GPS/WAAS flight inspection, the system monitoring, the transmission errors from the geostationary satellites, the database integrity, and influences to the precision and availability via other transmitters. In other countries, the idea using WADGPS can be found in several projects.

2.5 The tunnel concept

This is a new idea for landing procedures. In the past, a 3-degree tangential to the runway approach is established for most of the airports and their runways. But in many places these approaches are directly over the city. For example, the approach for the National Airport a.k.a. Reagan Airport is along the Pontomac to avoid influences to the buildings downtown. The instrument landing systems nowadays are only capable of these procedures. If a DGPS is installed, the position information is calculated on board the aircraft and can be transmitted via the connection between ground GPS and airborne GPS receiver to the traffic control operator. Otherwise special approaches of more than 3 degrees and curved can be calculated on the ground. Such an approach, together with an accuracy window, can be transmitted to the aircraft. The pilot, together with the highly accurate DGPS navigation, is able to keep the aircraft inside the horizontal and vertical window. Following this information, a high precision landing can be done nearly automatically. Because the aircraft has to fly inside these windows that look like a tunnel, it is named 'tunnel concept.' A draft drawing of these ideas is demonstrated in figure 2.10 and the requirements for the DGPS or an other navigation system for this tunnel concept is lined out in table 2.5.

		Terminal Area	CAT I (200 ft DH)	CAT II (100 ft DH)	CAT IIIa (50 ft DH)
Availability		99.999 %	95 %	95 %	95 %
Continuity of function		99.999 %	6×10^{-6} (15 s)	10^{-7} (15 s)	10^{-7} (30 s)
Horizontal	95 %	± 0.3 m	± 110 ft	± 75 ft	± 27 ft
accuracy	10^{-7}		± 315 ft	± 190 ft	± 90 ft
Vertical	95 %	(Baro)	± 32 ft	± 15 ft	N/A
accuracy	10^{-7}		± 80 ft	± 35 ft	N/A
System Integrity		10^{-5}	10^{-7}	10^{-7}	10^{-9}

Table 2.5: Tunnel requirements. [41]



Tunnel #1 (CAT I, II, IIIa, IIIb)

OUTER TUNNEL 10^{-7}

	GLIDESLOPE = 3.0 DEGREES						HALFWIDTHS IN FEET					
HEIGHT	GPIP	50	100	200	250	300	400	500	750	1000	1250	1500
LATERAL	200	236	310	400	420	440	528	617	838	1058	1279	1500
VERTICAL	0	NA	65	110	118	126	158	188	266	344	422	500

INNER TUNNEL 95%

	GLIDESLOPE = 3.0 DEGREES						HALFWIDTHS IN FEET					
HEIGHT	GPIP	50	100	200	250	300	400	500	750	1000	1250	1500
LATERAL	27	51	75	110	118	126	158	192	275	358	442	525
VERTICAL	0	NA	16	34	37	40	52	63	93	122	151	180

Figure 2.10: Predefined requirements and graphical display of the Tunnel. [41, 42, 57]

The companies building GNSS (Global Navigation Satellite System), such as Honeywell and Litton together with Wilcox and Novatel, are developing experience in reaching these accuracies with their systems.

2.6 Tests with GPS and DGPS

As the GPS has only been used globally since 1993, only test results of the accuracy of the IRS-GPS navigation can be outlined. In several countries tests where made with different GPS receivers, but the results are nearly identical. Nowadays the requirements, the safety, and the installation process for a DGPS or WADGPS are the main problems for the ICAO (International Civil Aviation Organization), the CAA (Civil Aviation Authority), and all national authorities.

2.6.1 Tests in Europe

In Germany, the Institute for flight guidance at the university in Braunschweig has made the first approach with a DGPS- system (see below). For this test flight, an SEL GPS receiver was used together with a highly accurate platform inertial navigation system CAROUSEL IVa, a telemetry system, and computers on-board the test aircraft Dornier DO-28.

The DLR in Braunschweig has made some tests of GPS receivers and their accuracy. Two different SEL receivers were tested. The last one was the SEL-ALCATEL system GLOBOS AN 2000 and LN 2000. The tests took place in 1991 near the regional airport of Braunschweig with a test aircraft DO-228. The aircraft is equipped with a highly accurate reference system called AFES, which calculates a flight path with an accuracy less than 1 m online via telemetry, laser radar reference data, and a laser gyro strapdown inertial navigation system. During the flight test, the number of satellites received was enough, but for small periods of time (less than 4 minutes, during maneuvers) the GPS receiver had reduced accuracy. The average position error of this GPS receiver in 1991 during the optimal satellite receiving times was about 10 m.

Other studies, for example the EGNOS (European Global Navigation Overlay Service) developed by ESA (European Space Agency), are complemented by the first outline of a space system Safety Case and a training package explaining the contents. For example the content of Safety Case for the GNSS space domain are the mission requirements, the safety requirements, a safety management system, the design, engineering and operation requirements and the resources. To complement these regulatory activities EUROCONTROL has taken other initiatives in the program SAPPHIRE (Satellite and Aircraft Database Programme for System Integrity Research). This project is established by EUROCONTROL and assisted by Lufthansa, Litton Aero Products, Dornier, Racal Survey, Deutsche Flugsicherung, Crossair, and British Airways. SAPPHIRE consists of two parts: the data recording onboard commercial airliners and the development and operation of a database update and access unit. This second part is divided into three phases:

- phase I: evaluation of satellite navigation performance in the operational environment
- phase II: failure detection and identification by RAIM (Receiver Autonomous Integrity Monitoring) and AAIM (Aircraft Autonomous Integrity Monitoring) algorithms
- phase III: core for EGNOS test and validation program.

The data recordings take place in aircrafts A340 and A321 of Lufthansa, Saab 2000 of Crossair, and B747-400 of British Airways. The ground reference stations of the DGPS are Local Area and Racal SkyFix stations. The data evaluation is done offline via optical disks. At the end of the project, which was started in 1994, SAPPHIRE will provide a database from which the performance of GNSS (Global Navigation Satellite System) over time can be evaluated.

2.6.2 Tests in the United States

The FAA Technical center is the FAA Satellite Navigation Program Office's flight-test facility for evaluating enhancements to GPS for use as a precision approach landing system. Four types of GPS receiver technology were tested: the SEQ (sequential receiver), CAID (carrier aided receiver), NCOR (narrow-correlator spacing receiver), and KIN (kinematic receiver). These abbreviations themselves have no particular significance other than as an indication of the receiver technology.

The SEQ is a two-channel sequential receiver that operates in GPS or DGPS mode as well as being integrated with an IRS. All data were processed by a twelve-state Kalman filter, evaluating the position, velocity, acceleration, and clock frequency error out of the time division multiplex pseudo range and range rate measurements. For the DGPS, a ground station equivalent to the airborne system is installed which transmits the corrections via VHF data link at 0.5 Hz update rate.

Receiver	method	SA	Diff. Update Rate	Pos. Update Rate	Vertical error	Crosstrack error	Average VDOP	No. of Appr.
2-channel SEQ	none	off	N/A	1 Hz	12.7 m	7.7 m	1.7	18
"	IRS	off	N/A	10 Hz	8.5 m	8.1 m	1.7	8
"	DGPS	on	0.5 Hz	1 Hz	11.2 m	5.9 m	2.0	33
"	D/ IRS	on	0.5 Hz	10 Hz	8.4 m	4.3 m	2.0	33
5-channel CAID	DGPS	off	1.0 Hz	2 Hz	5.1 m	4.7 m		18
"	DGPS	on	1.0 Hz	2 Hz	7.0 m	6.1 m		10
10-channel NCOR	DGPS	on	1.0 Hz	5 Hz	2.1 m	1.2 m	1.7	35
On-the fly KIN2	DGPS	on	0.5 Hz	2 Hz	1.0 m	1.0 m	1.9	18

Table 2.6: GPS test results. [41]

In table 2.6 the "method" means the augmentation whether the pure GPS navigation, the differential GPS (DGPS), the supported IRS by GPS (IRS) or the supported IRS by differential GPS (D/IRS) was used. One column shows if the SA-code was on or off and the "Diff. Update Rate" means the update rate of the ground station using the DGPS. The "Pos. Update Rate" is the rate of position update and the errors are divided into two parts, one for the vertical and another for the horizontal (crosstrack) direction. These errors are the mean values of all approaches (see "No. of Appr."--mean number of approaches) and are evaluated during the final (2 NM from touch down). To get a realistic error description of probably 95 per cent, two times the standard deviation is added to the mean values.

In the United States, the Honeywell company together with the FAA built a GNSS team to look for the requirements of a DGPS on several airports in the United States.

In 1992, the Wilcox company together with the FAA demonstrated and tested their GPS/DGPS system in Atlantic City. They reached 1.03 m lateral error and 2.01 m vertical error. One year later their ground system was implemented in a demonstration program in France and first tests of CAT IIIb approaches are done in the USA. Together with the NovAtel GPS receiver and the Litton LTN-400, they built the GLS (Global Landing Sytem). The LTN-400 selects all data of radio navigation systems like VOR, DME, IRS, DGPS, OMEGA etc. together and provides highly accurate navigation. Different investigations are being done together with the University of Calgary for implementing two-antenna systems in an aircraft. With two antennas installed at a distance of about 20 m at the tail and the middle of an aircraft, these experiences should demonstrate the possibility of measuring the pitch and azimuth of the aircraft.

The intentions for GPS, DGPS, WADGPS, or similar systems is to look to a single sensor for low-cost enroute and landing navigation systems, especially to utilize curved approaches, to get taxi and ground vehicle guidance, and to improve landings on uninstrumented airfields and runways.

2.7 Other GPS-like systems

In addition to the GPS system installed by the United States of America, the **GLONASS** (**G**lobal **O**rbiting **N**avigation Satellite System) with 24 satellites is build by Russia (former USSR). The GLONASS may work similarly to the GPS and the information about the system is not well documented, but a lot is known about GLONASS. It should be mentioned that GLONASS uses a different reference system, which is not known accurately, for deliberate lack of precision (like the GPS civil mode). Otherwise, the GLONASS has no s/a mode and no multiple codes. The system transmits its signals on an L-band in the neighborhood of those used by GPS. The signal-to-noise ratio is about 4 dB less than that of the GPS. A lot of commercial GPS receiver systems are able to receive and evaluate the signals of GLONASS.

Other satellite-based systems are planned in addition to the GPS for transmitting the communication information as well. In contrast to the GPS, transponder based satellite systems are being discussed. These systems use the Doppler effect, evaluate the position of the user on a ground station, and transmit via satellite the navigation information to the user. This two-way communication system can only evaluate navigation information for a limited number of users and in approximately one second time periods. The accuracy can be less than 10 m, but these systems are not compatible with the GPS or GLONASS.

2.8 GPS and DGPS Errors

The errors of the GPS and DGPS are based on the availability of the satellite transmission data. So the installation of the antennas onboard the aircraft is a critical point because one has to choose a position where the influence of most flight maneuvers is the least. But if the satellite information is lost, an AHRS can calculate for a short time the position and velocity until the GPS has locked to the satellites again. This means that a coupled DGPS and inertial navigation system together can evaluate high-accuracy enroute navigation data. While in the terminal area during landing configuration, special requirements must be adapted if the satellite data are not available.

Another problem for precision approaches (such as CAT III) is DGPS use requiring communication with the ground GPS station. The requirements for such a link between aircraft and ground must be high. If the communication via satellite or VHF fails, a hybrid navigation system (AHRS - DGPS) can provide a high-accuracy flight path calculation for a short time. Therefore, issues regarding the accuracy of the DGPS system depend on those times when the GPS either loses some satellite tracking or loses communication with the GPS ground station.

The GPS ground station generates the satellite error corrections for the onboard GPS. If this error calculation is faulty, the whole accuracy decreases and no indicator can be installed to report this fact to the onboard GPS system and, of course, the pilot. This is one of the most critical errors which can only be flight checked if a WADGPS (wide area DGPS) is installed and a lot of different GPS ground stations can be checked against each other.

Possible interference with GPS frequencies near the airport are another problem that must be avoided. The GPS signal is very weak, and, assuming a standard GPS receiver, a modest level of jamming power can stop GPS operations. The result is loss of navigation for all aircraft within the jammer area.

Nevertheless, the GPS or DGPS is a highly accurate navigation facility that will be installed and used on several airports because such a system increases the accuracy for the whole of aircraft navigation. These systems drop the price for navigation systems in aircraft as well as at airports. Otherwise, if all GPS receivers are able to receive as well the data of the Russian satellite navigation system GLONASS, the errors may decrease and the availability may increase. With such a worldwide system based on the data from two different satellite systems from two different countries, a changing of the radio navigation philosophy can take place. In this case the flight inspection and flight testing community also has to change and to rethink their work. But before this future scenario is reality, a lot of new requirements have to be initiated and all errors and influences, etc. have to be discovered and eliminated.

3. CONVENTIONAL ENROUTE NAVIGATION SYSTEMS

This section describes the conventional navigation systems normally used nowadays for enroute navigation.

3.1 DME

The **D**istance **M**easurement **E**quipment (DME) has a range of about 200 NM and measures the direct distance to the ground station in nautical miles. The pilot knows only the radial distance to the station and the information of two stations is generally not sufficient because two arcs have two crossing points. Therefore, more DME stations must be used to give proper position information. A so-called multi-DME receives data from all DME stations around the present position and calculates the position of the aircraft by additionally eliminating the errors of the used signal--if sufficient stations are present.

The DME works as follows: a DME airborne system transmits query pulses which are received by the ground station. The pulse is transmitted back to the airborne system with a fixed known time delay. The time difference measured on board between the transmission and receiving of the pulse is equivalent to the distance between aircraft and DME-station:

$$\text{distance} = f\left(\frac{t_{\text{transmitter}} + t_{\text{receiver}} - 50\mu s}{2} \right) \qquad (8)$$

(where the 50 µs is the time delay). The DME works in a frequency of 960 to 1215 MHz. The pulses themselves are like bell shaped curves with an ascent and descent of 2.5 µs ± 0.5 µs and a pulse width of 3.5 µs ± 0.5 µs.

The system on the ground is named transponder while the airborne system is named interrogator. The system is established to evaluate the distance between ground and airborne systems up to 20 NM. The pulse form is outlined in figure 3.1 and the repeat frequency for the calling-pulse-pairs should be less than 30 Hz. Each DME station must have the capability to handle up to 100 aircraft receivers. A VOR is located near most of the DME stations, so the pilot can evaluate the correct position of the aircraft in the geographical coordinate system. Therefore, the transmission frequency has to be separated very well. Table 3.1 shows the channels for the VOR/DME stations.

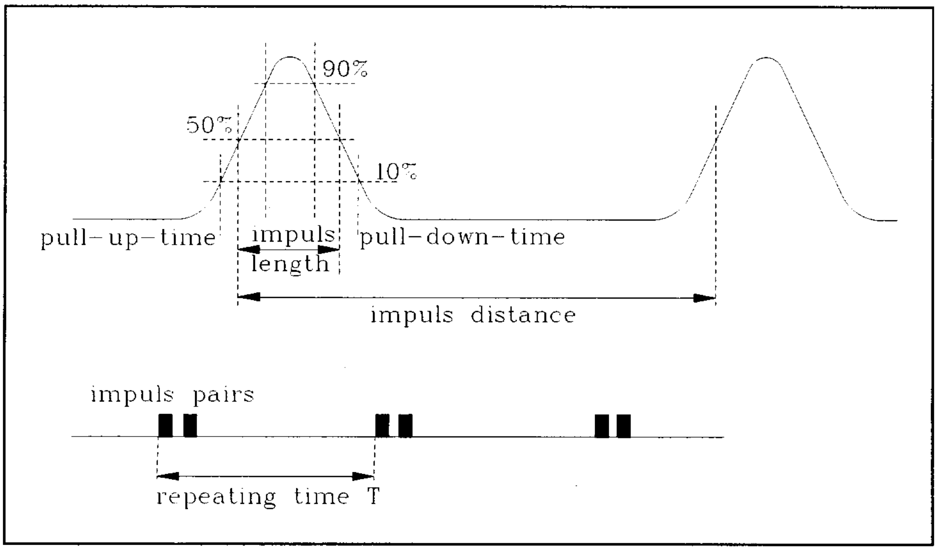


Figure 3.1: DME pulse form. [7, 8]

There exist a lot of errors for DME navigation that can be divided in two main groups--the stochastic and the system errors. The reason for these errors can be found in the DME ground station transponder as well as receiver faults or influences by the transmission. Counter cycle stability, quantum influence, signal/random ratio of the demodulated receiving signals, pulses deforming in the receiver, changing of the transmission time in the receiver, etc. are errors of the ground station and the receiver as well. Reflections on objects near the ground station and on the earth surface can influence the signal/random ratio. All these faults produce different distance errors. This is demonstrated in figure 3.2 as the 3-σ values for the various sources of errors. As an estimation of the maximum error, one evaluates:

$$\sigma_{\text{system}} = \sqrt{2 \times 76^2} \approx 107\text{m} \qquad (9)$$

and $$\sigma_{\text{stochastic}} = \sqrt{2 \times 43^2} \approx 61\text{m} \qquad (10)$$

channel	VOR frequency (MHz)	DME-calling-frequency (MHz)	DME-responding-frequency (MHz)
X		impulse-code-distance 12 μs	impulse-code-distance 12 μs
1	--	1025	962
16	--		
17	108,00		
59	112,20		
60	--		
63			1024
64			1151
69	--		
70	112,30		
126	117,90	1150	1213
Y		impulse-code-distance 36 μs	impulse-code-distance 30 μs
1	--	1025	1088
16	--		
17	108,05		
59	112,25		
60	--		
63			1150
64			1025
69	--		
70	112,35		
126	117,95	1150	1087

Table 3.1: channel classification for VOR/DME stations. [7, 8]

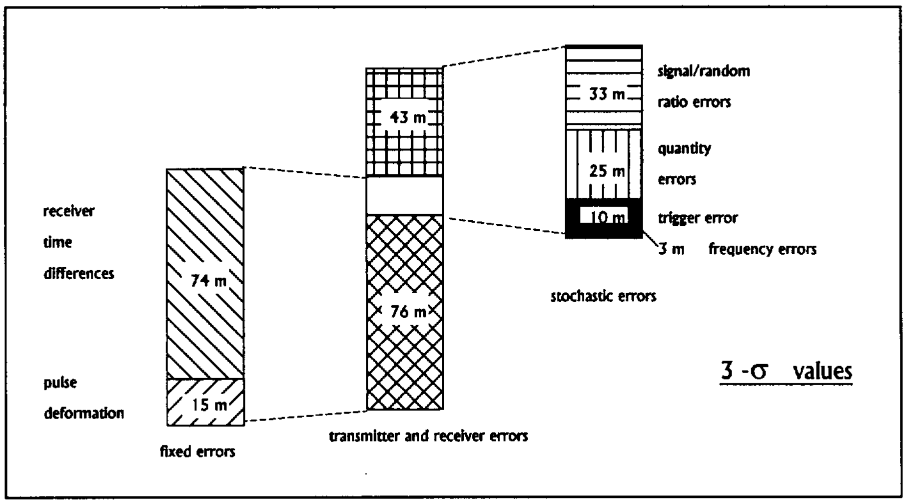


Figure 3.2: Errors of the DME system.

altogether a distance error of 168 m. These errors can be reduced because some of them are attached to the DME station and its signal processing. If different DME stations could be received, the faults of each station can be evaluated by comparing the distances with each other. With a suitable model displaying the errors of a DME station, the accuracy of the distance measurement can be improved. The position of the DME stations is well known. For example, they are listed in the DOD flight information publication supplement, and since the crossing point of more than two DME distances is unique, a present position of the aircraft can be calculated by the receiver. For the error correction of the DME station one needs more than three DME stations. Normally five DME stations make possible the calculation and give the feasibility for the error elimination.

The frequencies for the secondary radar systems (channel 1Y - 16Y; 60X,y - 69XY; 70Y - 79Y; 124Y - 126 Y) may not be influenced by the VOR/DME--otherwise other frequencies must be used.

3.2 VOR

VOR is the abbreviation for **V**ery High Frequency **O**mnidirectional Radio **R**ange. This system produces angle information with reference to the ground station. A VOR ground station with a single element antenna is displayed in figure 3.3. At some places, VOR ground stations are installed in addition to DME or TACAN and they are called VORTAC. The VOR has been usable since 1946; therefore, it is one of first installed radio navigation systems. As of 1992 in the United States, 962 stations were working and the FAA planned another 58 stations up to the year 2000. The number of stations is attached to the crossings of airways because flying on a fictitious airway means flying on a determined heading between fixes (VOR stations). The range of a VOR station is about 100 to 150 NM and is limited by the use of VHF frequencies. The number of user receivers is about 200 000 in the United States.

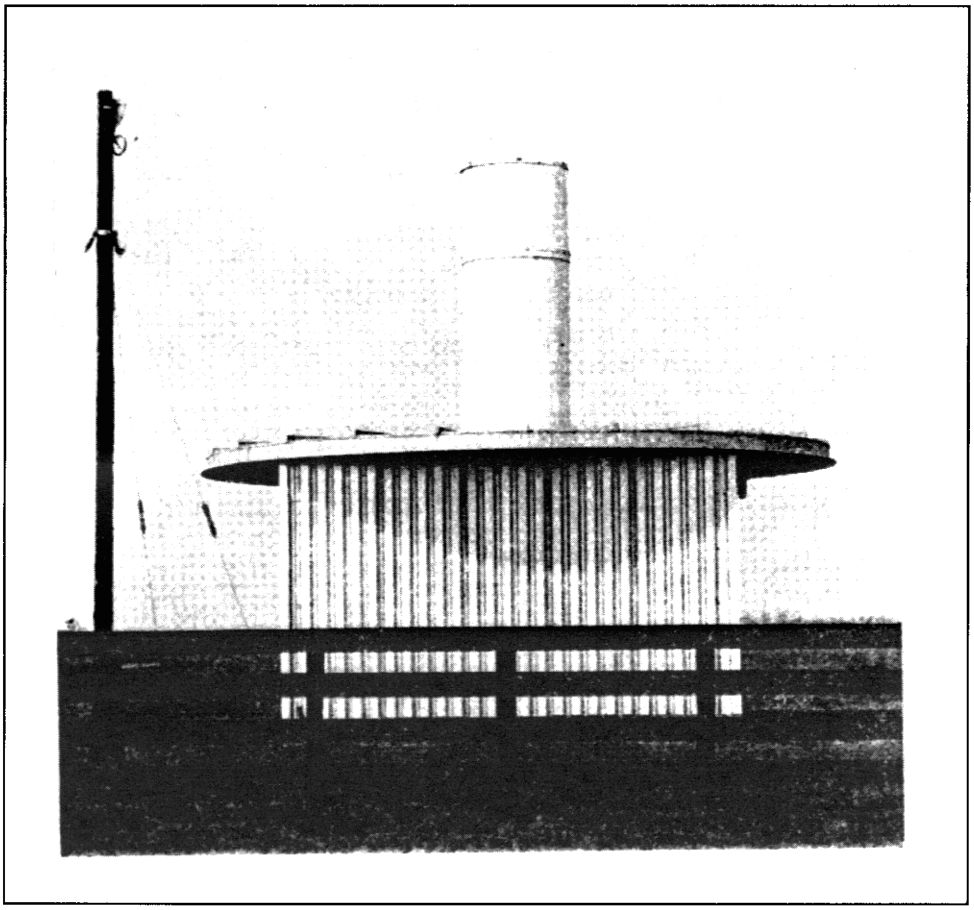


Figure 3.3: VOR-S ground station with single element antenna. [39]

The VOR works with a carrier frequency of 108 to 118 MHz and transmits an azimuth dependent signal that is received onboard the aircraft. The receiver evaluates the azimuth. The azimuth dependent signal consists of a 30 Hz oscillator while the phase corresponds with the azimuth. Rotating a dipole with 30 rotations per second and superpositioning this signal with the carrier frequency provides an amplitude modulation (AM) of 30 Hz that produces the azimuth dependent signal. For the evaluation of the azimuth information at the receiver, a 30 Hz base oscillation is transmitted on a 9960 Hz carrier frequency as frequency modulation (FM) with a frequency deviation of ± 80 Hz. This signal will be added as an amplitude modulated signal to the VHF frequency. The separation between the two 30 Hz oscillations is very simple as well as the evaluation of the azimuth as phase difference because magnetic north is equivalent to that direction where the phases are equal. In addition, a voice signal (300 Hz to 3000 Hz) and the identification (1020 Hz) of the VOR station is added by amplitude modulation. The following figure 3.4 shows the VOR frequency spectrum.

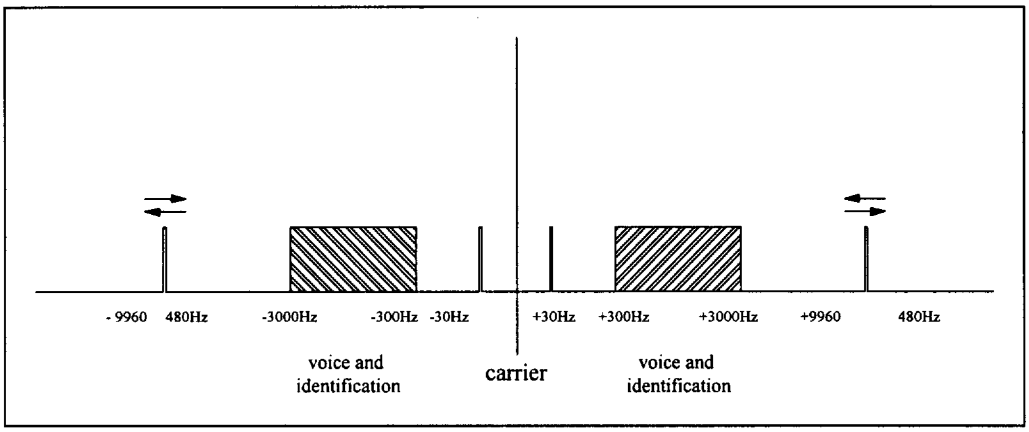


Figure 3.4: VOR frequency spectrum. [39]

For the transformation of the principle idea to a VOR station, the principle of the goniometer is used where the mechanical rotation of the antenna is not practical. The goniometer transmits the signal from fixed antennas and produces on two different outputs amplitude modulated oscillations (30 Hz). The covering curves are sine and cosine curves with a frequency of 30 Hz, rotated by 90° against each another. Figure 3.5 shows the antenna diagram of this principle. The goniometer outputs are sent to two pairs of antennas rotated by 90° against each other. At the onboard receiver, the sum of both oscillations can be received. The voltage at the onboard antenna is:

$$U_e = U_e \cdot (\cos\psi \cdot \sin(\omega \cdot t) \cdot \cos(\Omega \cdot t) + \sin\psi \cdot \cos(\omega \cdot t) \cdot \cos(\Omega \cdot t)) = U_e \cdot \sin(\omega \cdot t + \psi) \cdot \cos(\Omega \cdot t) \quad (11)$$

with Ω the carrier frequency, U_e the maximum of the received voltage, and $\omega = 2 \cdot \pi \cdot 30Hz$.

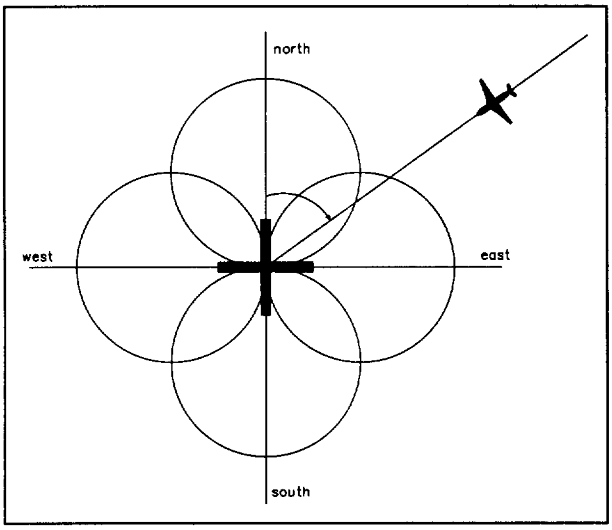


Figure 3.5: Explanation of the goniometer principle showing the antenna diagram. [39]

The azimuth ψ is equivalent to the phase angle of the 30 Hz oscillation. The linearity and constancy of the electrical modulators must be very high therefore the realization of the goniometer is difficult.

Each VOR station must have a monitor to shut down the system if the system is out-of-tolerance. Therefore, a field detector is installed near the ground station to receive the transmitted signal and send the demodulated signal to the monitor system.

The receiver onboard the aircraft evaluates the signal to determine which channel is switched on. By transforming the frequency and amplifying the signal it can be demodulated. The separation of the voice, identification, 30 Hz signal, and 30 Hz reference signal is done by filters. A frequency discriminator provides the 30 Hz signal that is input for a phase bridge. One of the signals is connected to the azimuth selector which is a phase shifter providing data between 0° and 360°. On the azimuth selector of the crosspointer instrument, the azimuth that shall be flown is set by the pilot. The outputs of the phase bridge are connected to the crosspointer instrument that provide a difference voltage of Null if the azimuth on the selector is equivalent to the received signal. The crosspointer instrument also shows differences up to ±10^o by a needle. Additionally, a "from-to" indicator informs the pilot as to the course of the aircraft being to or from the VOR station.

The error of the VOR system azimuth information based on the system itself is less than 1^o. The errors based on reflections from obstacles or terrain and interference with other radio navigation systems are normally higher. For example, the reflections show at the receiver different azimuth information because the phase difference is evaluated between the reflected and direct signal.

To decrease the reflection errors on the terrain, a compatible Doppler-VOR (DVOR) system was developed. In the DVOR, the two 30 Hz oscillators are changed--which implies that on the centered antenna the 30 Hz oscillation is transmitted with amplitude modulation on the carrier frequency. Besides this center antenna A_0, a circular antenna array is mounted at a distance of R that can be interpreted as a rotated signal on a circle. The frequency of the circular antennas is shifted by ±9960 Hz to the carrier frequency. Rotating the circular antennas with a frequency of 30 Hz, the azimuth dependent frequency modulation is provided with the doppler effect. The frequency difference can be calculated by:

$$\Delta F = F \cdot \frac{R \cdot \omega}{c} \tag{12}$$

with F the carrier frequency, c light velocity, $\omega = 2 \cdot \pi \cdot 30Hz$. Since the frequency difference shall be between ±480 Hz (ICAO) this implies a circle radius between 7.1 m and 6.5 m for the frequency area 108 KHz to 118 KHz. For two receivers (E_1, E_2) located with a difference of 90^o, the receiver frequency (ΔF) of the circular antenna array is:

$$[\Delta F]_{E1} = \Delta F \cdot \cos(\omega \cdot t) \tag{13}$$

and $$[\Delta F]_{E2} = \Delta F \cdot \sin(\omega \cdot t) \tag{14}$$

Thus the azimuth difference of 90^o is equivalent to the phase difference between the 30 Hz oscillations.

The hardware realization of a DVOR is shown in figure 3.6. The transmitter system together with the commutator is located in a small building while the 39 side-band antennas are mounted on a platform 3 m up to 10 m overhead the station. The carrier frequency antenna in the middle and the other antennas are situated on a circle with a diameter between 30 m and 40 m. So the dimensions of the DVOR system are large. The monitor dipole is mounted at a distance of about 200 m away from the DVOR station. The main advantages for the DVOR station are that the large antenna basis and the FM transmission cannot interfere as high as the VOR signal. A comparison of the azimuth error depending on terrain reflections can show that the DVOR error is a tenth of the error of a conventional VOR station signal. Otherwise, the error of the DVOR signal has its maximum when the angle difference between receiver- and refection-azimuth has its minimum--while the VOR station has the maximum error when the difference is 90^o.

Figure 3.6: Doppler-VOR ground station. [39]

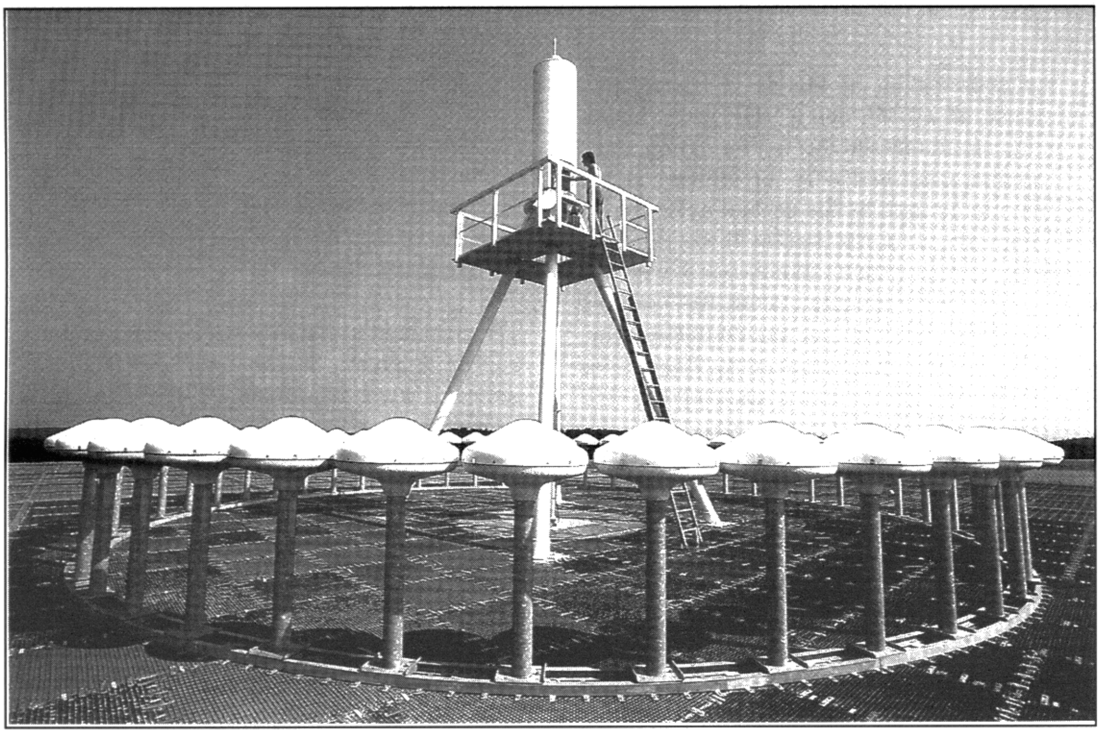


Figure 3.7: VORTAC ground station in Germany. [21]

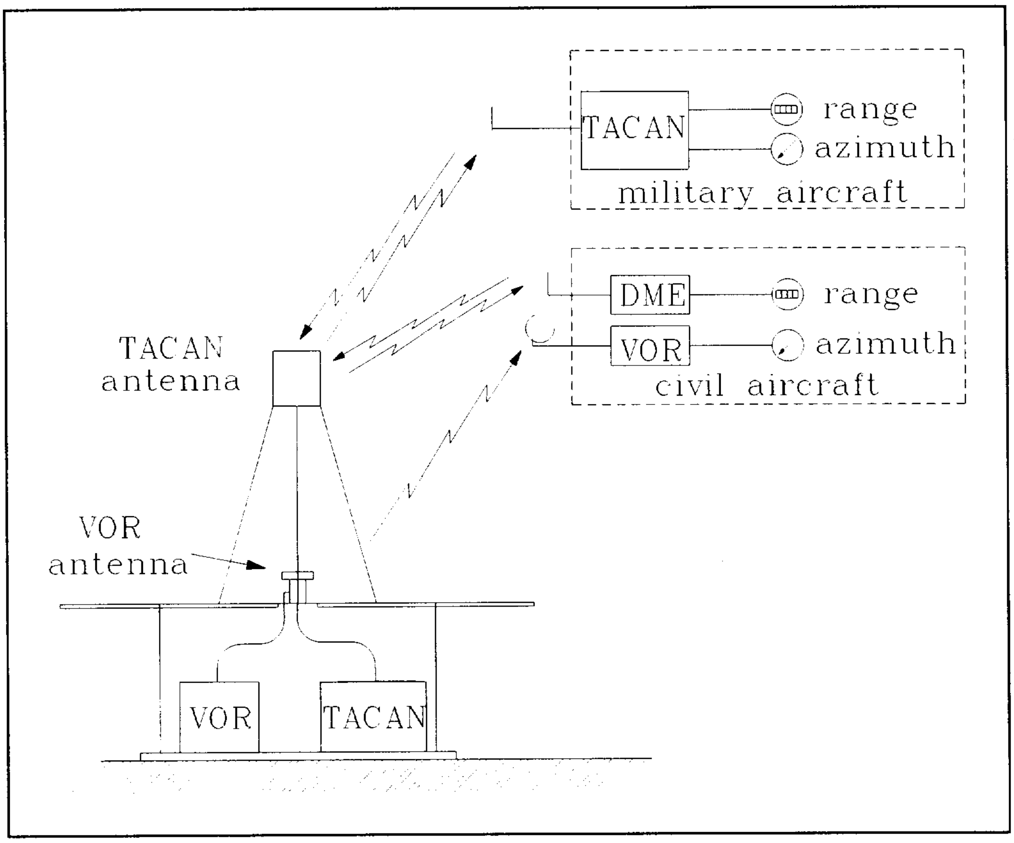


Figure 3.8: Configuration of a typical TACAN station. [7, 8]

3.3 TACAN

TACAN is the abbreviation of tactical air navigation system and consists of a DME and a VOR part. It supplies angle and distance measurements to a station. The TACAN system was evaluated only for military usage, but since 1959 it can be used by the general aviation. At several locations, the TACAN station (especially the DME component of this system) is connected with the VOR station. This is a so-called VORTAC station. Figure 3.7 shows a typical VORTAC station in Germany. The system works on the L-band between the frequencies 962 to 1214 MHz and this section is divided into 252 channels.

The ground-based hardware system consists of a middle antenna and one secondary antenna at a distance of 7.5 cm rotating at 15 Hz. This provides a rough tuning. Additionally, nine antennas rotate at 15 Hz at a distance of 45 cm from the middle antenna. This provides fine tuning. The rotation of the antennas is realized by a mechanical rotation of a 15 Hz motor having an accuracy of 1%. 15 Hz and 135 Hz pulses are transmitted which can be used to evaluate the azimuth information by comparing the phases between the azimuth and non-azimuth signals. The TACAN station works analogously with the DME and VOR station. The advantages for these systems are:

- the TACAN antenna is much smaller because the working frequencies (962-1213 MHz) are much higher than those of the DME (108-118 MHz). Therefore, these system can be used as mobile stations as well as on ships.
- the accuracy is higher because the rough and fine tuning principle is used.
- azimuth and distance are measured at the same high frequency channel.

The signals of a TACAN station can also be received by a DME receiver. So for some VOR stations a TACAN station is used to provide the DME distance. Military aircraft receive only TACAN information while civil aviation aircraft use the DME part of the TACAN station and the signal of a (probably co-located) VOR station. This situation is outlined in figure 3.8.

As an example, figure 3.9 shows the Collins AN/ARN-139(V) TACAN onboard system with the TACAN antenna, the bearing adapter unit, and the control unit. Such receivers are equipped with a rotating antenna and they are able to receive the data of up to 5 TACANs. The outputs are distance and bearing in analogue and digital form. The specification for the receiver and decoder can be found in the military standard (MIL-STD-291). The accuracy of the output is about ±0.2 NM for the distance and ±1.5° for the bearing.

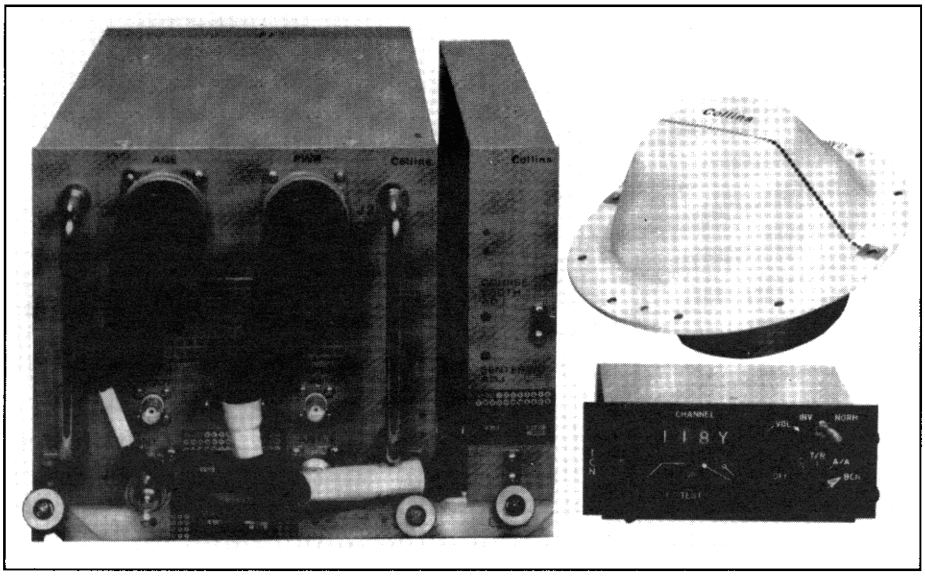


Figure 3.9: TACAN receiver, antenna and CDU of the Collins AN/ARN-139(V). [81]

3.4 LORAN C

The **LO**ng **RA**nge **N**avigation system (LORAN) was first installed in 1960 and has a range of about 1500 NM. The transmitter antennas on the ground are located mostly near the coast. For example, for the Atlantic route a lot of LORAN transmitting stations are available.

On the east coast of America from Newfoundland down to Florida, the stations 1H-0, 1H-1, 1H-2, 1H-3, 1H-4, 1H-6, and 1H-7 are located about 100 NM apart. The rest of this North Atlantic route from Newfoundland to Great Britain has only 4 stations: 1L-5 (Canada), 1L-6 (Greenland), 1L-5 (Iceland), and 1L-6 (Hebrides). According to the measurement principle, during the day a minimum of transmitting stations influence LORAN navigation, but at night very good overall navigation can be calculated. The transmitting antenna has a height of about 33 m and a radiated power of about 100 KW.

The LORAN receiver consists of 3 parts: the antenna, the EDO-receiver, and the indicator and control panel. The LORAN works at 4 frequencies:

channel 1	1950 KHz
channel 2	1850 KHz
channel 3	1900 KHz
channel 4	1750 KHz.

More than one LORAN system can work on one frequency without any conflicts if they use different pulse modulation. Three main groups of impulse modulation exist which are divided into 8 station rates. The distance between 2 pulse sequences is called the pulse repetition rate. Table 3.2 shows the possible pulse sequences.

With the identification (ID), each station is associated with a pulse distance group as well as a channel. Altogether, four channels in each of three main groups and eight pulse sequences per channel allows a maximum of 96 LORAN stations. As is well known, radio waves from transmitting stations are radiated in all directions. A portion of the waves travel along the earth's surface and are known as ground waves. Another portion is reflected from the ionosphere to the receiver. They are known as sky waves. In this case the range of the LORAN system is different, because the ground waves travel a maximum of 700 NM during the day, while during night hours these waves are limited to 400 NM. The sky waves can not be received during the day because solar radiation causes the underside of the ionosphere to be irregular. Thus the waves are absorbed rather than reflected. At night the sky waves reach a maximum of 1400 NM. The twilight period is the most critical receiving time for LORAN, because the ground and sky waves heterodyne with each other and that influences the evaluation. The accuracy of LORAN for the ground beam is about 2 to 3 NM at the edges of the transmission range.

short group 20 Hz		low group 25 Hz		high group 33.3 Hz	
pulse distance ms	ID	pulse distance ms	ID	pulse distance ms	ID
50.0	S-0	40.0	L-0	30.0	H-0
49.9	S-1	39.9	L-1	29.9	H-1
49.8	S-2	39.8	L-2	29.8	H-2
49.7	S-3	39.7	L-3	29.7	H-3
49.6	S-4	39.6	L-4	29.6	H-4
49.5	S-5	39.5	L-5	29.5	H-5
49.4	S-6	39.4	L-6	29.4	H-6
49.3	S-7	39.3	L-7	29.3	H-7

Table 3.2: Possible pulse frequencies for the LORAN system.

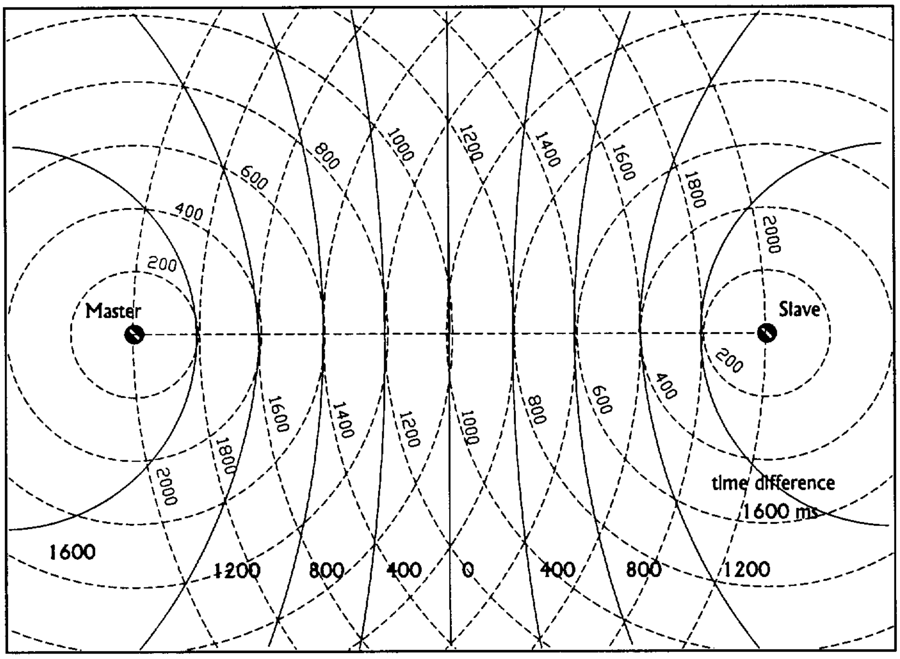


Figure 3.10: Time transmisson diagram for a LORAN master-slave system. [50]

The principle of LORAN navigation is the receiving of two pulses transmitted from 2 different transmission stations. For example, if an aircraft is the same distance away from two transmitting stations (say, 300 km)--where one is called the master and the other the slave--and the pulse frequency is 33.3 Hz, then the transmission time of each station to the receiver is

$$T = \frac{s}{c} = \frac{distance}{velocity} = 1\ ms = 1000\ \mu s. \qquad (15)$$

The difference of the time differences is 0. Analogously, if the position between master and receiver is 150 km and between slave and master 450 km, the time difference is 1000 μs. The geometric figure which has always equivalent differences to two stations or points are hyperbolas (see figure 3.10). Therefore, only a hyperbolic curve for the present position is known. Additionally, by using the pulse repetition rate of the transmitter the correct one of the two possible hyperbolas can be selected. A second measurement of master and slave transmitting stations is needed to determine a crossing point of two hyperbolas--which gives the position of the receiver.

The control of the receiver itself is very complex. First the channel has to be chosen as well as the pulse group S, L or H. On the display of the panel, the master and the slave pulse can be seen at a length of half of the pulse repetition rate. On the lower trace--the slave pulse--a blip can be seen which is a variable delay marker. This blip has to be moved until it is under the slave pulse. Thereafter, another function of the control panel adjusts the receiver gain and amplitude balance until the signals are of the same height and of the correct amplitude. If the two pulses are opened out, a fine adjustment has to be made where the pulses are displayed superimposed. After this fine adjustment, the distance can be evaluated by measuring the delay (or more precisely the hyperbola distance) by reading out of the display panel onto maps of the hyperbolas of the different LORAN transmission stations. With the second pair of LORAN transmission stations, one has to do the same work and the cross point of the two hyperbolas gives the present position of the vehicle.

The main problems with this radio navigation system are the complex operation and the receiving antenna also being used for communication--which influences a continuous navigation. Otherwise, for many years this LORAN system was one of the navigation systems used for crossing the Atlantic that gave relatively precise navigation for the whole day and night.

3.5 OMEGA Navigation

The OMEGA Navigation System evolved from World War II research in low frequency (LF) and very low frequency (VLF) radio wave propagation characteristics. Time and frequency precision standards further implemented progress toward individual station synchronisation. VLF frequency has the characteristic of propagating over and around geographical barriers and over long distances. This frequency is also stable. An advantage of using OMEGA is the low number of transmitting stations required. Only 8 stations are needed to provide a world-wide radio navigation. The OMEGA transmitting stations are located in Norway, Liberia, the United States, La Reunion, Argentina, Australia and Japan. To get such a solid very low frequency that provides world-wide coverage, special very large antenna systems have to be used. For example, one type of these antennas is located in Hawaii in a wide valley, where the monopoles are spanned between the mountains surrounding the valley. A second type is the so-called top-loaded monopole, where the aerial wire is spanned from a wide circle to a high antenna mast.

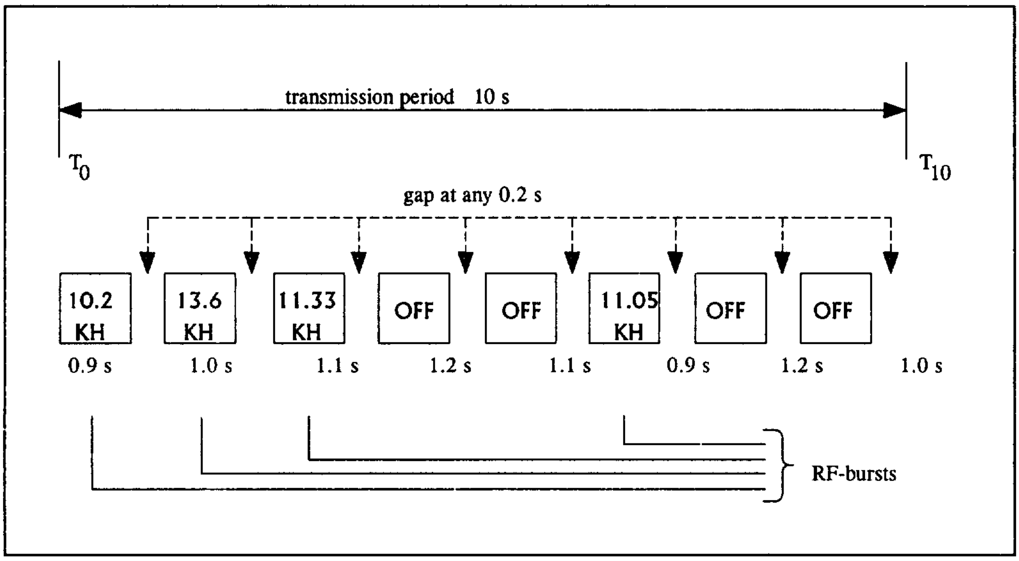


Figure 3.11: Transmission cycle of the OMEGA station A in Norway. [58, 59]

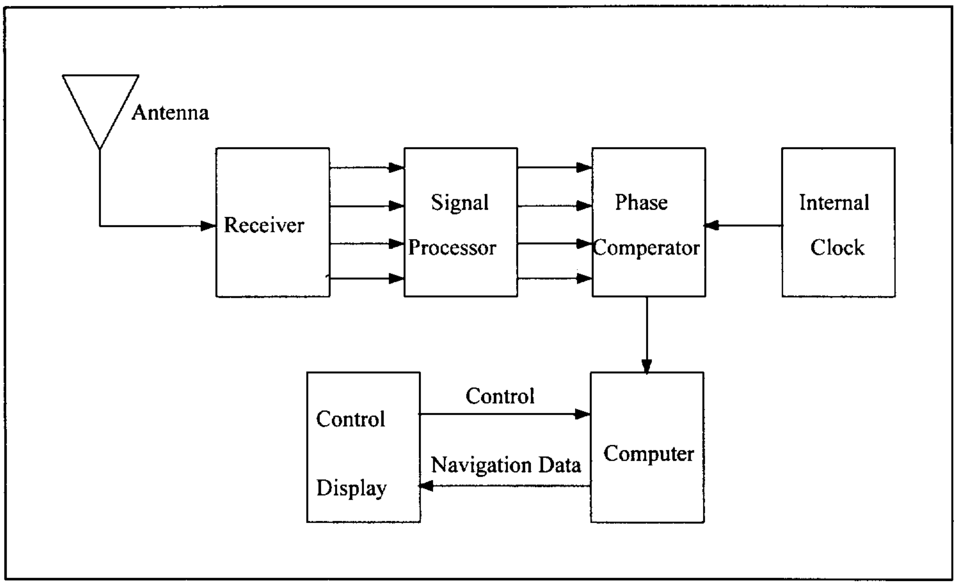


Figure 3.12: Typical airborne OMEGA navigation system. [58, 59]

The transmitters are two LITTON-built systems (one used as backup). They are implemented with atomic clocks. These clocks are used for synchronising because all eight stations must transmit at precise time and for exact intervals. The principal transmission diagram of the OMEGA stations is seen in figure 3.11. During the transmission period of 10 seconds, the eight time slots interrupted by 0.2 second gaps are used to identify the different OMEGA transmission stations. Each station transmits sequential RF bursts and in figure 3.11 the four RF-bursts of the Norway station are lined out. These staged patterns can be used by the receivers to identify the station.

A typical OMEGA airborne receiver, for example the LITTON LTN-211, consists of several parts as shown in figure 3.12. The receiver is a fixed-frequency, multi-channel unit generally capable of receiving either three or four OMEGA stations simultaneously. The signal is filtered, enhanced, and amplified by signal conditioning circuitry. To compare the internal clock with the phase angle of each signal, a phase comparator is added to the system. All calculation work is then done in the computer to display the position and other data on the display. Another task of the computer is to control all signals as well as the system.

The evaluation of the present position for a vehicle equipped with an OMEGA receiver works by regarding the phase angle. Since radio waves propagate at a constant velocity, the phase angle is a function of the receiver position or, more precisely, a function of range to the transmitting station. Using the transmission pattern to extract the frequency bursts, which indicate a unique OMEGA station, provides the geographical co-ordinates of the station. This information produces the present position. The accuracy of such a calculated position can be improved by regarding the propagation anomalies that are basically:

- Diurnal Effect
- Ground Conductivity
- Earth's Magnetic Field
- Latitude Effect and
- Earth Geometry.

The wave transmitted from the OMEGA stations are reflected by the ionosphere and the earth's surface. Because the distance between ionosphere and earth differs between night and day, this difference, named Diurnal Shift, can be taken into account in the computer program if the accurate Greenwich Mean Time (GMT) is known. The earth conductivity, meaning the different influences to the OMEGA signal by water, ice, desert, jungle, etc., can be compensated if a map of these conductions is stored in computer memory. The effects of the magnetic anomaly to the propagated VLF signal can also be corrected if the geographical position is known. The last two errors are connected with the nonspheroidal shape of the earth and the irregularity of ionospheric height due to the difference in pressure at various latitudes. In addition to these main errors, a lot of other effects can be regarded and eliminated. For example, the signal interference of the various wave guide modes and the direction of propagation must be known, signal-to-noise ratio (-20 to +20 DB) maps have to be developed to indicate which stations can be received best, etc. To calibrate the internal clock precisely, more than one OMEGA station signal has to be received. Normally three signals are used, which additionally increases the accuracy of the position information.

After turning on an OMEGA receiver, the GMT and the date must be entered in addition to the present position.

Since the OMEGA signals are received continuously, the ground speed and the track can be calculated. An OMEGA/VLF radio navigation system such as the LTN-3500 calculates the following output data:

GMT, **date**,
Present Position, *Present Track*, Ground Speed,
Waypoints, Distance, Time, Desired Track,
Cross Track Distance, Track Angle Error,
Heading, Drift Angle,
Magnetic Heading, *True Airspeed*,
Wind Speed and Direction,
Received Stations, Frequencies of these stations,
and available stations.

The bold typed signals above are input signals that are required for the system initialisation; while with the waypoint inputs, steering signals for the autopilot can be produced. The italicized input signals are normally sent from the air data computer or, if these signals are invalid, the magnetic heading and true airspeed can be entered using the display unit. For initialisation during flight, the present track must be entered in addition to the bold typed signals. The initialisation requires about six minutes before starting.

Some of the receivers are also capable of utilizing signals broadcast by the United States Navy VLF communications stations.

4. TERMINAL AREA NAVIGATION SYSTEMS

This section describes the terminal area navigation systems which are very important for aviation. The availability and accuracy of these systems guarantee the safety for all aircraft inside the terminal area of each airport which includes a safe takeoff and landing. The ground and taxiway equipments are not discussed here.

The description is divided into two main parts of navigation aids: visual and instrument landing systems.

4.1 Visual Glide Slope Indicator (VGSI)

The Visual Glide Slope Indicators (VGSI) are ground devices that use lights to define a vertical approach path during the final approach to a runway. The visual lights consist of not less than two and not more than four colors. Allowable colors are red, yellow, green, or white. Color sectors must be distinct and identifiable throughout the horizontal beam width at all intensity settings. Only red is used to indicate the lowest below-path sector of the system.

These systems work in an area 10° from either side of the runway centerline and from the touch-down point up to a distance of 4 miles. The main three VGSI are: the Visual Approach Slope Indicator System (VASI), the Precision Approach Path Indicator System (PAPI), and the Pulsating Visual Glide Slope Indicator System (PVGSI).

The VASI consists of either two or three light bars placed perpendicular to the runway. The light bars consist of one, two or three boxes aligned on the left or both sides of the runway. Each box contains three high intensity lamps behind a horizontally divided filter with both red colored and clear portions. In using the system, a pilot flies through the light bar nearest the runway threshold (no.1 bar) until it appears white, and undershoots the light bar beyond the touchdown point until it appears red. The aircraft will be on the visual glide slope when the number 2 light bar appears red and the number 1 light bar appears white. When the aircraft is not on the glidepath, the pilot will see a change on the number 2 light bar to pink if within ¼° and to white if within ½°. This situation is outlined in figure 4.1.

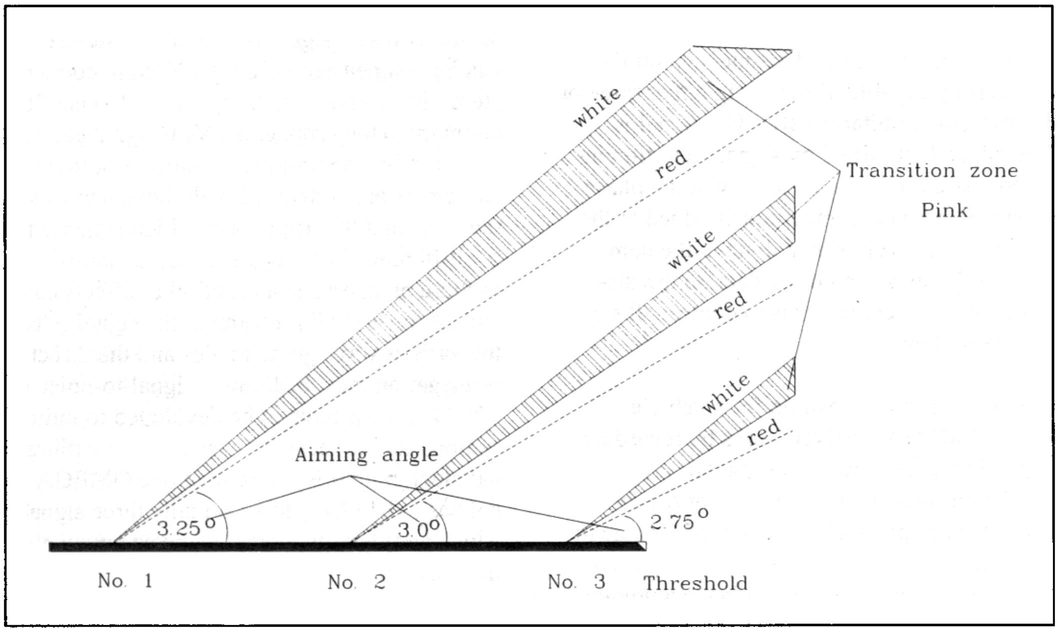


Figure 4.1: The visual glideslope system VASI with 3 boxes and the different light beam colors. [102]

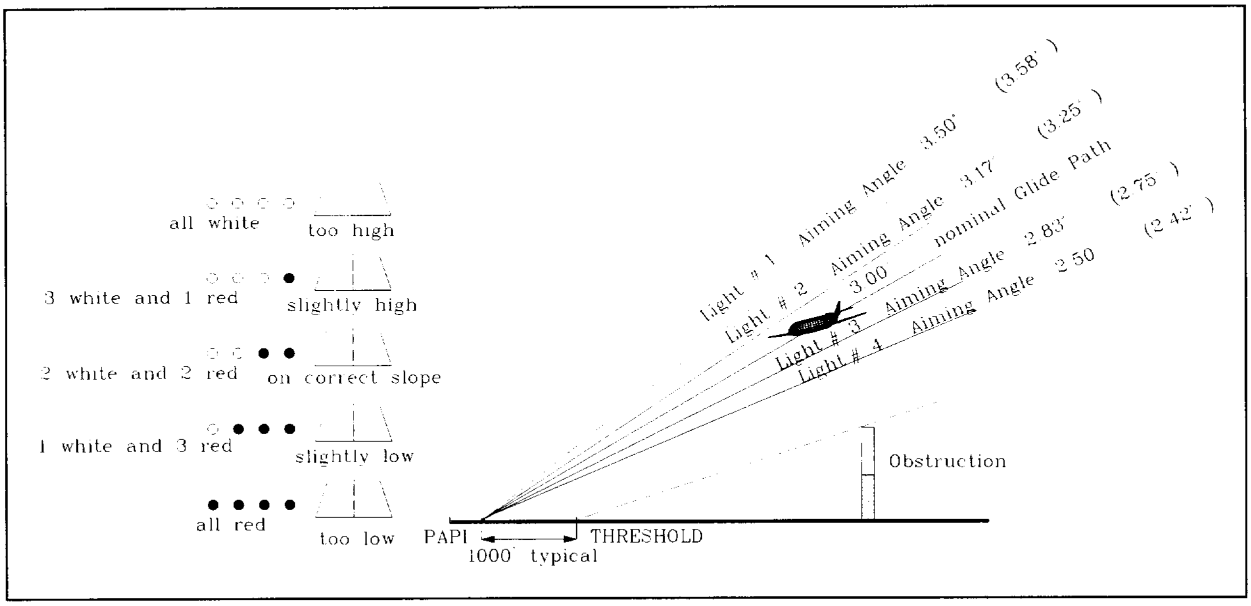


Figure 4.2: PAPI approach path and visual cues. [102]

The PAPI system uses a 2-color light projector system that produces a visual glidepath as shown in figure 4.2. Each light box consists of at least 2 optical projectors that produce a single beam of light. The upper part of the beam is white while the lower is red. The on-path width is the difference between the angles of light boxes 2 and 3 when a four-box system is installed. Normal installation requires 0.33° (sometimes 0.5°) between light box settings 1 and 2, 2 and 3, and 3 and 4. The on-glidepath indication is two red and two white lights on the light bar. The number of red lights increases when the aircraft goes below the glidepath while the number of white lights increases when going above it.

The PVGSI normally consists of a single light unit projecting a two-color visual approach path. The below-glidepath indication may be either a pulsating or a steady red light, while the above glidepath indication is a pulsating white light. The on-glidepath indication is a steady white light or alternating red and white light. The on-path width of the steady white light is approximately 0.35°.

4.2 ILS

The instrument landing system (ILS) is an air-derived information system for the guidance of an aircraft to the runway for landing purposes. This system was standardized by the ICAO in 1953 in order to achieve worldwide uniformity of the requirements and operational characteristics of the system. This standardization comprises carrier and modulation frequencies and their tolerances as well as the installation arrangements of the different system components. Moreover, in 1962 three categories with different levels of precision were defined.

The ILS on the ground is composed of three different parts: the localizer, serving for horizontal guidance and transmitting in the frequency range of 108 - 112 MHz; the glide-path transmitter operating in a frequency band of 328 - 335 MHz for vertical guidance; and two marker transmitters at 75 MHz which mark the distance to the runway at two different points.

For horizontal guidance, an electromagnetic field is generated in space known by "clearance." At the end of the runway, an antenna system radiates patterns with spatially distributed different modulation frequencies. On the right side of the centerline, the approaching aircraft receives a signal amplitude-modulated by 150 Hz, whereas on the left side a 90 Hz signal is received (figure 4.3). In an area of ± 2.5° from the centerline, the transition from the 150 Hz signal to the 90 Hz signal is nearly linear. The difference in depth of modulation (DDM) is a proportional measurement of the aircraft deviation from the centerline. Beyond ± 2.5° up to ± 35°, a nearly constant amplitude of the 150 Hz or 90 Hz modulation only is received. It serves as an unambiguous indication of the direction of deviation.

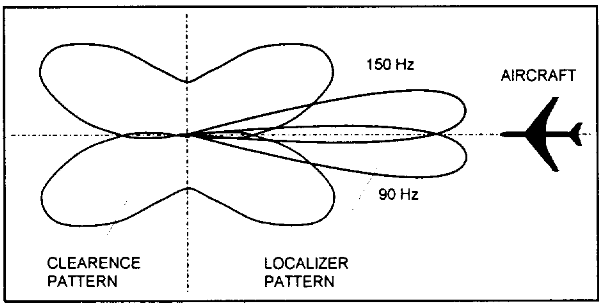


Figure 4.3: Electromagnetic field of the ILS localizer.

Multipath reflections by airport buildings, irregular terrain, and other flying or taxiing aircraft cause interference. That leads to bends and oscillations of the generated clearance course. These problems are widely reduced by the "localizer" patterns shown in figure 4.3 which are generated by an antenna system of high directivity. Here the beam width of radiation is limited to a section ± 10° from the centerline and the illumination of reflecting objects is widely reduced. Clearance and localizer patterns have to be generated simultaneously. In a dual-frequency system where the localizer signal is generated 4 or 9 KHz below the clearance frequency, crosstalk of the clearance signal to the localizer indication is reduced by the capture effect. This effect leads to a suppression of the lower amplitude signal in the common demodulator of the receiver.

Vertical guidance is accomplished by the glide slope system which generates a horizontal glide plane elevated by 2 to 3°. Again a spatially modulated field comparable to the localizer system is generated. This time the electromagnetic carrier field of the 90 Hz and 150 Hz modulation is vertically arranged as outlined in figure 4.4. The linear range of the difference in depth of modulation spans ± 0.5° from the desired elevated glide plane. This arrangement requires a higher directivity of the antenna system compared to the localizer. In order to keep the antenna array height below 10 m, benefit is taken of the ground reflection mode if possible. In this mode, the conducting ground acts as a mirror which virtually doubles the length of the antenna arrangement. Because of its considerable height, the glide slope antenna is assembled about 150 m aside the runway and 300 m from the threshold.

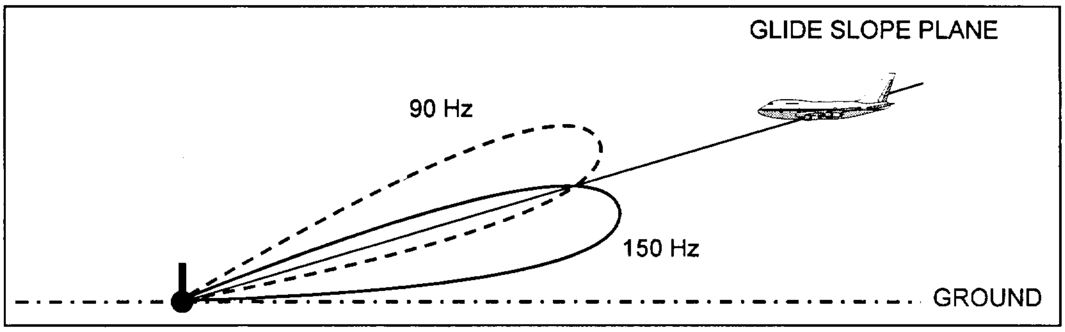


Figure 4.4: Electromagnetic field of the ILS glide-path.

In addition, the ILS comprises two marker transmitters installed in a distance of 7 km (outer marker) and 1.2 km (middle marker) from threshold on the extended centerline. Horizontally oriented dipole antennas radiate perpendicular patterns which are keyed and amplitude modulated by different tones.

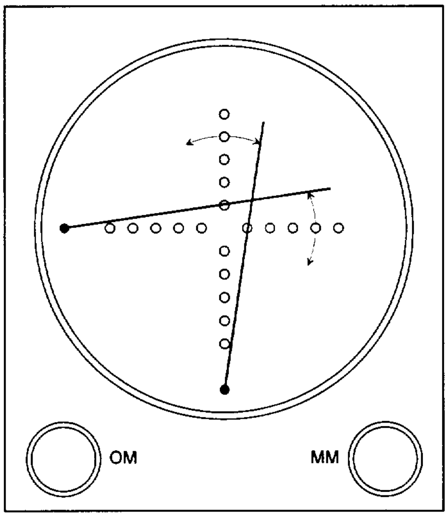


Figure 4.5: ILS pilot's display.

The on-board ILS system receives and demodulates the signals from all three subsystems. A signal processor adapts the signals to the pilot's display. This is schematically shown in figure 4.5.

The horizontal (localizer) sensitivity is 0.5° for 1 dot (range ± 2.5°). The vertical (glide slope) sensitivity is 0.1° for 1 dot (range ± 0.5°). The marker signals are simply displayed by two lights, one for the outer marker and one for the middle marker.

4.3 MLS

The microwave landing system (MLS) was developed in an international competition invited by the ICAO in 1972. The intention was to improve the ILS performance regarding angular coverage and accuracy to render possible selected and even non-linear glide paths. MLS provides position information and various ground and air data for precision approach and landing purposes. Azimuth and elevation angle as well as distance are measured to provide position information in a wide coverage sector.

The MLS on the ground is composed of four parts: the approach azimuth equipment, the approach elevation equipment, a means for the encoding and transmission of essential data words, and distance measuring equipment

(DME). All four parts include monitor, remote control, and indicator equipment. The basic MLS can be expanded by one or more of five additional functions that serve for back azimuth information, flare elevation information, precision distance information (DME/P), encoding and transmission of additional auxiliary data words, and a wider proportional guidance sector. In the aforementioned contest, the proposal of the US for a time reference scanning beam system (TRSB) was selected for world wide implementation. The TRSB MLS angle and data functions operate on any one of 200 channels in the frequency band of 5030 - 5091 MHz. These channels are paired with selected channels in the DME frequency band of 960 - 1215 MHz for the distance measuring equipment (DME/P).

A summary of the characteristic data of the MLS is given here to exhibit the high requirements for an MLS flight test system.

System Coverage for the Approach Sector:

Distance	20 NM (up to 30)
Horizontal	± 40 °
Vertical	0 – 15 ° (up to 30 °)
Altitude	0 – 20 000 feet

System Coverage for the Missed Approach Sector:

Distance	5 NM
Horizontal	± 20 °
Altitude	0 – 5000 feet

System Accuracy (2 σ):

	Bias	Noise
Azimuth	0.054 ° ...0.315 °	0.054 ° ...0.315 °
Elevation	0.07 ° ...0.38 °	0.07 °
Distance	8.6 m ...86 m	8.6 m ...86 m
Azimuth	0.106 °	0.106 °

Sampling Rate	≥ 5 Hz
System Capacity	200 aircraft

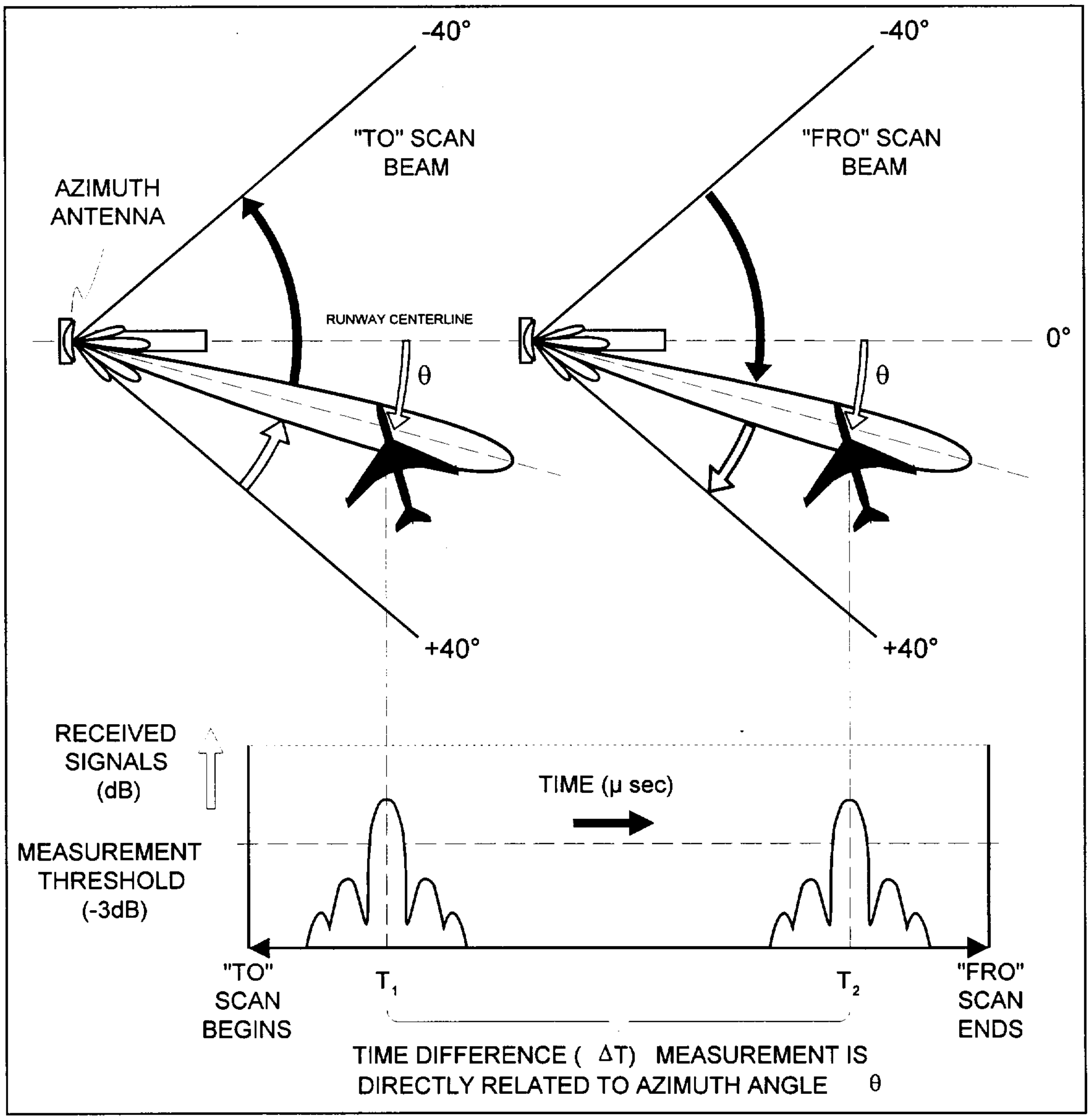


Figure 4.6: MLS time reference scanning beam principle.

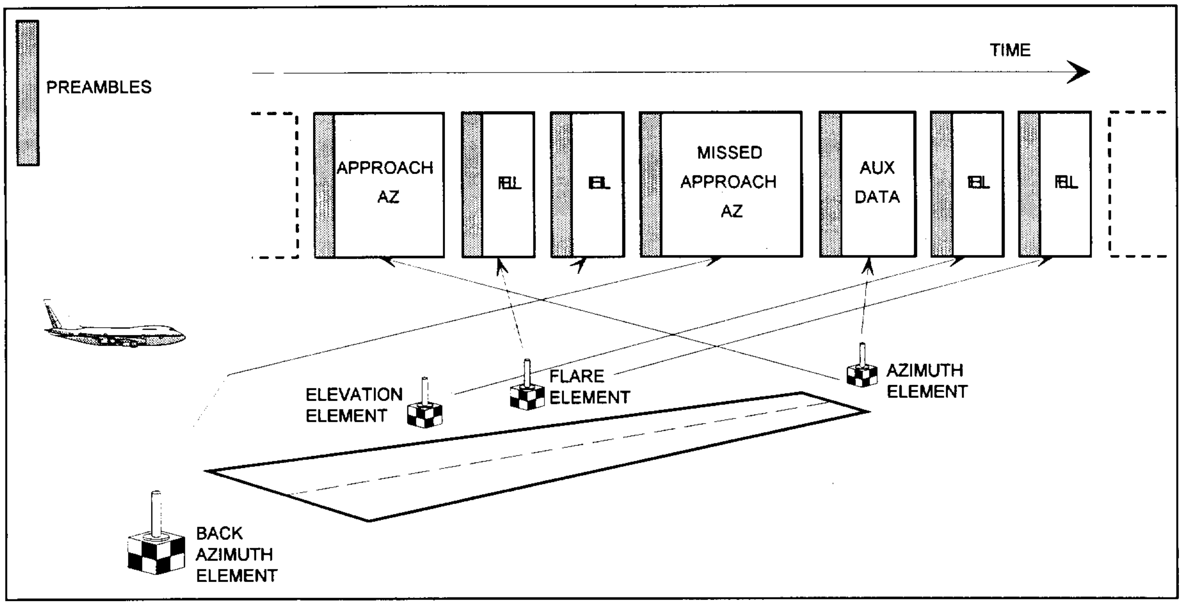


Figure 4.7: MLS time division multiplex sequence.

The time reference scanning beam principle utilized by the MLS is illustrated in figure 4.6. Here the measurement of the azimuth angle is taken as an example. The ground azimuth antenna generates a beam with high directivity in the horizontal plane and low directivity for full coverage of the 15 ° (or up to 30 °) approach sector in the vertical plane. This beam scans a sector of ± 40 ° in the horizontal plane with a linear time relationship. The beam starts at + 40 ° from the runway centerline, moves to – 40 ° with the "to" scan and back to + 40 ° with the "fro" scan, all with the same constant speed.

An Aircraft flying at an azimuth angle of θ with respect to the runway centerline receives two signals during a complete scan cycle. The time difference of these two signals is directly related to the azimuth angle θ. By proper selection of the measurement threshold, the unwanted sidelobes of the signal radiated by the ground antenna can be suppressed (see figure 4.6).

The same principle is also applied to the elevation angle measurement. This example also illustrates the air derived principle of the MLS system. The angle θ is unknown to the ground system and is generated on board the aircraft only. The ground transmissions are not addressed to specific aircraft and can be received by any aircraft within the coverage of the system.

The ground antennas for the different subsystems computing azimuth, elevation, missed approach azimuth, missed approach elevation, flare, and auxiliary data output a time division multiplex sequence as shown in figure 4.7 In order to identify the particular function to follow, a preamble signal is transmitted which consists of a radio frequency carrier acquisition period, a receiver reference time code, and a function identification code. The onboard system decodes the appropriate measurement values in the same time division multiplex sequence. Each function transmitted is repeated at rates shown in Table 4.1

Function	Average rate (Hz)
Approach azimuth guidance normal rate high rate	 13 ± 0.5 39 ± 1.5
Back azimuth guidance	6,5 ± 0.25
Approach elevation guidance	39 ± 1.5
Flare elevation guidance	39 ± 1.5
Basic data	1...6.25
Auxiliary data	≥ 1

Table 4.1: Transmitting rates of MLS functions.

At a given facility, the high rate of the approach azimuth guidance function is used if the proportional guidance sector is not greater than ± 40 ° and flare elevation guidance is not provided.

More details on the specification of the MLS are given in [44].

5. RADIO FREQUENCY PROBLEMS

In this chapter, the main radio frequency problems such as coverage and multipath propagation (which are more or less applicable to all radio navigation systems) are discussed.

5.1 The Coverage of Radio Navigation Systems

Navigation station radio propagation is subject to a number of variable factors such as variations in the refractive index of the atmosphere or the terrain along and near the great-circle path between transmitter and receiver.

These factors influence the coverage of the navigation system under consideration and therefore have to be investigated during the system planning. This can be done by computer simulation and additional flight tests for verification. After installation, periodic flight inspection tests have to be performed to detect considerable changes in coverage due to equipment degradation or alteration in the transmission path. In the first approach, the mentioned variable factors can be introduced statistically.

The necessary information on the long-term median basic transmission loss of a radio frequency link can be derived from a transmission loss atlas for aeronautical service bands. [30] Curves are presented to estimate transmission characteristics of electromagnetic radiation at frequencies ranging from 0.125 to 15.5 GHz for antenna elevations as low as 25 ft and as high as 22 300 statute miles above the earth's surface.

A special propagation model for ground/air telecommunication links was developed at the Institute for Telecommunication Sciences (ITS, U. S. Department of Commerce, Office of Telecommunications, Boulder, Colorado) for the Federal Aviation Administration (FAA). Both the model and the computer program evaluating the propagation model are published in [31].

The propagation model is applicable to ground/air telecommunication links operating at radio frequencies from 0.1 to 20 GHz at aircraft altitudes less than 300 000 ft. Ground station antenna heights must be greater than 1.5 ft, less than 9000 ft, and at an altitude below the aircraft.

For the ground station, the following parameters are included:

a) facility site elevation above mean sea level (msl),
b) antenna height above site surface,
c) antenna pattern,
d) polarisation,
e) frequency,
f) equivalent isotropically radiated power (EIRP) and, if present,
g) antenna counterpoise parameters.

For the propagation path, the model includes allowance for:

a) effective reflection surface elevation above msl,
b) ground reflection coefficient,
c) surface reflection multipath,
d) refractivity index of the atmosphere,
e) tropospheric multipath,
f) atmospheric absorption,
g) horizon geometry,
h) horizon effects and behind the horizon,
i) diffraction and forward scatter.

The propagation model is evaluated by three computer programs:

1. Power density program,
2. station separation program, and
3. service volume program.

These programs generate the following outputs:

1. Power density available at a particular altitude versus distance from a ground-based transmitting facility;
2. the desired-to-undesired signal ratio, D/U, available at an isotropic receiving antenna versus the distance separating desired and undesired facilities;
3. constant D/U contours in the altitude versus distance space between the desired and undesired facilities.

Once the station is installed, test flights are conducted to measure the field intensity of the radio service under consideration within the desired operational service volume. If the minimum signal strength required for the standard navigation receivers as given in Table 5.1 are not achieved, the service volume is restricted or measures for enhancement are taken.

navigation aid	VOR	ILS		DME / TACAN	MARKER
		LOC	GS		
signal strength in µV in service volume	5	5	15	22	1700
antenna gain in dB	– 13.5	- 6.7	- 6.6	– 5.7	+ 8.6

Table 5.1: Minimum required signal strength for air navigation facilities. [102]

The signal strength given in Table 5.1 is measured at the terminals of a receiving antenna. To relate these values to the minimum secured field intensity values of the radio service (as given, for example, in [93]), the gain of the antenna must be known. The required antenna gain to generate the signal strength given in Table 5.1 is also specified in the same table. If the real antenna gain is higher or lower than the listed values, the corresponding signal strength should also be in accordance with it. This means that the antenna gain of a flying test aircraft has to be known in its spatial distribution. In other words, the complete calibrated antenna pattern of the combination antenna-aircraft is important. The main aspects and procedures for the calibration of aircraft antenna radiation patterns are given in [93] and [9] .

5.2 The Multipath Propagation Problem Area

All radio navigation systems make use of electromagnetic waves as the medium for position determination and, in most cases, also for information transmission. The propagation path of electromagnetic waves usually suffers from reflection, refraction, diffraction, and scattering. These unwanted disturbances many times lead to multipath propagation between the transmitter and receiver. As a result, two or more waves with different amplitudes and delays superimpose at the receiving antenna. The receiver that processes the antenna voltage sends a reasonably distorted signal to the analysis equipment. Here the navigation information is generated. Depending on the multipath conditions, this information can be falsified or even canceled under severe circumstances.

Strong multipath conditions have to be expected mainly near airports. There large buildings, hangars, the tower, radar antenna systems, and large aircraft on the runways and taxiways generate multipath waves. In mountainous sites, even the wider airport environment contributes to these disturbances.

For the optimisation of the antenna siting and also during the investigation of new radio navigation systems, it is very helpful to utilize procedures to detect interference caused by multipath and to identify the reflectors causing the multipath. That is why in the following sections several methods for the determination and investigation of multipath disturbances are outlined. These are the computer simulation, the Doppler measurement method, and the pulse measurement method.

5.2.1 Computer Simulation of Multipath

Computer programs to simulate the multipath disturbances of a radio navigation system in the approach and landing area of an airport were developed by the ELAB (Norway) and the Massachusetts Institute of Technology (MIT, USA) as reported in [27] and [28] . These programs include the airport area simulation program and a model of the navigation system under test.

The airport area simulation part of the program must include all reflecting and shadowing objects of significance within the direct and multiple propagation paths between the aircraft and the involved ground antenna. For realistic and reliable results, smaller details like fences and windows are significant. Obviously these details many times lead to a very extensive program. Moreover, all basic parameters that affect the propagation must be taken into account. These are, for example, the patterns and positions of the transmitting and receiving antennas and the physical terrain parameters.

The navigation system model comprises a detailed mathematical description of the functioning of the system under test. It is the central module of the simulation and generates the output data for comparison with the actual flight path parameters employed in the area simulation.

Several applications of these programs to new systems, such as MLS, have shown that even with great computational effort no results comparable to real measurements were achieved. Actually, the advantage of the computer simulation of multipath is the perfect reproducibility of a procedure like an approach and landing. Moreover, the general influences of parameter alterations like the construction of new buildings can easily be detected. [38]

5.2.2 Multipath Recording by Doppler Measurements

The well-known Doppler effect implies that an increase in frequency occurs if the oscillator of a wave moves towards the receiver. A decrease in frequency is observed if the oscillator moves off from the receiver. In the general case, the receiver or reflector is located off the line of the actual speed vector of the moving oscillator by an angle β. Then the observed Doppler shift f_d in frequency is given by

$$f_d = \frac{f_T \cdot v \cdot \cos\beta}{c_0} \tag{16}$$

where f_T is the oscillator frequency, v is the motion speed of the oscillator, and c_o is the velocity of light if electromagnetic waves are considered. This relation exhibits that a few hundred Hz of Doppler shift only can be expected at a ground station if a medium speed test aircraft transmits an oscillator signal in the order of 1000 MHz.

As an example, figure 5.1 illustrates the Doppler frequency shift pattern of a moving test aircraft **F** (speed 120m/s, oscillator frequency 1000 MHz). Two obstacles **R** with reflecting surfaces are presumed and the corresponding lines in the frequency spectrum received at the ground station **B** are outlined. Here the direct signal is received at a frequency of f_T + 250Hz and the reflected (multipath) signals at f_T - 100Hz and all around f_T + 300Hz.

It is important to notice that this method supplies the multipath-to-direct signal amplitude ratio (M/D) and the angle β mentioned above only. Moreover, the angle determination is ambiguous.

5.2.3 Multipath Recording by Pulse Measurements

The principle of pulse measurements for the evaluation of multipath propagation is illustrated in figure 5.2. A test aircraft at the position F transmits a very short pulse S_F which amplitude modulates a carrier frequency. The carrier frequency is allocated in the frequency band of the radio navigation system under test. This pulse arrives at the ground station B together with reflected pulses from obstacles like R. At the output of the receiver, the signal S_B with the shortest delay time is observed as the direct signal. All reflected signals have an additional delay of Δt.

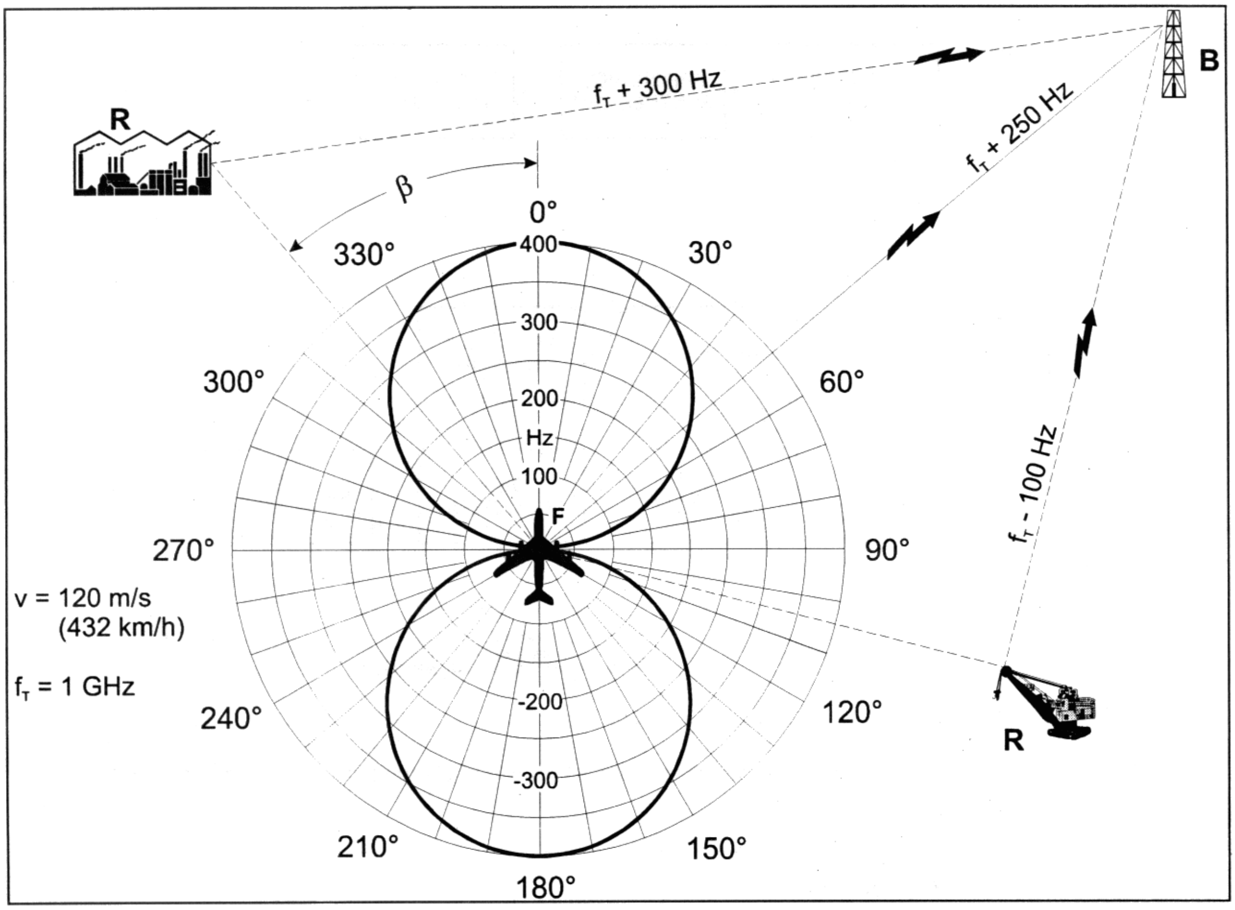


Figure 5.1: Doppler frequency shift pattern of a moving aircraft.

The multipath to direct signal ratio M/D can easily be determined by amplitude comparison of the detected pulses in the signal shape of the receiver output. The time delay Δt indicates the locus of the corresponding reflector R. This locus is an ellipse with the focal points F and B as long as a planar system is presumed. In a spatial system, an ellipsoid has to be considered and the evaluation becomes much more complex.

The shortest measurable time delay Δt equals about the 6 db (50%) width of the transmitted pulse. If the spatial resolution is denoted by Δs, then

$$\Delta t = \frac{\Delta s}{c_0} \qquad (17)$$

A resolution of 30 m hence requires a pulse width of 100 ns only.

5.2.4 Multipath Measurement Systems and Results

The principle of multipath recording by Doppler measurements was mentioned already in section 5.2.2. In the early 1980s, a typical system was developed with close cooperation between the Technical University of Braunschweig and the DLR in Germany. It is illustrated in figure 5.3.

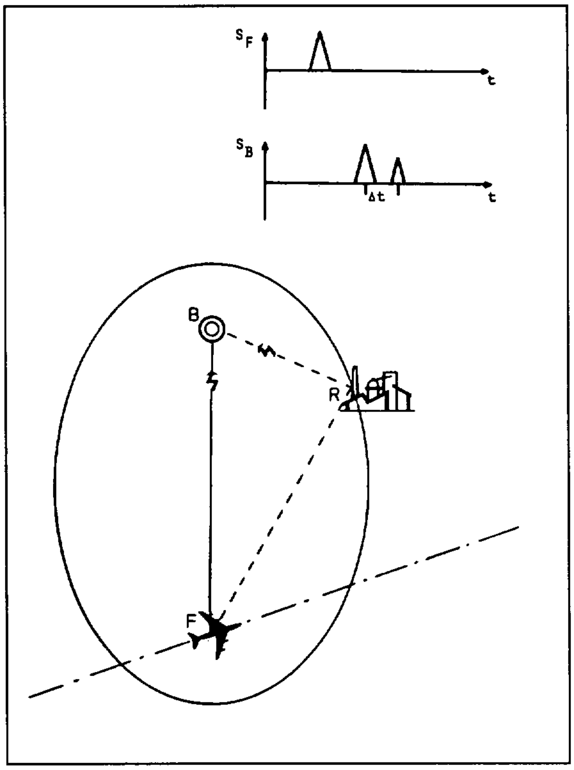


Figure 5.2: Principle of pulse measurements for multipath evaluation.

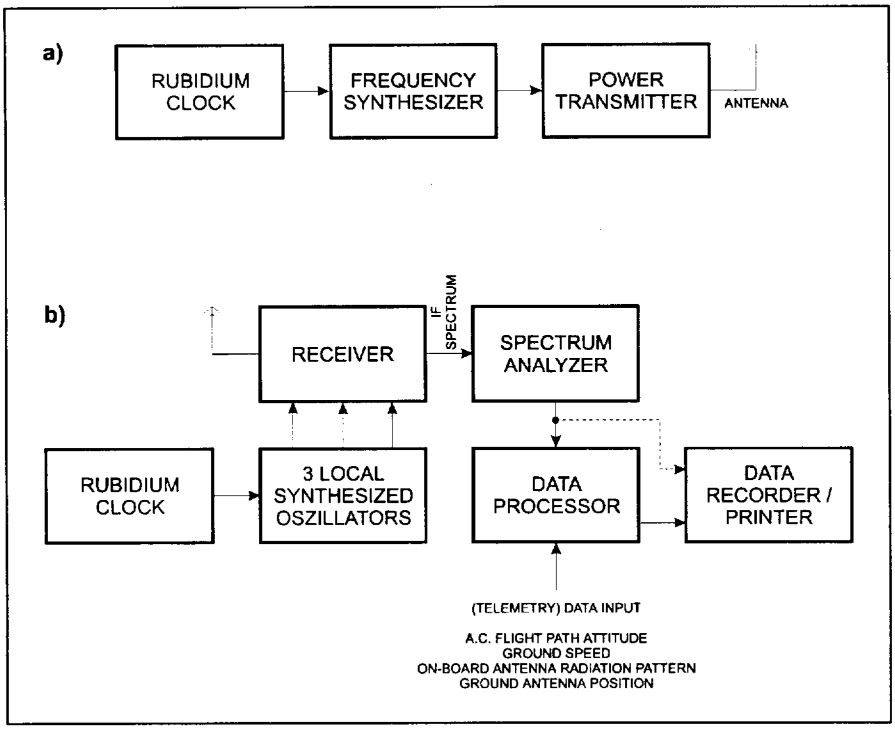


Figure 5.3: Multipath doppler measurement system, a) on-board components, b) ground components.

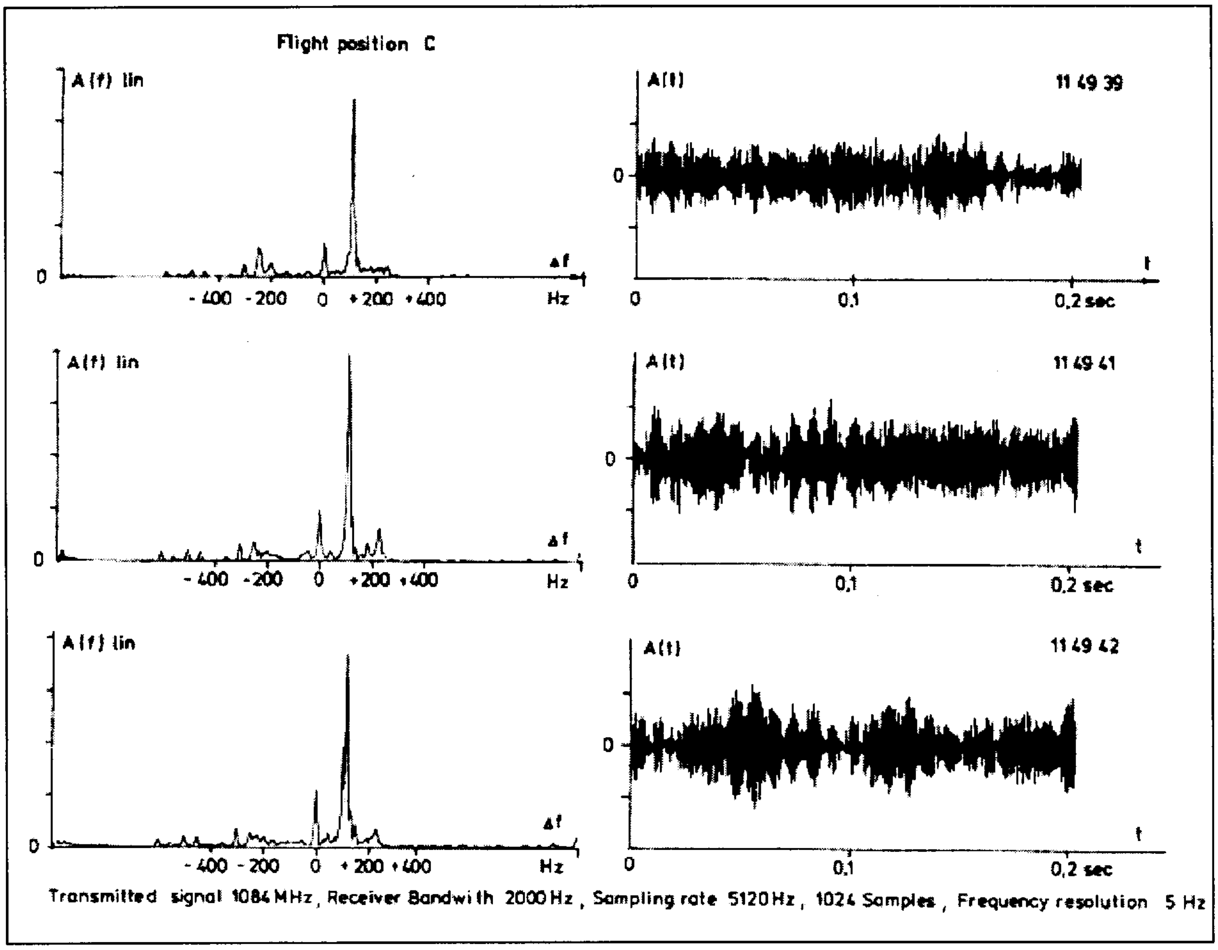


Figure 5.4: Salzburg Airport RWY 34 circling approach, received signal versus Doppler shift Δf and time t.

The on-board part comprises a rubidium clock to generate a highly stable clock frequency as an input to the frequency synthesizer. This device supplies the unmodulated carrier frequency in the desired navigation frequency band to a power transmitter that feeds the on-board antenna.

A ground antenna receives the transmitted direct and reflected radio waves. This antenna is usually placed near the same position where the antenna of the navigation system in question is located. The ground receiver heterodynes the received frequency mixture in three stages down to a very low intermediate frequency spectrum in the audio frequency range. To meet the high demands of frequency stability, the three required local oscillators are controlled by a rubidium clock. A spectrum analyser stage separates the individual spectral lines and generates analogue and digital output signals for recording and/or further data processing. For further evaluation, additional data inputs supplied by a telemetry link are necessary (see figure 5.3). With that, the angle of β as given in figure 5.1 and the M/D ratios of the reflected waves arriving at the receiving antenna are computed.

Usually, the radiation pattern of the on-board antenna is not circular. Hence the radiated power of this antenna into different directions can vary up to 10 dB and sometimes even more. Therefore, the individual M/D ratios have to be corrected for radiation pattern variations.

As an example, some Doppler measurement results taken at Salzburg Airport in Austria are illustrated in figure 5.4. This airport is situated one mile west of the city in a difficult mountainous site. Its runway at 1410 feet MSL is surrounded by mountains in the west (2500 feet MSL), south (6000 feet MSL) and east (3000 feet MSL) in a 2 to 5 NM distance. That is why the initial approach always starts from the north at 160°. Final approach to RWY 16 is guided by an ILS with limited coverage and no back course information. For approach to RWY 34, the aircraft first follows the 160° ILS guidance and then switches to a 130° visual circling approach. In a steady descent, this circling path of not more than 0.8 NM radius carries the aircraft to touchdown at RWY 34 threshold.

The measurements presented here were taken in intervals of one to two seconds during a test flight while the aircraft completed the last quarter of the circling turn to RWY 34. A frequency of 1084 MHz was chosen for the transmission of the test signal. For the reception of the direct and multipath signals, an omnidirectional antenna was positioned 1000 ft south of RWY 34. The plots comprise the complete receiver IF spectrum versus time and the corresponding signal amplitudes A versus frequency as supplied by the spectrum analyser. In the spectral representation of figure 5.4, the highest amplitude each time represents the direct path signal--here at about 100 Hz Doppler shift. There are smaller amplitudes in front of the aircraft up to +240 Hz and behind

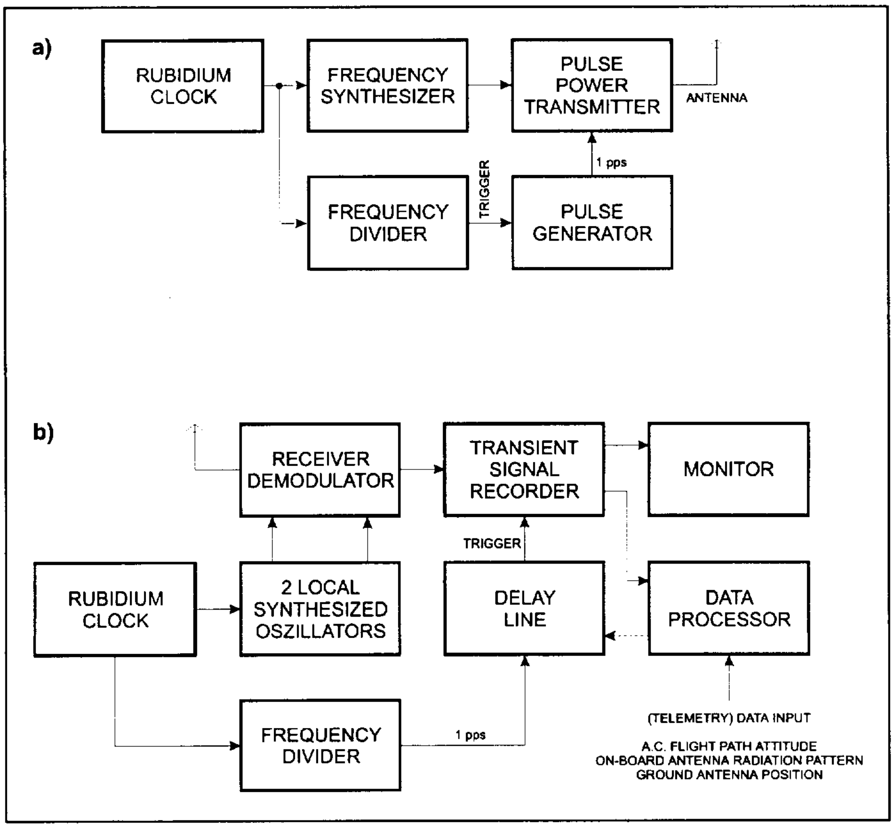


Figure 5.5: Multipath pulse measurement system, a) on-board components, b) ground components.

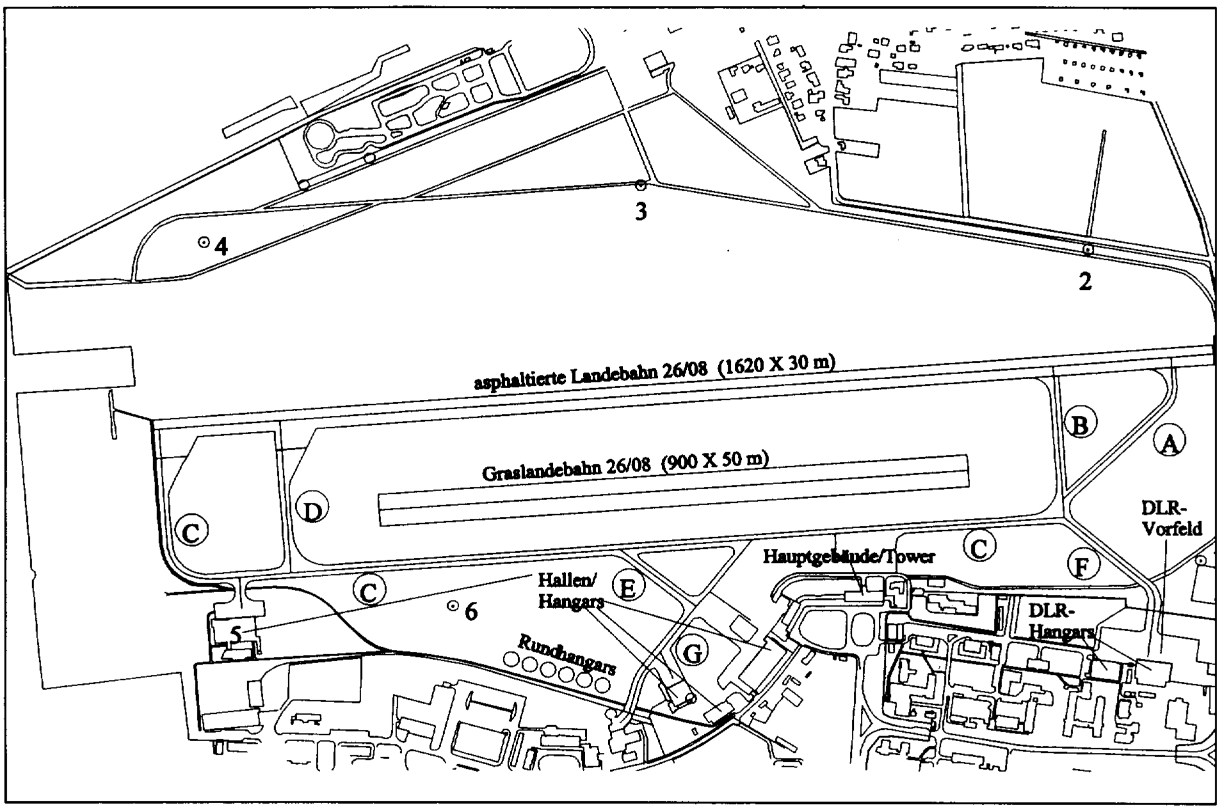


Figure 5.6: Braunschweig Airport and its vicinity.

the aircraft up to -240 Hz. A marked reflection is observed at 0 Hz which is 90° off the nose of the aircraft. Generally these field tests have shown that, linear scale presumed, M/D ratios of 0.1 to 0.3 are typical in the terminal area of Salzburg Airport.

The multipath recording by pulse measurements was previously outlined in section 5.2.3. The Doppler measurements discussed before are incomplete concerning locating the position of the reflector. To supplement these measurements, a pulse system was developed at the DLR. This is illustrated in figure 5.5.

The on-board components comprise again a rubidium clock, a frequency synthesizer, and a power transmitter exciting the antenna. The modulation signal is generated by a pulse generator. To achieve a high time stability, this device is triggered by 1 Hz pulses derived from the rubidium clock. The output signal of the transmitter consists of nearly Gaussian-shaped 100 ns pulses with a peak power of 1 kilowatt and a repetition rate of 1 Hz. The carrier frequency is determined by the synthesizer and depends on the radio frequency band the system under test makes use of.

A ground antenna is positioned close to the navigation system under test. This antenna receives direct pulses from the on-board antenna and reflected pulses from different obstacles. The receiver demodulates the composite pulse signal--a pulse train--for further processing in a transient signal recorder. Here the received pulse train is sampled every second at a rate of 100 MHz, digitized with 8-bit resolution, and stored in 2048 words until the next pulse train arrives. Meanwhile this data set is transferred to the quick-look monitor and data processor for further evaluation such as M/D determination and correction for the on-board antenna pattern. In order to capture the complete pulse train, just before the pulse train arrives the gate of the transient recorder is opened by a trigger pulse that is derived from the rubidium clock and controlled by a delay line. The necessary time delay depends on the travel time of the transmitted pulse and therefore on the spatial distance of the on-board and ground antennas. The optimal delay time is computed and set by the data processor.

The operational range of this arrangement is >25 km with an M/D ratio down to -15 dB presumed. The resolution of different time delays between signals is 100 ns. This equals a distance of 30 m between reflecting surfaces. The total dynamic range is 100 dB if automatic gain control is applied to the receiver.

Braunschweig Airport is a facility with several companies and organizations as residents dealing with flight research and development. That is why this airport many times serves as a testbed for new radio navigation systems and procedures like MLS, PDME, and GPS for terminal area navigation, landing, taxi, and ramp management. It is very important to know the multipath situation at this airport as a criterion for the system under test. Extensive multipath measurements by means of the pulse system outlined above were made in conjunction with the navigation test flights. Figure 5.6 illustrates Braunschweig Airport with its operational installations like runways and taxiways. Moreover, some significant points are marked by numbers and letters. The total airfield is surrounded by a metallic fence. In some sections this security arrangement is duplicated by a military Y-shaped barbed wire fence. Other large reflecting objects are hangars below F, G, and number 5, as well as the tower building.

As an example, a measured reflection pulse pattern is shown in figure 5.7. This pattern was recorded during a landing procedure of the test aircraft on grass runway 08 - 580 meters west of the ground station position at point A in figure 5.6. First the pattern illustrates the noise floor of the receiver at about 17 dB, the signal levels of the first (direct) pulse at 63 dB and 5 reflected pulses with amplitudes between 55 and 48 dB. Thus the M/D ratios are observed to be in the area of -8 to -15 dB at this point. The additional time delays of these pulses are 243 to 1293 ns, corresponding with 73 to 388 m additional travel distance. Moreover, the 3 dB pulse width of the measurement system is observed to be 77 ns. That shows a resolution of 23 m. The broader pulses come from two reflection signals that are close together and cannot be separated by the system.

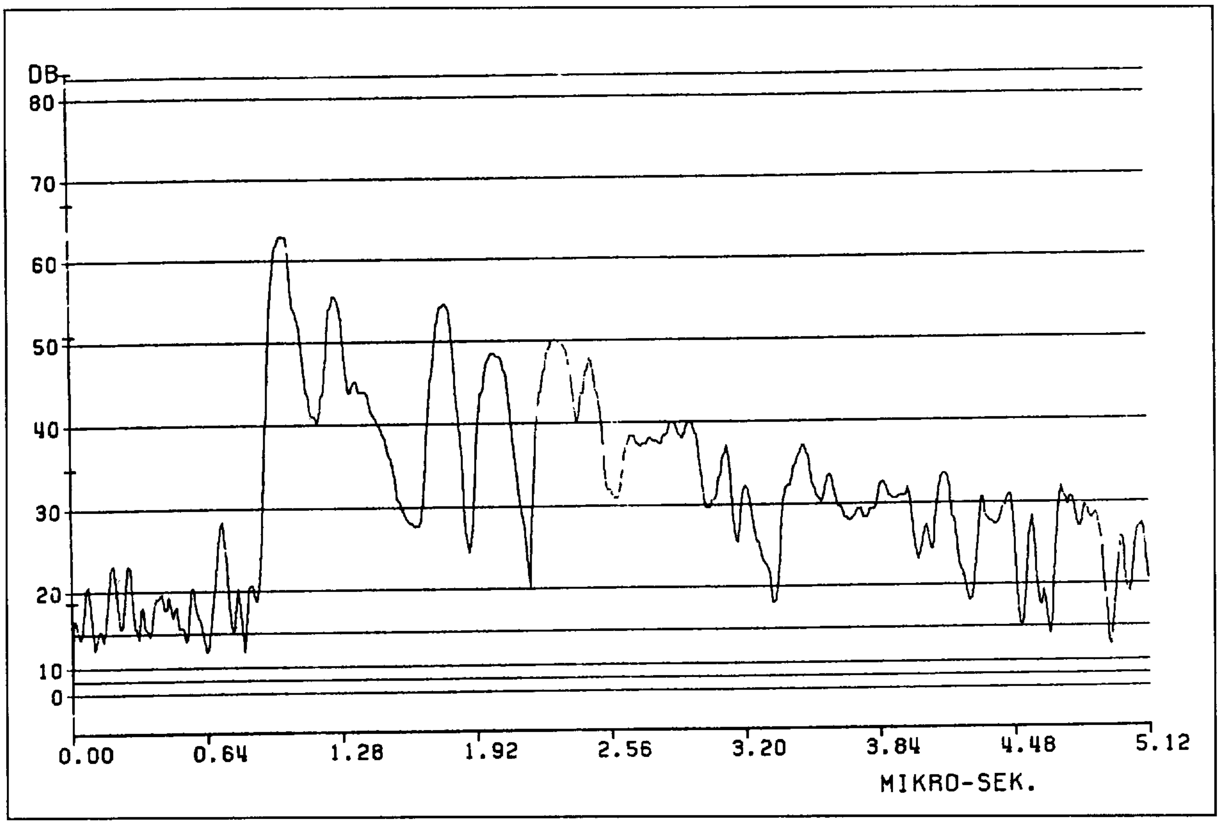


Figure 5.7: Measured reflection pulse pattern at Braunschweig Airport.

Recently the aforementioned DLR pulse measurement system has been considerably improved as reported in [38] . First, in the on-board system (figure 5.5) the single pulse was replaced by an optimized group of 15 pulses as illustrated in figure 5.8. Instead of simple amplitude modulation, the transmitter now takes advantage of a binary phase shift keying (BPSK) modulator. In the ground system, the signal after demodulation first passes through a correlator. Here the pattern generated on-board and distorted by the radio link is compared with the undistorted pattern stored in the ground. Thus each pulse group (direct and reflected) generates a correlation peak with the width of a single pulse in the pattern of figure 5.8. The advantage of this correlation method is that much less radiated power is required to achieve an acceptable signal-to-noise ratio in the resulting data output. Instead of 1 kW peak power for the single pulse, less than 10 W peak power for the pulse group is required.

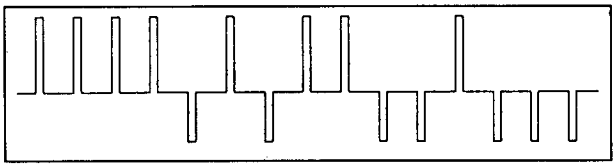
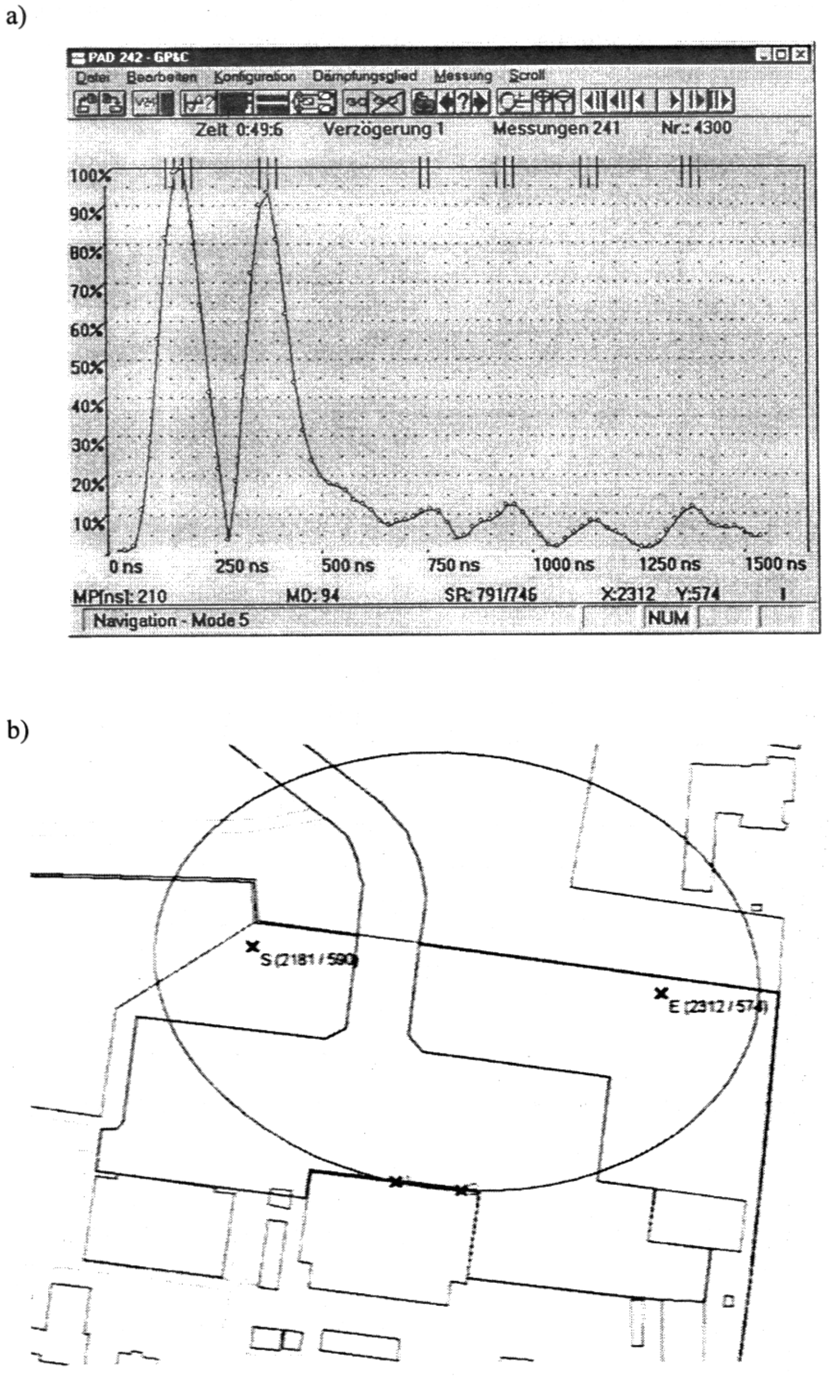


Figure 5.8: Pulse group pattern for BPSK modulation.

In addition, the data processing software was improved and the computing speed was increased considerably. This has enabled realtime plots during taxi and flight tests as illustrated, for example, in figure 5.9. Here the situation in front of the DLR hangar H is described. The correlation pulses shown in part a of the figure are derived from the direct signal pattern (first pulse) and reflected pattern (second pulse). The ellipse in the figure part b, with focal points S (transmitter) and E (receiver), represents the possible loci of the reflector.



Zeit 0:49:6 Verzögerung 1 Messungen 241 Nr.: 4300

MP[ns]: 210 MD: 94 SR: 791/746 X:2312 Y:574

Navigation - Mode 5

Figure 5.9: Multipath record in front of DLR hangar H, a) correlation pulses, b) ellipse as locus of reflector.

6. FLIGHT INSPECTION INSTRUMENTATION SYSTEMS

The chapter shall describe the different test panels and instruments to be used for the flight inspection. Naturally the instrumentation depends on the application and the flight test procedures to be done with the test equipment. Besides the instrumentation, layout and size must be adapted to the type of aircraft. Another aspect to be considered is the influence of signals, antennas, etc. to the basic instrumentation of the aircraft itself. Therefore, all flight inspection equipment has to be strictly separated from the basic aircraft instrumentation and the influences are checked by Electro-Magnetic Interference (EMI) tests. Those radio receivers used by general aviation and the military should be utilized and tested as well.

Most of the **F**light **I**nspection **I**nstrumentation **S**ystems (FIIS) are special equipment for the application of the flight inspection procedure. An important issue regarding this inspection is the accuracy of the reference data that are used to control the radio navigation system. That means the flight inspection data must be calculated with a higher degree of accuracy than the tested systems. For example, if a DME station is tested, the DME receiver itself calculates the data with an accuracy of about 180 m. The position of the aircraft respective to the DME ground station (evaluated by the flight inspection equipment) must have a measured accuracy of less than 180 m. Additionally, the reference data of the flight inspection must be evaluated by other navigation systems to determine the errors influencing the DME receiver. All these things have to be noted when choosing flight inspection instrumentation.

The older flight inspection systems used radar information or theodolite measurements. These two systems evaluate highly accurate flight path reference data, but the work load of these systems is very high. Not only do the transport and installation consume a lot of time, but in addition the results must be manually calculated which costs a lot of time and money. Therefore, the time interval between flight inspection and test result using such hardware was very large and a lot of facilities could not be inspected because of their geographical position.

The next step in the evolution of flight inspection was the use of automatic data calculation onboard the aircraft. This would prove to be of great benefit. The theodolite operators could be eliminated, and through the in-flight calculations all facilities could be inspected in nearly all weather conditions. Most of the flight inspection teams used inertial navigation systems (INS) for onboard autonomous navigation for the new generation of instrumentation; but of course the errors of these systems are time variant and one has to use additional supporting information. In most countries, the flight inspection equipment includes the following instrumentation:

- *Navigation computer or Interface (NCI):* This is the heart of the flight inspection instrumentation and consists of all interfaces to the receivers and other systems required for the navigation evaluation of the inspection system. At this point all data are joined together and the evaluation of the navigation is done. All other programs for the inspection, such as calculating differences, frequency shifts, calibrations, etc., are computed by this main system.
- *Control and Display Unit (CDU):* By these systems all--or the most significant--data can be displayed. This is the man-machine-interface between the operators onboard the inspection aircraft and the hardware. Some displays are minimal, such as single LED, row of LED's, or lightning rows; while others, such as monitors, can show either numbers or graphics. These are optical displays that are normally only for control and observation purposes, not for the documentation after the flight inspection. For this documentation of the flight inspection, one or more printers or plotters are onboard the aircraft. The installation of these systems is difficult because most of the printers and plotters are not flight tested and cannot pass the certification for flight instruments. Additionally, one must be aware that reconfiguration or construction may affect the aircraft certification. All the control, display, and printing systems are located in one or more inspection crew consoles--plus a portion for the pilots in the cockpit.
- *Storage Unit (SU):* All data handled by the NCI must be stored on tape for off-line evaluation. For such an airborne tape recorder, a frame has to be designed which includes all reference data for the flight inspection with the highest practicable recording rate. Additionally, the data of the facilities having to be inspected must be stored. The number and kind of these data could be very different because on an airport various radio navigation systems can be located. For off-line evaluation, fixed frame tape records are desirable to minimize the changes in the analysis programs. In addition, a telemetry system can transmit all data to an evaluation station on the ground; where realtime computation evaluates the reference, differences, etc. and displays all signals simultaneously.
- *Inertial Reference Unit (IRU):* Since 1970 inertial reference systems have been available for general aviation. Nowadays these systems produce such highly accurate reference data for position, velocity, acceleration, angle, etc. that these systems must be part of an inspection instrumentation system. As described in section 2.2.2, the accuracy of the systems can and must be upgraded by using radio navigation fixes. For flight inspection purposes, DME signals (for example) which were not inspected yet are used as supporting data. Otherwise the data of an inertial navigation or reference system is needed for the flight guidance. The inspection flight path especially can be stored and initialized using waypoints. With the position data of the inertial navigation, these paths can be flown and reproduced with high accuracy as often as necessary. Naturally these data are important for analysing the inspected radio navigation systems.

- *Additional Systems (AS):* For the inspection of several systems, other data from the aircraft are needed--for example the airspeed, the height, etc. Therefore an air-data computer, flux-valves or magnetometers, radio navigation systems, antennas, special switches (air-ground switch, landing light switch etc.), and other aircraft equipment have to be installed in addition to the flight inspected systems.

6.1 The FIIS of the FAA

The FAA in the United States had an FIIS as described above. In their test aircraft, which is very large and heavy, an NCI and a CDU (with Cathode Ray Tubes and various displays and analogue recorders), as well as SU, IRS, and AS are installed in the rear of the aircraft. This Automatic Flight Inspection System (AFIS) was reconfigured in 1993 and is now installed in the Beechcraft Super King Air 300 (the Sabreliner), and the BAe 125-800 aircraft. This system is now fully digitized and consists of the latest technology available for aircraft systems and sensors. All functions can be controlled and performed with a keyboard and that has reduced the technical interface requirements.

The NCI has the same function as in the older system, but the capability has increased because the computer's memory has now one megabyte of RAM and allows an additional one megabyte for future expansion. This system is able to generate circular and straight-line flight maneuvers for the flight inspection or can generate flight plans flown by the rest of the aviation community. With the more powerful computer, the sampling rates and the data resolution are increasing while the calculation time is decreasing. For example, the acquisition of information increased from two times a second to eight times a second in the upgraded AFIS and the accuracies are within 0.2 % of the tolerances specified by the United States Standard Flight inspection manual. The keyboard of the computer is a standard keyboard with additional keys for selecting the flight inspection modes, functions, and commands. The program for the computer is loaded through a QUANTEX tape cartridge model 2765 that is portable and not installed in the aircraft. It is used monthly to load current facility data into the AFIS system.

The heavy and large CDU in the older AFIS was replaced by only one display for the pilot. With this display the pilot is able to monitor the collected data and to use the system for flight planning and flight guidance. The IRU is a special laser gyro strapdown inertial navigation system build by Honeywell (the 'Honeywell Special Mission LASEREF Inertial Reference Unit') and has a position accuracy of less than 0.8 NM/h without using supporting data.

The SU of the old AFIS was an analogue recorder that has been replaced by a printer plotter in the new system. The GR33 RMS Printer Plotter is a totally digital system and can be programmed to synchronously print up to speeds of 1200 lines per minute.

With the loaded programs and data, the AFIS is a totally automatic system which can be handled very easily. Five different basic modes or programs are normally used with the AFIS:

1. *Self Test Mode*: For all computers and systems, self test programs are standard to test all I/O-facilities. For this complex AFIS, all interfaced systems (including the aircraft systems used for the flight inspection operation) have self test programs. Of course, it also includes a test for the computer's hard- and software and evaluates the performance of the whole inspection system.
2. *VORTAC Mode*: This mode evaluates the electrical beam characteristics of the VOR and TACAN systems. Two subprograms can be run for this flight inspection:
   Radial inbound and outbound paths:
   a) Mean alignment error of the radial.
   b) Worst minimum/maximum total error and range.
   c) Minimum/maximum bend and roughness conditions.
   d) Scalloping errors and range.
   e) Modulation levels.
   f) Signal strengths.
   g) Usable range of facility.
   h) Establishing cross over points.
   Orbital paths (clockwise and counter clockwise):
   i) Mean alignment error (over selected sector or sectors).
   j) Worst minimum/maximum error and bearing.
   k) Minimum/maximum roughness, scalloping error, bearing, and modulation levels.

In addition, the signal strength Automatic Gain Control (AGC) is monitored in the case of VOR and a phase coherence test is performed for TACAN.

3. *ILS-1 Mode:* (Instrument Landing System) The flight path for this mode can be flown either clockwise or counter clockwise at a set distance from the localizer. The inspection of the localizer includes the crosspoint deviation in front and back courses, the lowest clearance values, and the bearings at which it occurred in each sector. The data are monitored on the CDU and recorded. The following data are calculated:
   a) Localizer sector clearances.
   b) Signal strengths throughout areas inspected.
   c) Width and symmetry.
4. *ILS-2 Mode:* This mode is primarily to inspect the glideslope; therefore, the flight path is planned at a constant altitude inbound along the runway bearing. During this mode the glideslope AGC and modulation levels are monitored while the evaluation of the radiated signal can be used to inspect:
   a) glideslope width,
   b) symmetry,
   c) structure below path,

  d) clearances, and
  e) alignment.

5. *ILS-3 Mode:* The following conditions of the Localizer, glideslope, and marker beacons are monitored:
   a) Glideslope and Localizer alignment.
   b) Modulation levels and structure.
   c) Widths and signal levels of marker beacons.

   This mode is to calculate the worst structure in the zones 1, 2 and 3 in nautical miles (NM) for the glideslope and Localizer that are the front and back course conditions.

In addition to this AFIS, the FAA has a SAFI (Semi-Automatic Flight Inspection) system for the global flight inspection of VOR, VORTAC, and TACAN. In this system the main idea is to fly as long as possible and record all data for off-line computation. This flight inspection is done with the older aircraft in which the instrumentation and inspection system has not yet replaced. The output tape of these systems includes the following data:

a) Bearing of VOR or VORTAC or TACAN.
b) Distance of TACAN or DME.
c) Whether the receiver is automatically or manually tuned.
d) Receiver sequential operation numbers.
e) Receiver signal level.
f) Facility modulation levels.
g) Aircraft attitude.
h) Aircraft altitude.

6.2 Commercial Flight Inspection Instrumentation Systems

Flight inspection in each country is a governmental job. Therefore, in the past the flight inspection instrumentation systems were designed and constructed by official groups of the associated ministry. For example, the military radio navigation systems may be inspected by a military group associated with the ministry of defense; while the inspection work for the civil radio navigation systems may be done by the ministry of transportation. In this case a lot of different systems are installed in the inspection aircraft that are not compatible with each other. Nowadays these incompatible systems and the decreased budget for flight inspection lead to using commercially designed and built systems or transferring the flight inspection work to commercial companies.

Some countries have changed their policy for flight inspection by commercializing this work. For example, in Germany the DFMG (**D**eutsche **F**lug**m**essgesellschaft) is a private company that sells flight inspection to the German government and other countries in Europe and the Middle East. This company uses an AERODATA system. So as the costs increase, other countries will follow this method where the inspection work is done by private companies. The task of the government is to determine the procedures and the handling of the flight inspection. In the Netherlands, the flight inspection changed from the government group to the NLR--which will use an AERODATA system for the work. These are only two examples of using a commercial flight inspection system. In other countries, different inspection systems are installed in the inspection aircraft.

For small countries, the flight inspection has been done in the past by the United States FAA flight inspection group or by the French DGA. Now some countries have changed their policy in favor of either establishing their own flight inspection group or buying flight inspection from the private inspection companies. So one can see all the facets of flight inspection in the different countries.

The heart of each flight inspection system is the computer that combines all the data of the different radio navigation receivers and is capable of displaying and storing the data at the inspection aircraft. A lot of companies designed such computer systems in the past and will also design them for the future flight inspection systems. Systems are built by companies in the United States--for example E-SYSTEMS, GULL, LITTON, SIERRA, etc., in France by SFIM, in Germany by AERODATA, in Norway by NORMARC, or by companies in other countries in the world. As examples, the onboard equipment for some of the commercial flight inspection systems are displayed in figures 6.1 to 6.3. In figure 6.1 one can see the French CARNAC 21 system while figure 6.2 shows the US system of the LITTON company, and figure 6.3 shows that of the SIERRA company. These companies are now selling the reference technology for the flight inspection in addition to the hard- and software for the integration and display of the data from several receivers. This means that the new generation of commercial flight inspection systems uses different analysis to calculate a highly accurate flight path and all other reference data needed. In this section, a summary of the functionality of the main systems is described because the flight inspection--as well as the flight testing--of radio navigation systems will be making use of these systems.

The main functions of the commercial flight inspection systems are very similar. The old analogue displays which required a lot of space are no longer installed. Nowadays a graphical color display (adapted PC-terminal for aircraft usage or a Laptop LCD display) shows all inspected data. In figure 6.4 such a graphical output on the LCD screens is outlined. The flight inspector is able to change the displayed data, the display velocity, the ranges etc. This makes flight inspection more flexible and transparent. A CPU, in most systems a PC (personal computer), calculates the results. Several interfaces collect the data of the radio navigation systems and other important transmitted data. All new receivers have a serial bus--normally the ARINC 429 bus. The hardware of these buses is described in the ARINC documentation. In addition to the displaying of data on a screen,

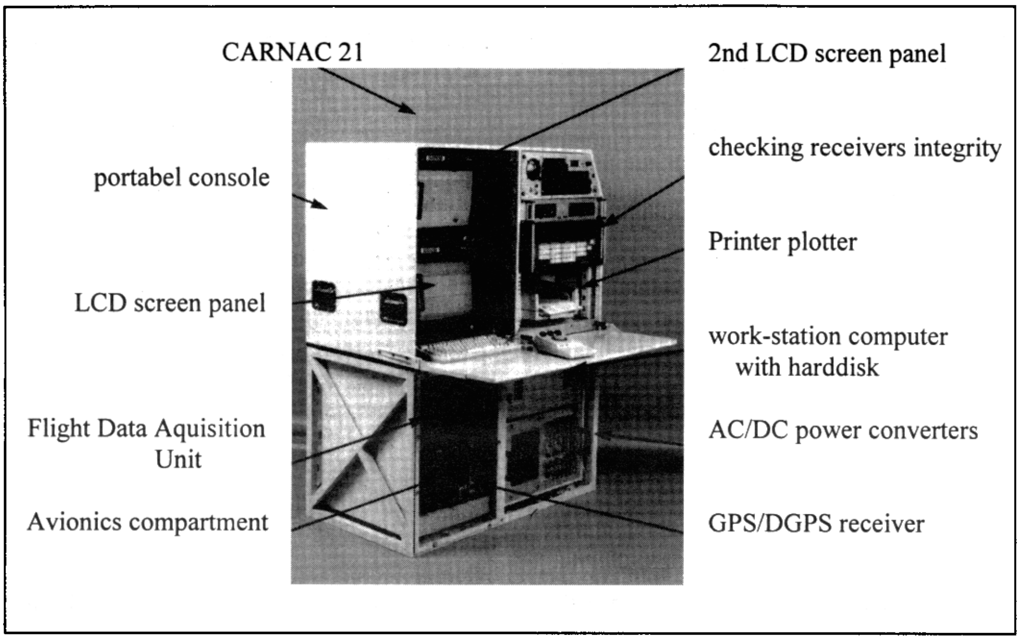


Figure 6.1: The CARNAC 21 flight inspection system of the SFIM company (on-board equipment). [61, 87]

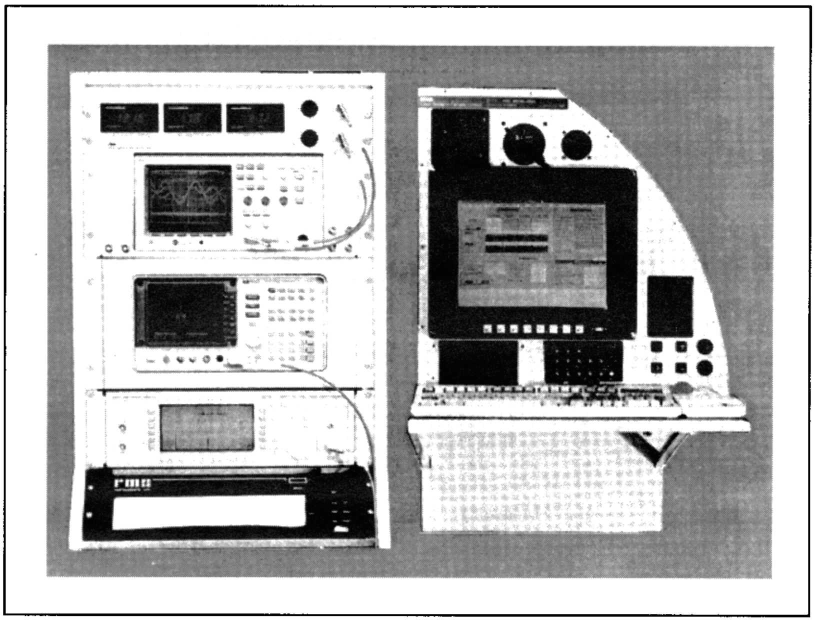


Figure 6.2: The LITTON flight inspection system (on-board equipment). [60]

all data during the inspection flight has to be stored. Therefore a magnetic tape recorder, disk drive, or optical disk drive is part of the flight inspection system. These recorders are not soley used for storing data because in most cases they will have the capability of loading the operating system and the main programs as well. The computers may run under several different operating systems--typically DOS, WINDOWS, or UNIX.

The programs for the flight inspection work show the results of the flight inspection in the form of curves or digital data. The graphical display can be modified during the flight testing to look at special effects of the radio navigation systems; for example range, angle, or distance errors, differences of frequencies, etc. But in the air, not all signals of the flight inspection or testing can be observed by the personnel. So on the ground immediately after the inspection flight the recorded data can be reviewed and one can analyse other data or special error effects. This can be helpful for the inspection paperwork and in determining if additional flight tests must be done if errors occur. At the home base of the flight inspection group, these reviews of the inspection data can be started again for special interpretations. In some of the commercial systems, it is feasible to train the inspection personnel on the ground. So new inspectors can simulate different scenarios for the flight inspection of radio navigation systems as well as simulate special error situations and their identification or interpretation.

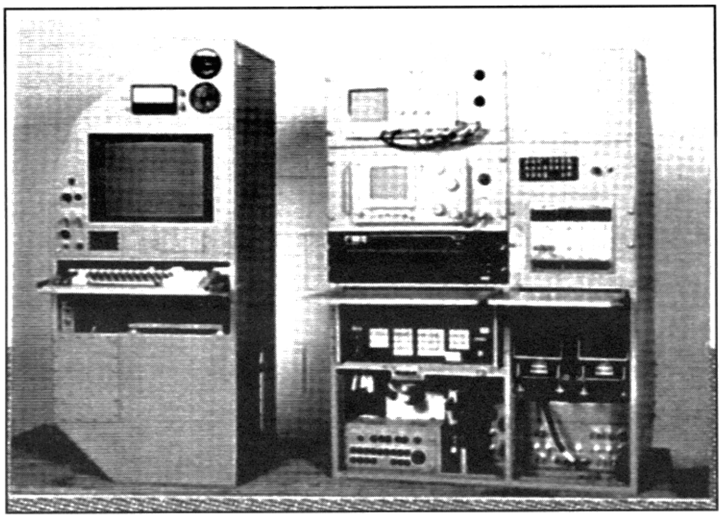
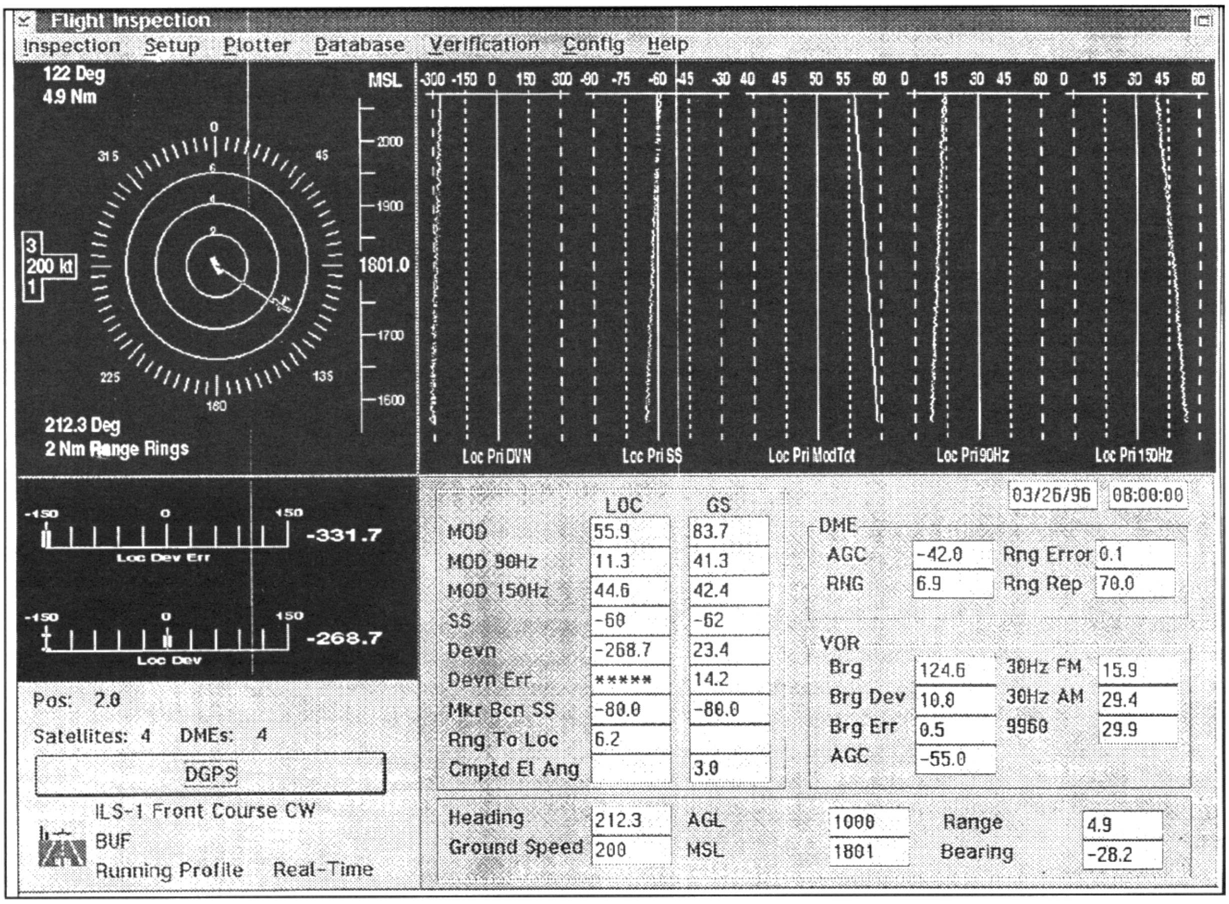


Figure 6.3: The SIERRA flight inspection system (on-board equipment). [89]



03/26/96 08:00:00

	LOC	GS
MOD	55.9	83.7
MOD 90Hz	11.3	41.3
MOD 150Hz	44.6	42.4
SS	-60	-62
Devn	-268.7	23.4
Devn Err	*****	14.2
Mkr Bcn SS	-80.0	-80.0
Rng To Loc	6.2	
Cmptd El Ang		3.0

DME

AGC	-42.0	Rng Error	0.1
RNG	6.9	Rng Rep	70.0

VOR

Brg	124.6	30Hz FM	15.9
Brg Dev	10.0	30Hz AM	29.4
Brg Err	0.5	9960	29.9
AGC	-55.0		

Heading	212.3	AGL	1000	Range	4.9
Ground Speed	200	MSL	1801	Bearing	-28.2

Pos: 2.0

Satellites: 4 DMEs: 4

ILS-1 Front Course CW

BUF

Running Profile Real-Time

Figure 6.4: Screen display on a flight inspection LCD display. [15]

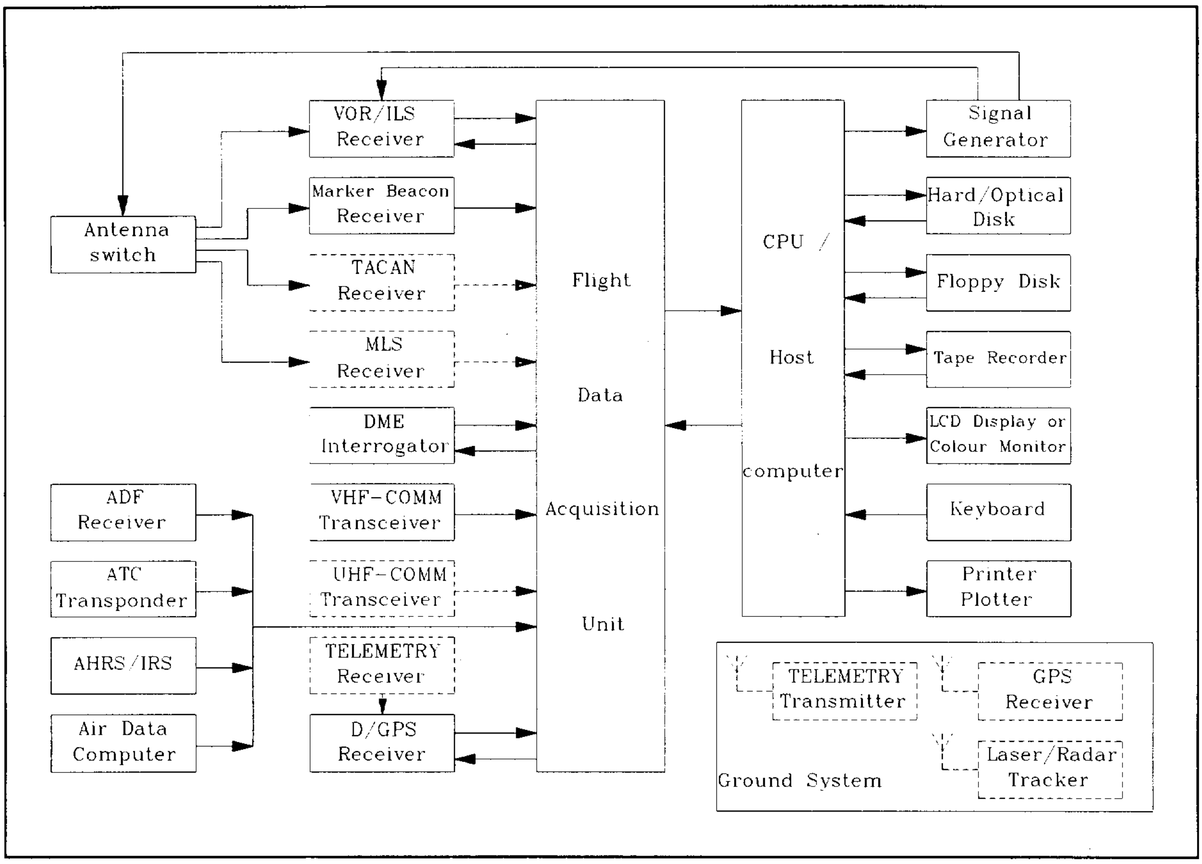


Figure 6.5: Flight inspection system of the new generation. [87]

Most of the commercial inspection systems are equipped with the associated avionics. The layout of such a system is displayed in figure 6.5. As described above, digital avionic systems are used as standard equipment for flight testing. The following receivers are normally part of such a commercial system: VOR, ILS, DME, Marker Beacon, GPS/DGPS, Attitude sensor, static inverter, and VHF communication receiver. In addition MLS, TACAN, and ADF receivers are installed together with analogue and audio interfaces for special systems used with the basic instrumentation of the aircraft. These are the systems for the radio navigation test facility. An inertial navigation system (AHRS or IRS) together with an air data computer (ADC) will be used for the calculation of the reference data. The important signals for the route of flight are displayed on indicators similar to the pilot instrumentation--for example crosspoint meter and DME indicator. Additionally, oscilloscope control systems are installed to inspect (and examine special effects of) the receivers or the transmitted data. The systems are designed for 28 VDC power and have requirements for about 40 Amps.

The differences between the inspection systems are the layout of the graphical displays, the computer programs, the workload, and space for the inspection system onboard the aircraft. All systems are modular and can be installed in each aircraft. The dimensions are adapted to the structure of the aircraft and their airframes. Normally the systems will be modified for the used aircraft and, in addition to the basic equipment, antennas for the several receivers of the flight inspection system must be installed. This is a critical part of the installation for the safety of the aircraft because the positions of the antennas have to be chosen very accurately to avoid EMI influences between them. Therefore, antenna diagrams have to be measured to indicate critical situations for the basic instrumentation as well as for the analysis of the flight inspection data.

The workload of the inspection system depends on the avionic equipment and the flight inspection order. That means, the equipment onboard the aircraft must be adapted to the inspection of the specific radio navigation system and the requirements for this system. For example the visual glide slope indicator (VGSI) can be inspected without any additional inspection equipment while a CAT III landing system inspection needs a lot of additional avionic equipment to measure and to calculate a high accurate navigation. So the workload differs between 70 kg up to 200 kg. All systems must work in a temperature range between -30 °C and +65 °C.

The main difference between the several commercial flight inspection systems is the calculation of the reference data--especially the position analysis. They also differ in the associated hardware. A lot of companies use GPS or DGPS for high accuracy flight path calculation. The establishment of GPS-only based reference navigation has already begun. So the inspection analysis uses GPS data in addition to other ground supported navigation systems. To get such high accuracy position data during the flight inspection or flight testing, different hardware can be adapted to the airborne system. For example, a laser radar tracker is installed on the ground and transmits its data to the aircraft. This system must be adjusted very accurately to the geographical coordinate frame of the airport. The accuracy of the tracker itself is less than 1m but the range depends on the visibility between tracker and aircraft as well as the weather conditions. Other radar trackers can work on all weather conditions but they cannot achieve the high accuracy needed for the flight inspection. Another possibility for calculating a high accuracy flight path is the usage of cameras observing landmarks or the baseline of the runway. With these systems, the reference can be evaluated by backprocessing all data during an approach. The accuracy is high enough for flight inspection. But the actual inspection can only be continued if the backprocessing of data is finished. This may double the time for the inspection. If the evaluation and interpretation of the flight inspection can be done post-flight, this method can be used. But as the air traffic at the aerodromes increases, the flight inspection time must decrease and produce results as soon as possible.

The position reference calculation in the future will be a DGPS-based data calculation. Nearly all inspection systems use an inertial reference system like AHRS (attitude and heading reference system) or IRS (inertial reference system). The pure accuracy of these systems is not sufficient for the flight inspection or testing. Therefore, supporting information from different radio navigation systems has been used to increase the accuracy. While in the past Multi-DME, radar trackers, etc. have been used as supporting data, today the GPS sends very high accuracy data. Combining the inertial reference system data together with the GPS data, one can calculate accurate position information as well as angle information. To the extent that the accuracy depends on that of the inertial reference, the costs of the flight inspection system are increased. This is the reason to look for a cheaper system only based on GPS. For correcting the velocity, acceleration, and angle error of the inertial systems, one needs highly precise position and/or velocity data. A GPS on its own cannot achieve an accuracy of less than 10 m. If one uses a ground GPS station fixed on the airport and equipped with a telemetry system or a transmitter to send the corrections of the satellites and the time error to the onboard GPS receiver (called DGPS), the accuracy of the GPS position increases to less than 0.2 m in all directions. But a ground GPS station must be established before flight inspection and that means the position for the system must be known very accurately in the geographic coordinate frame. In figure 6.6, such a ground DGPS station is displayed consisting of a GPS receiver and a transmitting station. Enroute navigation accuracy is about 10 m to 100 m for pure GPS. Perhaps in the future--if wide area GPS stations (WAGPS) are available--this accuracy can increase considerably. But in that case this information will be used by the whole civil aviation community, and the flight inspection and flight testing groups will have to look for higher accuracy systems or analysis to verify the information of these and other stations and systems.

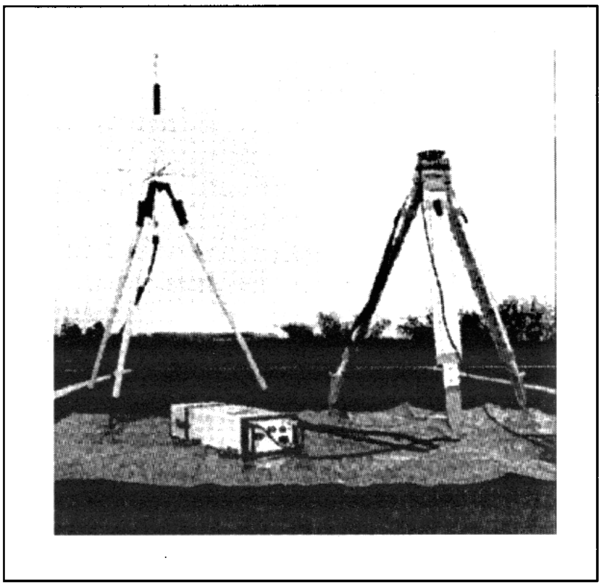


Figure 6.6: DGPS ground station for flight inspection with GPS receiver and transmitter. [2, 20]

One of the first systems for flight inspection using this technology of DGPS is the CARNAC-21 flight inspection system from SFIM industries. They use a ground-based GPS surveyor receiver by ASHTECH, the TENUM telemetry transmitter, and the same systems onboard the test aircraft to achieve an accuracy of 0.15 m (Y) and 0.20 m (Z) for terminal facilities calibration. All other companies will follow this method of using a DGPS-based aircraft position fixing system. For example, the AERODATA company has a so-called AeroNav-H system that includes a communication system via satellite INMARSAT C. This communication can also be used for correcting data from a ground GPS station or transmitting other data between aircraft and ground or between different aircraft.

7. FLIGHT TEST METHODS

Since the number of radio navigation systems differs substantially between several nations, different procedures are chosen to make flight inspection. Flight inspection generally is a precise quality measurement of signal(s) associated with air navigation facility radio navigation systems. In some countries the communication facilities are part of the flight inspection, but this is not discussed here. The standards of the design for air navigation facilities are documented in the Convention on International Civil Aviation Organization (ICAO) and the flight inspection has to verify that the signals from radio navigation systems conform with the standards throughout their published service volume. Different types of flight inspection have to be done:

- Site Evaluation: Determination of the suitability of a proposed site for the installation of a navigation system.
- Commissioning: Verifying the operational requirements of a facility prior to certifying for use.
- Periodic: A regularly scheduled flight inspection to determine that the facility will still support its requirements and still meet the standards.
- Special: These are all flight inspection for special purposes. It is not practical to describe all such circumstances for these inspections. For example, equipment modifications, malfunctions that are detected by users, reconditioning after outage, etc., are conditions for special flight inspections.
- After Accident: A flight inspection after an accident is only performed if the accident Coordinator or Investigator requests it.
- Reconfiguration: If a radio navigation ground facility is modified or has altered performance, flight inspection has to verify the reliability of the system performance and the eventual extended services.
- Surveillance: This inspection is to determine the performance of a facility by unscheduled flight inspection.
- Surveillance of Aeronautical Services: This type of flight inspection means to check all services associated with or belonging to radio navigation--for example runway conditions, construction activities, air traffic control, etc.

In addition to these types of flight inspections, new procedures and techniques have to be developed, tested, and integrated into the "normal" flight inspection services. The inspection of radio navigation systems is very different in different countries and normally does not include all services described above. A lot of circumstances are responsible for the restrictions to the procedures discussed above. Effective scheduling of resources, money, and task accomplishments is one of the most critical and complex aspects of the flight inspection function and this is normally very different between the several countries. Aircraft availability and time must be carefully balanced as well with flight inspection and procedure requirements, air crew qualifications, and training and aircraft maintenance.

Naturally for each radio navigation system special procedures have to be followed for flight inspection. In the following sub-chapters, the main principles of the different procedures are explained. The procedures are determined by the government and are based on the error characteristics and the description of the systems themselves.

One of the critical parts of the flight inspection is to evaluate a high accuracy reference for the position, the aircraft angles (heading ψ, roll ϕ and pitch θ), the track of the flight, and the distance and track to the radio navigation system. For a lot of flight inspections this information is provided by geographical points that were established at fixed positions around the radio navigation system. The procedure to obtain this reference information is to fly directly over these fixes and check or record the measured signals in order to determine the differences with the inspected system. Nevertheless, this method is faulty and not very precise. Another approach is to use a theodolite system that is normally located at the base of the radio navigation system antenna. This method can only be used if the inspected system is located on or close to an aerodrome. The positioning of the theodolite has to be done very accurately because the operator of the theodolite must be in sight of the inspection aircraft during the whole flight. Therefore, interferences with buildings and other obstructions must be regarded as well as the frequency interference with other navigational aids, etc. because the theodolite operator has to transmit the reference information to the inspection aircraft. Additionally, information evaluated at the aircraft has to be transmitted to the theodolite operator--for example when the aircraft reaches a fix. The third method is an inertial reference system-based high accuracy navigation evaluation onboard the aircraft. This system needs an inertial navigation system and supporting information of a radio navigation system such as a DME, TACAN, GPS, PAR, or other surveillance radar information. With the supporting information, the errors of the inertial reference system can be calculated onboard the inspection aircraft. The high accuracy position, angle, and track information can be recorded in addition to the radio navigation system information. This last method has the advantage that the flight inspection can be done as long as the recorder is able to store the flight inspection signals. Simultaneously, the calculated differences or other information can be displayed on a monitor. Otherwise the flight inspection personnel are able to check a lot of radio navigation aids in parallel without any restrictions to geographical points or areas. That allows the inspection of radio navigation aids during normal flight hours with a minimum of restrictions to the air traffic. Such modular and hybrid systems onboard an inspection aircraft are very effective--but expensive--because a lot of computers, interfaces, telemetry, and an inertial navigation system must be installed together with the calculation software.

Nevertheless, for a lot of radio navigation systems the accuracy of the simple flight inspection method using geographical fixes is sufficient. In the following sections, the main flight inspection procedures for the radio navigation systems are outlined.

7.1 Flight Inspection of the VOR

The Very High Frequency Omnidirectional Range (VOR) system is the standard short range radio navigation system used by most of the aircraft. For testing a VOR facility, the entire area used must be inspected; which means an analysis of 360° of azimuth around the facility. Normally during the flight inspection the course, the flag alarm, and the AGC have to be recorded and plotted for the analysis onboard the testing aircraft. A lot of different test equipment is prepared for an automatic test of VOR systems. But a test can also be realized without these complex systems. In these cases a high accuracy reference must be used--such as a theodolite--to measure the aircraft magnetic heading. The main problems in testing the accuracy and certification are influences of the test system itself to the received signals of the VOR. For example, propeller modulation causes intermittent but rapid flag indications. All those effects have to be excluded from the test system before flight inspection--which implies a good calibration procedure for the test system.

The VOR flight inspection requirements are divided into several different checks:

- Identification: means to inspect the identification signal for correctness, clarity, and possible detrimental effect on course structure. A flight test should show if the indent signal has affected the course. The test is done while flying on course twice within radio line-of-sight of the station--once with identification turned on and once with it turned off. Where voice/code identification is installed, the voice identification modulation is adjusted at the facility to approximately 30 percent and the code identification not to exceed 8 percent. Influences of ATC, ATIS, etc. have to be regarded as well.
- Voice: Analogous to the identification test, the voice communication on the VOR frequency is checked for clarity, signal strength, and effect on course structure.
  Tolerance: ±5 mA.
- Sensing and rotation: At the beginning of the flight inspection, the omnibearing selector (OBS) has to be rotated to the azimuth of the radial being flown while the position of the aircraft in azimuth to the station is known. When the crosspointer is centered, the "FROM_TO" indicator will indicate "FROM." Now begin a counterclockwise orbit, keeping the course deviation indicator centered by rotation of the omnibearing selector (OBS). The radial bearing should continually decrease.
  Tolerance: none.
- Checkpoints and reference checkpoint: Checkpoints can be any type of reference such as bridges, houses, road/river intersections, buildings, or other forms of reference available in the area. Otherwise high accuracy inertial navigation systems supported by GPS can be used as reference onboard the inspection aircraft--which is more accurate and flexible than geographical marks. Theodolites and laser radars can also provide high accuracy navigation. For example, an operator can transmit a 1020 Hz tone to the aircraft if a position is reached.
  The checkpoints are needed at least every 20° of azimuth to fly an accurate track with the inspection aircraft and to measure the errors of the VOR station with high precision. If the aircraft is equipped with an accurate flight guidance system and an automatic recording system for all signals of the VOR, less or possibly no checkpoints are needed.
  For the flight inspection, a reference point is selected at a distance between 10 and 20 miles from the antenna on the 90° or 270° radial. This checkpoint will be used in establishing the preliminary course alignment and can serve as a reference point for subsequent inspections of course alignment, course sensitivity, and meter readings. When crossing this checkpoint, all data including the MSL altitude have to be recorded and can be used for error analysis and correction during the actual and later flight inspections.
- Modulation and Polarisation: At the inspection aircraft, all voltages used for the flight inspection have to be monitored during the flight test and later on the ground in order to analyse possible modulations. When out-of-tolerance conditions are found, other VOR stations can be used for cross-checking to determine whether the receiver produces a malfunction or the VOR station is maladjusted.
  For the polarisation check, the following two different methods can be used in each quadrant of the VOR station. The *Attitude Effect Method* includes a straight and level flight at a distance of 3 to 12 miles towards or away from the station. Perform a roll-maneuver with a 30° bank each way with a minimum of heading deviation. Crosspointer deviation, as checked by the recorded course, is the amount of polarisation. The second method is called *Heading Effect Method* and this check includes a flight exactly over the position of the VOR station antenna and marks this point while flying with different headings--normally in all quadrants. The difference in indicated position is the polarisation error.
  Other methods as well can be used to evaluate the vertical polarisation error.
  Tolerance: 2°.
- Enroute and terminal radials: Fly enroute radials either inbound or outbound along the entire length of their intended use. Normally the enroute radials should be flown at a minimum of 1000 feet (or higher in mountain areas) above the highest terrain or obstruction along the radial to distance of 40 miles. During this flight on the electronic radial, the position may be recorded frequently at known reference points. The difference between reference point and VOR measurements evaluates the alignment error. Additionally, the approaches, holding areas, etc. have

to be analysed for possible undesirable close-in or over-station characteristics.

The terminal area must be checked as well, whereas the holding patterns, procedure turns, approach and missed approach, and departure routings have to be inspected. These tests need a highly accurate reference because the procedural altitudes must be maintained where each segment (except the final segment) shall be flown to an altitude of 100 feet below the lowest published minimum descent altitude to the Missed Approach Point (MAP). Also, the approach radials between the Final Approach Fix (FAF) and the Missed Approach Fix (MAF) have to be inspected during on-site evaluation, commissioning, or when required. In some approach areas, the VOR signals are used as support for the instrument flight procedures. In this case, periodic flight inspection of the radials for the Standard Instrument Departures (SID) and the Standard Terminal Arrival Routes (STAR) must be done.

Tolerance: alignment = 2.5°; roughness and scalloping = 3.0°; course sensitivity = 20° ± 2°.

- Orbits: Orbits are to be conducted to determine course error distribution and coverage throughout 360° of azimuth. A prescribed circular track around the station has to be flown using highly accurate checkpoints or other precise guidance for navigation. During this test the omnibearing selector is rotated every 10° of azimuth by switching the selector automatically and the results of the test must be recorded with marks at the precise position checkpoints. The selected altitude for the test flight--1000 feet above terrain or obstacles--shall be the minimum altitude for instrument flight rules. Basically restricted areas for the VOR system have to be monitored if any changes require issuance of a NOTAM and/or listing in the Airman's Information Manual.
- Coverage: Coverage of the VOR is considered to be the usable area within the operational service volume and is determined during the various checks of the VOR. The coverage of the VOR signal is 40 miles and that means obtaining a minimum signal of 5 microvolts at this distance. If the coverage is less than 40 miles, additional flight tests have to evaluate the restrictions for the VOR system. The reasons for these restrictions are very different, for example out-of-tolerance roughness, scalloping bends, alignment, and/or interference rendering the facility unusable in certain areas, etc. which are factors other than signal strength.

  Additional checks are required when signals of two VOR stations are needed for the navigation on, for example, an airway. In this case, at the mid-point both systems must provide an adequate signal with little difference of intensity.

  Tolerance: signal strength = 5 mV (AGC).
- Frequency Interference: An office will furnish information on all known possible areas of radio interference, their identification, bearing from the facility, and whether the interference is co-channel or adjacent channel. For the investigation of suspected radio frequency interference, a spectrum analyser should be used.
- Airborne and ground receiver checkpoints: The airborne receiver checkpoints are designated over well-defined ground checkpoints at specific altitudes. Such checkpoints shall be established at a distance less than 5 miles or more than 30 miles from the VOR facility at an altitude of at least 1000 feet AGL and must be selected in an area that will not interfere with normal traffic patterns.

  Fly the aircraft directly over the selected checkpoint either toward or away from the facility and compare the electronic radial with the geographic azimuth.

  Ground receiver checkpoints will be on the airport ramp or taxiway where the airport traffic is not obstructed. The inspection itself is done with the aircraft receiving antenna over this checkpoint with the aircraft aligned toward the station. Position the aircraft receiving antenna alternately in three additional positions 90° apart and check for alignment stability. Alignment should remain within 2° of the selected radial. If such a checkpoint is established, it should be marked for further flight inspection on the pavement.

  Tolerance: alignment = ±2.0°; heading effect = ±2.0°; signal strength < 15mV; flag alarm current > 240 mA.
- Monitor: The monitor check is conducted to determine the amount of course shift that will occur before the alarm system is activated. The monitor has to be checked during commissioning inspections and any time the reference radial alignment has changed more than 1° from the previously established setting without a monitor alarm. The check may be made over the reference checkpoint.

  In a lot of VOR facilities, two monitors are installed. If the monitors are connected in parallel, out-of-tolerance conditions for either transmitter are confirmed by both monitors before transmitters are changed or the facility is shut down. Otherwise, if dedicated monitors are installed, they do not switch to each other to verify the alarm condition that implies a monitor check to both transmitters.

  Tolerance: shall indicate alarm when the course shifts more than 1.0°.
- Standby Equipment and standby power: For this test a part of all checks of the flight inspection has to be done with the station operating on normal power as well as operating on standby power.

  Tolerance: alignment shall exceed 2°.
- Associated NAVAID's: Inspect the facilities associated with the VOR, such as marker beacons, DME, lightning aids, communications, runway lights, etc.,

concurrent with the VOR flight inspection to the extent they support the instrument flight procedures.

A lot of diagrams must be plotted to describe the different error sources. These figures provide the base for evaluating the reasons of errors. They help to discuss and to explain most of the errors and influences seen in the recorded data of the inspected station. As an example, some outputs of a VOR flight inspection are lined out in figures 7.1 to 7.3. The first diagram shows the signal intensity around the VOR station. One can see the intensity in µV and the VOR signal strength in dBm. In figure 7.2 the error signal of the VOR station is plotted over the azimuth from 0° to 360°. Additional information about the mean square error (-0.1°), the minimum error (-1.8°), the maximum error (1.5°), and the maximum error variation (0.7°) completes this direction error drawing of the VOR station. The last figure 7.3 is an example of the 30 Hz amplitude modulation in percent. In addition, the absolute crosstrack error between 1° and 5° is lined out. Together with other error and signal diagrams, the condition of the inspected VOR station can be documented.

7.2 TACAN/DME Flight Inspection

The Tactical Air Navigation System (TACAN) is a short range, omnidirectional air navigation system and is sometimes co-located with VOR to form a VORTAC. TACAN is installed as an independent aid, or DME may be installed as a separate facility to provide distance information. In parallel with the VOR flight inspection, a highly accurate reference must be used--for example a theodolite, an inertial navigation system, radar information, etc. The TACAN/DME flight inspection requirements can be divided into the following check parts:

- Identification: This check is made to ensure the identification is correct and is received throughout the operational service volume. Therefore, for all checks of the system the identification has to be recorded. If the station includes a VOR, which includes a VORTAC, the identification is checked by code and voice identification in different sequences. The code identification shall be correct, clear, distinct, without background noise, and not affect course characteristics throughout the coverage limits of the facility.
- Sensing and Rotation: Perform sensing and rotation checks at the beginning of each inspection to verify correct rotation of the antenna.
- Reference Checkpoint: Analogous to the VOR flight inspection, a well-defined checkpoint has to be selected located 10 to 20 miles from the TACAN antenna (for DME checks see distance accuracy). This checkpoint will be used in establishing the preliminary course alignment and can serve as a reference point for subsequent checks of course alignment and monitor.
- Distance accuracy: During the whole inspection on the radials, the orbits, and the approach procedures the distance information of the TACAN/DME has to be controlled. The mileage information is cross-checked with the reference information coming from pilots, marks "over" ground checkpoints, or other highly accurate navigation information. The comparison between the reference, which is transformed and scaled into the TACAN/DME coordinate frame, and the DME distance determines the accuracy of the facility. The differences do not have to be evaluated at altitudes below a vertical angle of 5° because the difference between slant range and chart range is less than 0.5 of 1%. (5° is approximately 1000 feet altitude above the antenna at a distance of 2 miles.)
  Within 25 miles of the antenna, the ground facility may reply false pulses. This can only be checked by using an oscilloscope.
  Tolerance: 3% or 0.5 mile slant range.
- Terminal and enroute Radials: All radials supporting and necessary under instrument flight rules (IFR) procedures have to be inspected. A minimum of eight radials should be checked separated by 45° to a distance of 40 miles, although the minimum enroute altitude for each airway segment or terminal segment has to be determined. Enroute radials either inbound or outbound along the entire length of their intended use at an altitude of 1000 feet above the highest terrain or obstruction have to be flight inspected.
  The difference between the distance information of TACAN/DME and the highly accurate reference has to be calculated during the flight on the electronic radial while flying on course with minimum heading change. As described above, determine course structure and alignment by analysing the errors on reference points or between the reference paths, and by analysing possible undesirable close-in or over-station characteristics. At least that position should be reached when the minimum signal strength (less than 22µV) is detected.

Inside the terminal area, the radials sufficient to encompass the holding patterns, procedure turns, approach, and missed approach/departure routings have to be evaluated. In this case, approach approved procedure radials have to be flown to 100 feet below specified altitudes and the radials 5° each side at the minimum altitude from 3 miles outside to 3 miles inside the final approach fix. In this area, a condition of unlock usually accompanied by rapid changes in AGC and oscilloscope indications of a loss or distortion of the cycle modulation components is not permitted. Commissioning inspections shall be made from overhead the station outbound to the range limits. At least minimum signal strength must exist within 4 miles or 4.5°, whichever is greater, on the furthest side of the geographical fix for the radials/DME forming an intersection. The signal must be free from interference at all authorized altitudes.

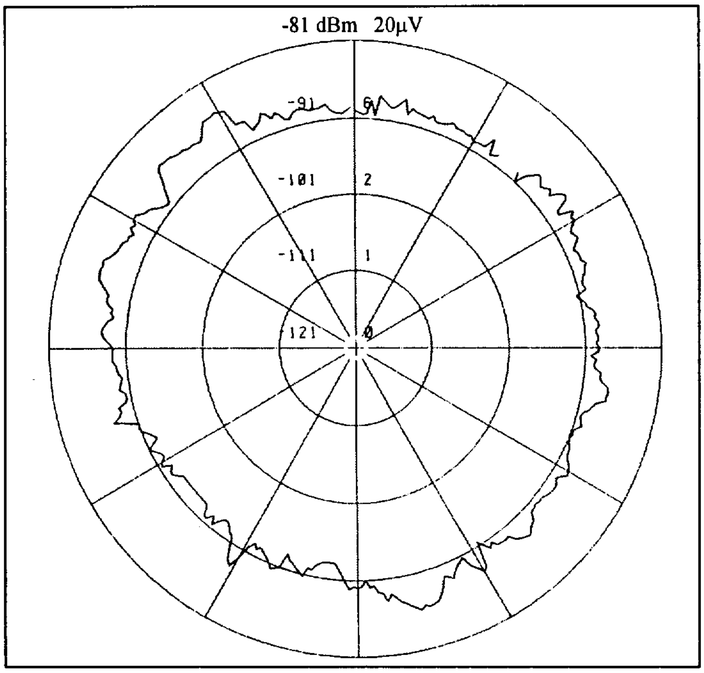


Figure 7.1: Signal intensity of the Chambery-Colombier VOR at a distance of 100nm. [23]

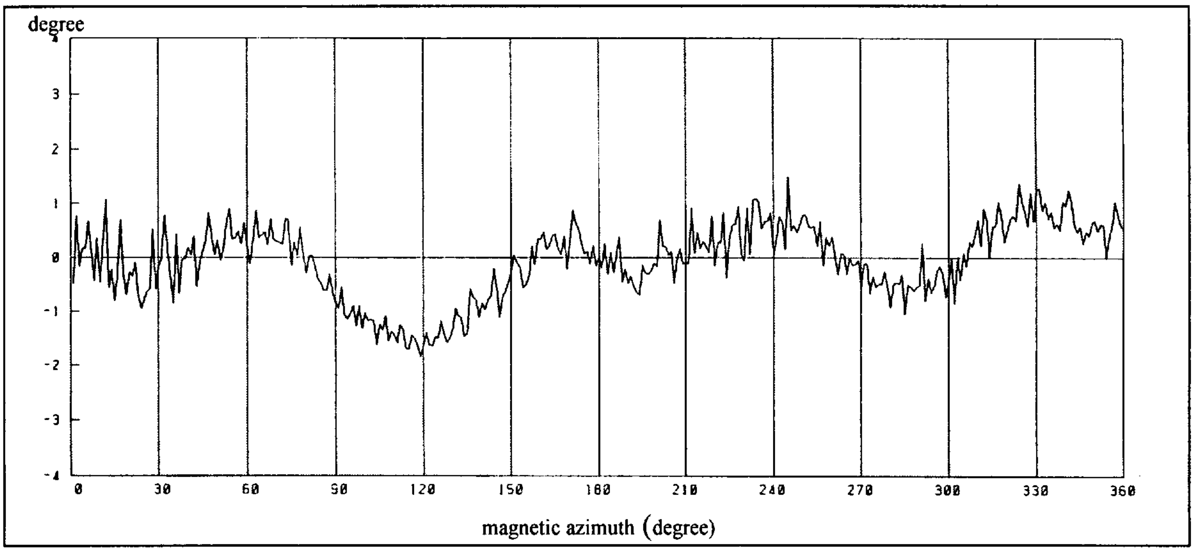


Figure 7.2: Error of the Montelimar VOR during high altitude inspection. [23]

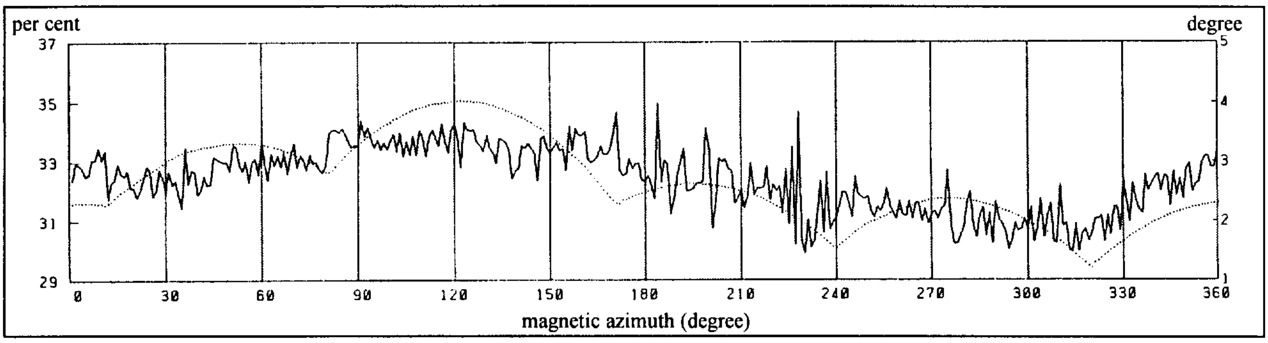


Figure 7.3: VOR 30 Hz AM modulation Chambery-Colombier VOR in per cent. [23]

Tolerance: 2.5^{o} of correct azimuth for the alignment; < 3.0^{o} of the average course for roughness, scalloping and other course aberrations:

up to 10 000' MSL:	*0.25 miles*	*--in any 5 miles along the radial*
up to 20 000' MSL:	*0.5 miles*	*--in any 10 miles along the radial*
over 20 000' MSL:	*1.0 miles*	*--in any 20 miles along the radial*

deviation of the course due to bends < 3.5^{o}.

- DME fixes: Distance measuring equipment co-located with a facility on which a holding course is predicated may be used to establish a fix in view of, or in addition to, a radial or course from another facility. All such DME fixes shall be checked concurrently.
- Orbits: As described for the VOR flight inspection, analogous flight tests have to determine course error distribution and coverage throughout 360^{o} of azimuth.
- Coverage: For site and commissioning inspection, one complete 40-mile (for special TACAN/DME classes only a 25-mile) orbit shall be flown to evaluate the coverage of the DME. All data of the DME have to be checked and the accuracy of the distance data is inspected using reference data (ground checkpoints, etc.). If the facility is unusable in certain areas, a restriction will result.

  The minimum reception altitude for the TACAN/DME facility at a given point or intersection will be determined by flying at the minimum desired altitude on course for 5 miles beyond the point, and then across the course 4 miles on each side of the radial. Both azimuths and/or distance indicator must remain "locked on" with no flag showing, and course and/or distance information must be within tolerances (signal strength > 22 μV or higher as read from the AGC meter).

  Tolerance: 40 miles at the minimum altitude
- Frequency Interference: see VOR flight inspection
- Receiver checkpoints: see VOR flight inspection, normally the identification shall be signed at the receiver checkpoint as follows:

  DCA-VORTAC
  116.3 (CH 110) 147/327
  1.5 miles

  This sign shows the identification, channel, course selected, and distance to the antenna.
- Monitor: The purpose of this check is to assure that the monitors will detect and cause an alarm at a specified shift of azimuth. For this check, position the aircraft exactly over the reference checkpoint inbound or outbound while the course condition is changed from normal operating to the alarm point (in both directions) and returned to the normal operation. At each condition the amplitude of shift to the alarm point has to be determined as well as the return to normal operation.
- Polarisation: Polarisation effect results from horizontally polarized RF energy being radiated from the TACAN antenna system. For the flight inspection, see VOR.
- Standby Equipment and Power, Remote Controls, Associated NAVAID's: see VOR.

7.3 Glide Slope Indicator Flight Inspection

The Visual Glide Slope Indicators (VGSI) are ground devices that use lights to define a vertical approach path during the final approach. The several different types of VGSI are: the Visual Approach Slope Indicator (VASI), the Precision Approach Path Indicator (PAPI), and the Pulsating Visual Glide Slope Indicator (PVGSI). The lights of these indicators have different colors (red, yellow, green, or white) to indicate whether the aircraft is on the correct glide path or not.

The flight inspection of the VGSI with an accuracy of 0.25^{o} to 0.5^{o} can only be realized if a high accuracy reference is available. For example, if the aircraft is equipped with an accurate inertial navigation system, the signals of an instrument landing system (ILS), a microwave landing system (MLS), or a precision approach radar (PAR), the demanded accuracy may be achieved. The flight inspection checks the overall appearance and the usability of the glideslope indicator system as viewed by the pilot on the approach. The flight inspection requirements are as follows:

- Light intensity: The normal intensity settings of the VGSI's for daylight operation are 100%; for twilight periods, 30%; and for hours of darkness, 10%. These different intensities may be checked during an inbound flight by changing the intensity manually.
- Glidepath angle: The VGSIs provide vertical guidance for a VFR approach or the visual portion of an instrument approach. The aircraft has to be positioned inbound on the runway centerline in the below path sector for the procedural intercept altitude or 1000 feet. Proceed inbound while maintaining constant airspeed and altitude while recording the reference information and marking or identifying at each checkpoint. During the flight inspection the points of on-path indication are used to calculate the glidepath angle; therefore, all indications of below-path, above-path, first and last on-path have to be marked and saved on the record. Another method can be used if a theodolite or a PAR is available. In this case, the operator on the ground tracks the aircraft from the beginning of the inbound flight to the ground on the actual path. The pilot advises the operator when the aircraft is exactly on-glidepath. The glidepath angle is the average of at least two on-path flights.

  For each of the different VGSIs, special flight inspections can be used which sometimes accommodate local site conditions or other special features. These inspections are not outlined here.

Tolerance: 0.2° within the 3.0° glidepath. The runway reference point will be within ±50 feet for VASI and ±30 feet for PAPI.

- Angular Coverage: The VSGIs will provide coverage/obstacle clearance 10° either side of the runway centerline. This can be checked by observing the lights while crossing the extended runway at a 90° angle at a sufficient distance.
- Obstruction clearance: The VGSIs must provide clearance above all obstacles within the operational service volume. The flight inspection can not verify that specific below-path indications clear all obstacles within the operational service volume.
  For the flight inspection, the aircraft has to be positioned outside the normal glideslope and proceed inbound while definite below-path information shall be visible. A definite climb indication must be visible while maintaining clearance above all obstacles and show normally the RED light.
  Tolerance: The visual glidepath shall be at least 1.0° above all obstacles.
- System identification: The VGSIs must provide a glidepath signal that is easily identifiable and not interfered with by other lights such as taxiway lights, etc.
- Coincidence: The VGSIs visual approach path should not coincide with the one produced electronically by ILS, PAR or MLS if these systems are present. The tolerance between the glidepath angle of both systems is equivalent to the tolerance for the glidepath angle itself.

7.4 LORAN-C Flight Inspection

The Loran-C is a low frequency radio navigation system that transmits essentially in a closed loop and is self-monitoring. The maneuvers used for the flight inspection of Loran-C approaches consist primarily of tracks between waypoints. Before approaching, select the correct Loran-C Chain and the approach mode, then monitor all information of the Loran-C system and the reference information or record them while flying the track maneuvers. Evaluate and check the cross-track-distance to the next waypoint during the whole flight as well as when the waypoint is passed. The flight inspection requirements are as follows:

- Route and approach segments: Fly the entire route from a navigational aid (or fix) to the initial approach fix of the Loran-C system while maintaining the procedural altitude. Inspect feeder route segments as well as initial and intermediate approach segments. For the last ones, fly the entire route from each initial approach fix to the final approach fix and verify the Loran-C signal coverage. For the final approach segment of the instrument approach procedure, the inspection aircraft may be flown from the final approach fix to the missed approach point by descending to 100 feet below the minimum descent altitude. The segment between the missed approach point to a waypoint where the pilot can execute another approach or join the enroute structure must be inspected too. During all these flights the coordinates of the Loran-C system at all waypoints and fixes must be recorded together with the reference information. These checks should include the cross-track distance information during maneuvers as well. Additionally the envelope-to-cycle discrepancy and the signal-to-noise ratio have to be recorded and respectively checked.
- Course structure: This refers to the excursion characteristics of the Loran-C receiver crosspointer that include bends, roughness, and other aberrations. Other avionics equipment or areas with poor geometric dilution of precision (GDOP) can influence the transmitted and the Loran-C course. The procedures for checking these influences are described in the part "route and approach segments."
  Tolerance = ±0.3 NM of the desired track.
- Cycle slip: Normally the receiver will track the third cycle of the pulsed 100 KHz carrier for time measurements. A cycle slip can be caused by radio frequency interference, etc., and can be indicated by a difference of about 1.0 NM to the reference position. That is equivalent to a 10-microsecond error in cycles.
- Electromagnetic spectrum / signal-to-noise ratio (SNR): Electrical power lines (such as those close to the final approach segment--within ±1200 feet), factories, and radio frequencies are potential sources affecting the receiver performance. These errors can only be analysed by using a spectrum analyser. The signal-to-noise ratio is a ratio of signal strength to overall received noise. To check these effects, monitor and record all receiver signals.
  Tolerance: Interference shall not affect receiver performance, SNR = -6 dB or greater
- Envelope to cycle discrepancy (ECD): The envelope to discrepancy is the difference between the desired and actual zero phase crossing at the end of the third cycle of the Loran_C pulse. Calibrated ECD values outside the range of -2.4 to +3.5 microseconds may cause receiver tracking problems and have to be monitored and recorded during flight inspection.
- Position accuracy: This accuracy is the difference between the Loran-C receiver computed position and the correct geographic position as determined by a high accuracy reference system or visual checkpoints, etc.
  Tolerance: within ±0.3 NM.

7.5 ILS Flight Inspection

The instrument landing system (ILS) is either an integrated radio navigation system including localizer and glidepath that operates in the VHF and UHF band, or the

Interim Standard Microwave Landing System (ISMLS) which operates in the 5000 MHz to 5250 MHz frequency range. The single or dual frequency types of localizers are normally sited along the centerline of the runway and the Simplified Directional Facility (SDF) provides azimuth guidance. For the flight inspection of an instrument landing system (ILS) a highly accurate reference must be used because the accuracy requirements for the ILS itself is very high. The reference information can be provided by telemetering theodolites, onboard high accuracy inertial navigation data that are supported by surveillance radar information, or other radio navigation aids such as the GPS. The method to evaluate such high accuracy reference information is described at the beginning of this part. The evaluation of the reference data differs between the flight inspection systems. A description of all the different methods used is outlined in the chapter on commercial flight inspection systems.

	CAT I	CAT II	CAT III
Decision Height	200 ft	100 ft	50 ft
Localizer Alignment	0.042°	0.028°	0.014°
Localizer Displacement Sensitivity	0.035°	0.035°	0.021°
Glide Path Alignment	0.035°	0.035°	0.035°
Glide Path Displacement Sensitivity	0.035°	0.035°	0.035°

Table 7.1: ICAO requirements for the ILS categories. [45, 102]

Three ILS categories are established for different accuracy requirements. The categories are divided into CAT I, II, and III; which include different decision heights (DH) for landing: CAT I uses a 200 ft DH, CAT II uses a 100ft DH, and CAT IIIa uses a 50ft DH. Each category also specifies accuracies for the angle errors of the localizer and glide path. The values are 2-s values which means they must be available with a probability of 95%. The ILS the localizer and glidepath, which operate in the VHF and UHF bands, have to be certified. There are two basic types of localizers: single-frequency and dual-frequency. Localizers are normally sited along the centerline of the runway (RWY); however, some are offset from the centerline. Localizer-type Directional Aids (LDA) may be located at various positions about the runway. The locations and ILS Zones and Points are described in figure 7.4 for the different categories and in figure 7.5 for a typical offset ILS structure.

Before flight testing the ILS, the hardware for the reference calculation has to be installed on the airport as accurately as possible. As seen in table 7.1, for this test a very high accuracy reference flight path has to be evaluated. Thus the previously described methods for reference path evaluation will be used. The ground part of the inspection system can be a theodolite for older systems, a laser tracker for the current systems, and a GPS receiver with a transmission station for the future systems. All these ground systems have to be installed very accurately because their alignment is the basis for the accuracy of the whole flight inspection system.

During a specific inspection the 75 MHz Marker Beacon, the Compass Locator, the DME, the Lighting Systems, and the Terminal En Route must be checked. All the systems that work together and build the approach radio navigation aids for the air traffic have to be globally inspected. Thus during the flight inspection procedures, all data from all systems must be received and controlled.

The **localizer procedure** is mainly divided into the following parts and items:

- Modulation level and equality: This check measures the modulation of the radiated signal and obtains a crosspointer value which will be used as a reference for phasing. For both the *front course and back course procedure,* the modulation while inbound on the localizer--between 10 miles and 3 miles from the localizer antenna and on glide path--has to be measured.
- Power ratio check: This is performed to measure the ratio of power between the course and clearance transmitters of dual frequency localizers. For this check, a spectrum analyser will be used to compare the relative signal strength of the course and clearance transmitters with the course transmitter in RF power alarm mode and the clearance transmitter in normal mode. For this test, position the aircraft on the localizer on-course and in line-of-sight of the antenna.
- Phasing: This means to determine that the phase relationship between the sideband and the carrier energy is optimal. For front and back course procedure, fly on the appropriate azimuth at lowest coverage altitude between 10 and 3 miles while transmitting the crosspointer values to assist the ground technican in adjusting the phasing.
- Course sector width and symmetry: The purpose of this check is to establish and maintain a course sector width and ratio between half-course sectors that will provide the desired displacement sensitivity required at the procedural missed approach point (MAP) or threshold and be within the limitations of the procedural protected area. All types of localizers shall be tailored to a course sector width not greater than 6°

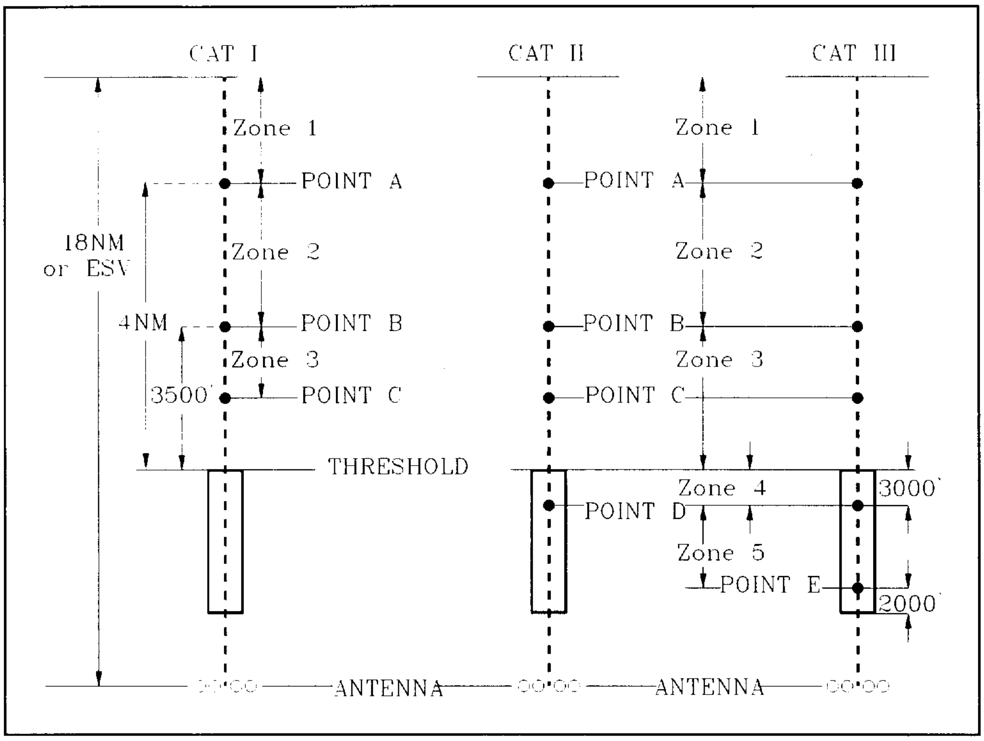


Figure 7.4: ILS zones for CAT I to III. [102]

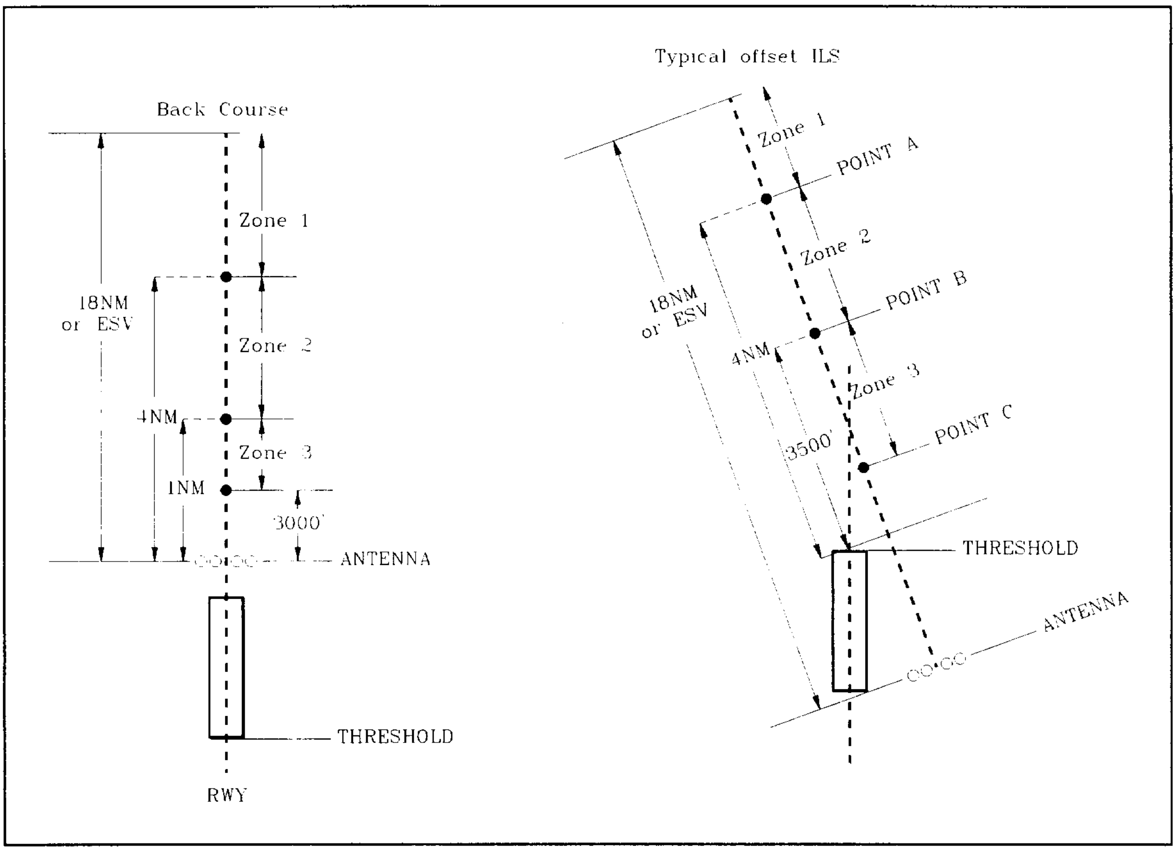


Figure 7.5: ILS back course and for a offset structure. [102]

and a linear sector width of 700 feet at different points for the various categories. As an approved procedure, the course sector width and symmetry between 4 and 14 miles from the localizer antenna has to be measured. This can be made by a crossing in each direction maintaining a constant airspeed over a checkpoint of known distance from the localizer antenna (e.g. outer marker etc.). If a high accuracy reference (theodolite, laser radar, DGPS calculation, etc.) is available, the two values can be calculated during one crossing.

- Course alignment and structure: These checks measure the quality and alignment of the on-course signal. The general check is to evaluate the course along the designed procedural azimuth starting at the furthest point required by the different categories. Maintain the published or proposed procedural altitudes through each approach segment until intercepting the glide path and then descend on the glide path to Point C (see figure 7.4) or runway threshold. For CAT I and lower category zones 1,2, and 3; for CAT II additionally zone 4; and for CAT III all zones from 1 to 5 must be inspected. Normally the course alignment has to be determined for the front course from a point one mile from the runway threshold to the runway threshold and for the back course from a point two miles from the antenna to a point one mile from the antenna.
- Glide path signals on the localizer back course: For the localizer back course, the glide path crosspointer, AGC, and flag alarm current during course structure have to be checked.
- Monitors - width and alignment: Prior to each test the facility has to be set at the monitor limit. If a monitor has detected an out-of-tolerance, this monitor shall be checked.
- Clearance: Clearances are measured to ensure that the facility provides adequate off-course indications throughout the service volume. Therefore, an orbit will be conducted at a radius between 6 and 10 miles from the antenna.
- Coverage: Coverage shall be evaluated concurrently with each required check during all tests.
- Reporting fixes, transition areas, standard instrumentation departures, profile descents, etc.: All facilities involved in these special fixes and procedures shall be checked in addition to the localizer to assure that all coverage parameters are within tolerance.
- Polarisation effect, identification and voice: The purpose of this check is to determine the effects that vertical polarisation may have on the course structure and to ensure that identification and voice are received throughout the coverage area of the localizer.

The procedure to inspect or test the **glide slope** includes the following parts:

- Modulation level and equality: This check measures the modulation of the radiated signal and establishes the balance of the carrier signals. Therefore, the modulation of the glide path while inbound on the localizer/glide path course between 7 and 3 miles from the glideslope antenna has to be measured.
- Phasing: This check determines that the correct carrier and sideband-only phase relationships are distributed to the antennas. For this check, proceed inbound 8 to 10 miles from the glide slope antenna along the localizer on-course, preferably at 1000 feet above glide slope site evaluation. Altitude may vary with terrain to provide line-of-sight. Maintain the level run and have maintenance adjust the phase until the crosspointer is the value found during the modulation equality check. Upon reaching a point one third to one half of the Glidepath angle, commerce a descent. Maintain this angular descent until reaching the runway threshold. Analyse the crosspointer trace during the descent portion of the maneuver. Additionally, checks for null reference phasing, sideband reference phasing, and capture effect have to be done.
- Null check: This check is conducted to determine the vertical angles at which the nulls of the individual glidepath antennas occur.
- Antenna offset: This check is performed to establish the horizontal antenna displacements on the mast. Use the same procedure as that described under phasing plus an adjustment for the horizontal displacement while the test aircraft parks on centerline at the runway threshold.
- Angle, width, symmetry, and structure below path: These parameters may be measured from the results of one level run, except when for specific ILS categories the actual path angle is required. A lot of methods dependent on the reference calculation can be used to measure the various signals:
  - For the glide path angle, position the aircraft beyond 190 μA/150 Hz glide path point on the localizer on-course or procedural designed azimuth. Maintain a constant airspeed. The altitude selected for the level run is usually the glide slope intercept altitude point corrected to the true altitude.
  - Fly inbound, mark checkpoints on the recording tape. Checkpoints are normally the outer marker and the glide slope antenna; however, any two checkpoints separated by a known distance may be used. A distance for each point is determined by using a time/distance ratio. The appropriate angle, width, symmetry, and structure below path are calculated from these values. etc.
- Clearance: This check is performed during a flight along the localizer on-course to assure that positive fly-up indications exist between the bottom of the glide path sector and obstructions.
- Mean width, tilt, coverage, and monitors: For this check
  - determine the mean width of the Glidepath between ILS points "A" and "B" (see figure 7.4),

- verify that the glide path angle and clearances are within the authorized tolerance at the extremities of the localizer course sector,
- evaluate the coverage concurrently with each required check, and
- ensure that the facility is set at the monitor's limit prior to each check.

All accuracy requirements for the localizer and the glide slope are summarized in table 7.2. This table shows the 95% confidence level for the different ILS categories outlined in the ANNEX 10 documentation report.

In addition to these tests, the standby equipment must be checked as well as the requirements for the instrument flight procedures.

	CAT I	CAT II	CAT III
Localizer			
alignment (average)	2.0 m	1.0 m	0.7 m
recommendation	1.0 m	0.7 m	0.3 m
displacement sensitivity	4.0 %	4.0 %	2.5 %
Glide path			
angle	0.75 %	0.75 %	0.75 %
displacement sensitivity	2.5 %	2.0 %	1.5 %
field strength	2 db	2 db	2 db
clearence	3 %	3 %	3 %
course structure	3 µA	2 µA	2 µA
modulation sum	0.5 %	0.5 %	0.5 %
modulation balance	1.0 µA	1.0 µA	1.0 µA

Table 7.2: Accuracy requirements for the localizer and glide slope inspection. [45, 102]

7.6 Future GPS Flight Inspection

As described in other parts of this report, the GPS system is not yet totally working, but the flight inspection of the system has been discussed previously. With the new technology of satellite navigation, flight inspection will embrace a transformation of ideology. GPS is an earth reference navigation system that is controlled by a ground station. The GPS receivers onboard the aircraft are computer equipped which builds a greater reliability and integrity into the system. Therefore, flight inspection will be mostly involved with certifying that the GPS instrumentation flight procedures are operationally safe, validating that the GPS signals-in-space support the flight instrumentation procedure, and certifying associated ground support facilities (precision approach).

In a first phase, GPS will provide navigation data for nonprecision approaches. In this phase a customized flight path is developed with the sequence of waypoints stored in a data base and designed to emulate an existing published approach using a conventional NAVAID. This data base has to be developed for all approaches at all aerodromes and a method must be established to determine how the data of the data base can be transmitted or updated in the GPS receiver software.

Otherwise the GPS signal-in-space supporting the instrument flight procedures has to be validated for accuracy, reliability, integrity, coverage, availability, and quality. Additionally, the anomalies or irregularities associated with the flight procedure in the approach environment--including multipath and interference, etc.--must be evaluated. Most of these problems may be neglected using WADGPS or similar systems.

The flight inspection procedures of GPS consist of tracks between waypoints that can, of course, be used as overlay approach maneuvers. Onboard the inspection aircraft, all data of the GPS - measurement status, altitude, HDOP, VDOP, track angle, latitude, longitude, ground speed, VFOM, velocity, HFOM, time, and sensor status--have to be recorded in addition to the following reference information: true heading, ground speed, pitch, roll, baro or other altitude, cross-track-distance evaluation, latitude, longitude, velocity, etc. The flight procedures are similar to the inspection of other navigational aids. The approach procedure has to be flown exactly on-path and by-path for evaluating errors during the flight. With these tests, two parts of the GPS approaches will be checked: the GPS signals for accuracy and availability during the maneuvers and the correctness of the waypoint initialisation for the approach procedure. All approach segments (initial, intermediate, final, missed approach) have to be flight inspected and the signal interference and coincidence must be determined as well.

However, the main problem for the flight inspection of GPS is the high accuracy of the system itself. Therefore flight inspection systems need a high accuracy GPS-supported inertial navigation system. For the first GPS installations for non-precision approaches, the accuracy of the installed flight inspection systems is sufficient. The accuracy of the inspection systems is about ±4 ft at the threshold, ±20 ft at a distance of 4 NM, and ±30 ft at a distance of 6 NM--while the accuracy of the GPS error specification is ± 340 ft at all positions. All data has an error tolerance of 95%. First tests have shown that the accuracy of GPS-based flight inspection systems using inertial navigation systems can be reduced to ±2 ft to ±2.5 ft at all positions for an instrument landing procedure. These systems are able to inspect all GPS-like navigation systems or the GPS-based approaches. But as outlined before, most of the GPS system errors can be detected and eliminated by a WADGPS where the central ground station can compare all signals of the ground GPS receivers.

7.7 Development of flight inspection

The establishment of GPS, DGPS, or WADGPS instead of the conventional radio navigation systems influences the flight inspection of radio navigation systems in a wide area. The table 7.3 shows the systems in the United States for 1992 and those planned for 2000 which have to be inspected. Regarding the timetable, some of the numbers of radio navigation systems will increase or remain at the same level as in 1992. The phase-out for most of the systems is coupled to the installation and availability of GPS. The change of the landing systems from ILS to MLS will probably be not completly realized because a lot of airports hope to get the GPS or WADGPS earlier. Otherwise the large number of VOR, DME, and ILS users will not change their policy as quickly and they plan to use their radio navigation systems past the year 2000.

Type Facility		LORAN-C	OMEGA	VOR VOR/DME	TACAN	ILS	MLS	NDB	GPS
FAA Facilities	1992	46	8	962	648	974	28	728	none
	2000	combined	Trans-	1020	633	1094	772	728	none
DOD Facilities	1992	U.S./CAN.	mitters	85	173	165	24	180	20
	2000	26	8	85	173	165	299	50	24
Civil users	1992	80 500	14 700	196 000$_{\text{VOR}}$ 89 000$_{\text{DME}}$	<100	125 000	50	170 000	1200
	2000	83 250	?	204 000 $_{\text{VOR}}$ 93 000$_{\text{DME}}$	<100	131 000	20 000	230 000	80 000
DOD users	1992	500	1900	12 500	14 500	10 500	700	11 800	6000
	2000	0	0	<500	4500	6500	10 100	4000	33 000
Int'l agreement		none	none	1995	none	1998	none	none	none
DOD expected phase out		1994	1994	2000	2000	2004	expanding services	N/A	Expanding services
FAA expected phase out		expanding services	depend on GPS	(1)	N/A	(1)	expanding services	N/A	Expanding services

(1) slow phase out with the implementation of GPS in next century.

Table 7.3: Present status and future plans of radio navigation systems in the United States.

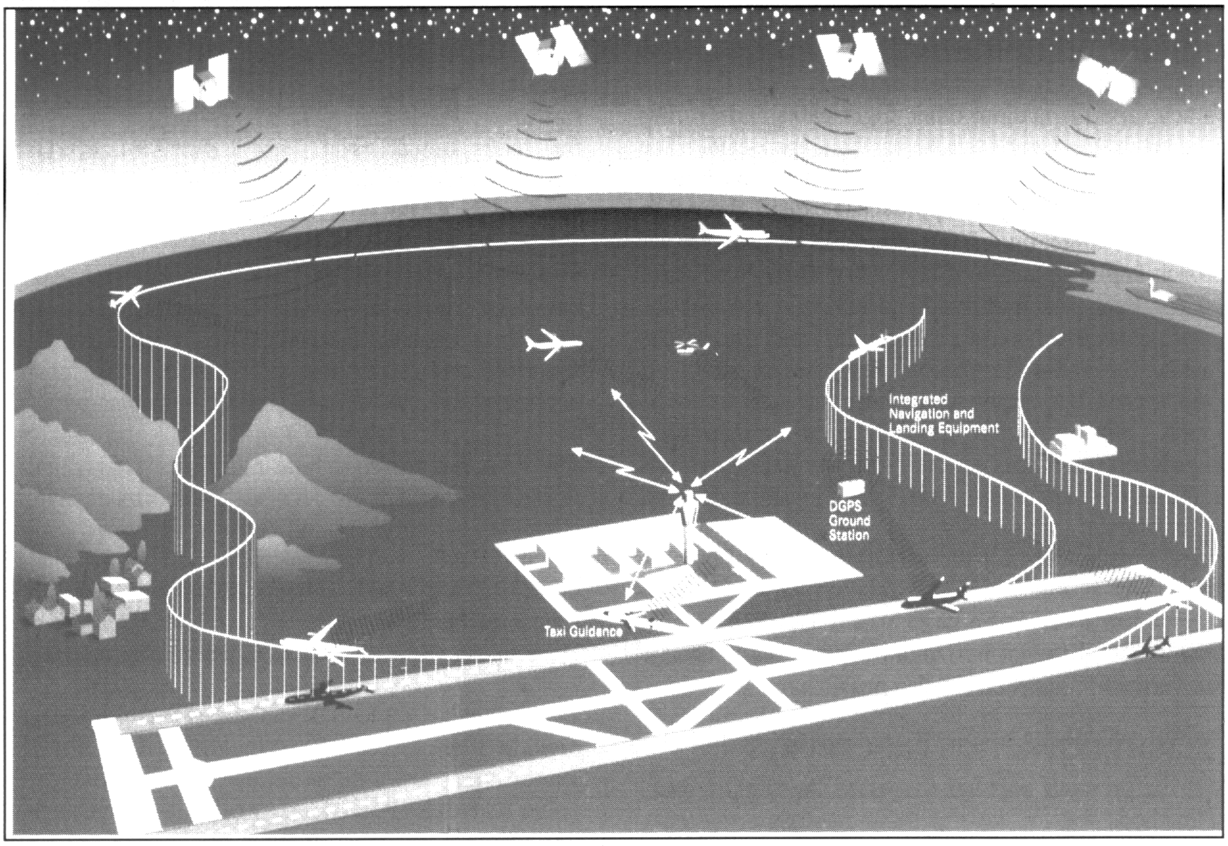


Figure 7.6: Future Differential GPS Navigation System in the terminal area. [19]

The airports as well as the airlines are waiting for the GPS-like navigation because the whole navigation can be based on one system. Problems with the correlation of the different navigation systems--especially the different coordinate frames--can be neglected. However, disturbances can interrupt the whole navigation system and only the highly equipped airliners would be able to navigate with their ground-independent inertial navigation systems if the GPS were jammed. Nevertheless, the accuracy of GPS-like systems is very high. Figure 7.6 shows the GPS-based navigation on a future airport. The takeoff, landing, and taxiway navigation are based on GPS data.

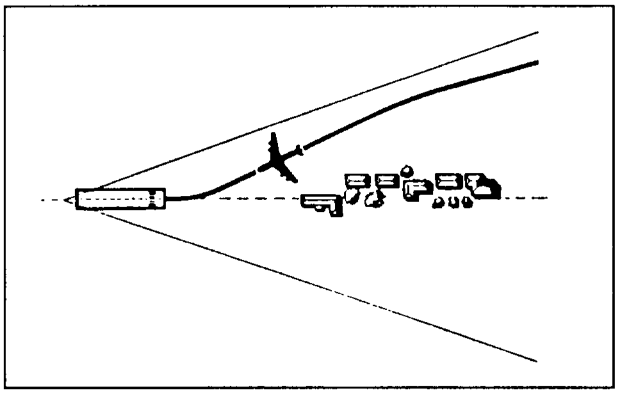


Figure 7.7: Different horizontal approach geometry. [83]

The figure 7.6 includes another part influencing radio navigation system flight inspection work. With this high accuracy GPS navigation, other flight paths and profiles can be established and have to be flight inspected. The figure 7.7 illustrates a different horizontal approach to an airport. Today most of the approaches extend about 8 to 10 miles in direction of the threshold. Using a 3°-approach implies a height of 200 ft in a distance of about 3800 ft. Each year the buildings in the vicinity of the airports change; therefore, multipath and reflections influence the radio navigation near the airports. If curved approaches can be used, these influences may be reduced. In other words, new approach configurations with reduced influences on the radio navigation systems and the airport approach noise, etc. should be helpful. But for curved approaches, high accuracy navigation systems must be used for the whole air traffic. The only system which is able to evaluate this navigation information for a low price and a large area is the GPS system. In addition to different horizontal approaches, a change to the vertical 3°-approach is also possible.

8. FLIGHT INSPECTION PROCEDURES

While the previous part has discussed the flight inspection methods for the several radio navigation systems, this part describes the procedures initiated and approved by the state government. Therefore, different procedures may be performed. Of course, the number of radio navigation systems installed and the geographic and economic situation of each country are the main influences for these inspection procedures.

The installation of a flight inspection system is very expensive because it requires an installed inspection system, one or more aircraft and, of course, a crew and organization. Therefore, a lot of countries buy flight inspection services from other countries which must have a flight inspection organization with enough capacity to inspect additional radio navigation systems in those other countries. Nevertheless, the inspection work is a governmental task. The following description shows the flight inspection systems in some countries and the development for the future. The 1996 conference for the flight inspection teams (held in Germany) had the title "Flight Inspection in a World of Change" which describes very well the actual situation. All flight inspection systems are now or will be replaced in the near future and the business of the flight inspection will be changed due to the installation of GPS to replace or augment the existing radio navigation systems.

8.1 Flight Inspection in the United States

The United States of America has charged its Federal Aviation Administration (FAA) with providing flight inspection of the common air navigation system and US military aids world-wide. Additionally, reimbursable services are done for other countries who are otherwise encouraged to establish their own flight inspection capability. The standards for the flight inspection are established by the United States Standard for Terminal Instrument Procedures (TERPS) or by special procedures for international, local, or Department of Defense (DOD)-owned facilities. The FAA provides flight inspection for 41 countries and consortiums.

The above description of the test procedures is extracted out of the United States Standard Flight Inspection Manual--which explains in detail the different inspections of the radio navigation systems. In the other countries, equivalent manuals describe the flight inspection.

The FAA has installed nine Flight Inspection Field Offices (FIFO) which are located in the United States and other countries of the world because all United States Air Force (USAF) navigational aids and systems--including those U.S. and reimbursable systems in overseas areas--also must be flight inspected. The following table 8.1 gives an overview of the FIFO's work and equipment.

The following table 8.2 summarizes the frequency of periodic flight inspections of the different facilities. The abbreviations are used as follows: Standard Instrumentation Approach Procedures (SIAP), Number of Navigation Facilities (NONF), Primary Navigation and Landing Aids (PNLA), total Flight time hours in the Year 1992 (FY-92).

Location	SIAP	NONF	PNLA	FY-92	aircraft type
Anchorage, AK (ANC)	292	791	288	1252	Convair 580 Sabreliner 80 Beechcraft F-90
Atlanta, GA (ATL)	1292	4119	1004	3706	4 Beechcraft BE-300
Atlantic City, NJ (ACY)	551	3604	760	3577	4 Beechcraft BE-300
Battle Creek, MI (BTL)	1916	5961	1078	4078	4 Beechcraft BE-300
Frankfurt, Germany (FRA)	373	696	270	1283	2 British Aerospace BAe-125-800
Honolulu, HI (HNL)	134	449	159	430	Beechcraft BE-300
Oklahoma City, OK (OKC)	687	4218	1037	5560	4 Beechcraft BE-300 2 British Aerospace BAe-125-800 3 Sabreliner 80 Sabreliner 40 Convair 580
Sacramento, CA (SAC)	794	3072	748	2794	3 Beechcraft BE-300 Beechcraft F-90
Tokyo, Japan (TYO)	0	552	240	1003	2 British Aerospace BAe-125-800

Table 8.1: Summary of the flight inspection field offices of the FAA. [71]

facility	workload	inspection interval (days)	inspection window (days)
Precision Approach Radar (PAR)	192	60 - 240	6 - 24
Instrument Landing System (ILS, ISMLS, SDF, LDA, MLS)	1416		
VOR / DME / TACAN / VORTAC	1537	1 cycle / 450 h (SAFI) 180 (Non-SAFI)	45 18
NDB	2070	450	45
LORAN-C		270	27
Approach Light Systems	12 270	with primary facilities associated with	--

Table 8.2: Frequency of the periodic flight inspections in the USA. [71]

The relatively high total flight hours for the Oklahoma City office are needed for the Semi-Automatic Flight Inspection (SAFI) which is explained below. The top two layers of management are located in Oklahoma City. The FAA has today two different flight inspection procedures: the semi-automatic and the automatic flight inspection.

The periodic inspection will be considered complete on the facility due date if the inspection is done within 10% of the specified interval prior to or after the facility due date. The window for annual inspection intervals shall be 30 days prior to or after the facility due date. If a periodic inspection is completed outside the specified window, the next inspection date will be predicated on the date the inspection was actually completed. Facility monitors are checked at twice the periodic interval listed. Special frequency inspections are used for the radar and instrument landing system prior to their classification. A so-called System Performance Analysis Rating (SPAR) determines each inspection and the interval of periodic inspections may be increased when no discrepancies have been assigned; otherwise, it decreases.

8.1.1 Semi-Automatic Flight Inspection (SAFI)

The SAFI method is a global flight inspection especially for VOR, VORTAC, and TACAN facilities in the United

States. For this inspection, a grid pattern is placed over the chart of the United States which shows flight inspection routing for the test aircraft. The grid chart itself is divided into several parts and the minimum requirement is for at least 60 degrees of alignment coverage in each quadrant per SAFI cycle. The flight path is computer controlled and will be recorded on digital magnetic tapes. In addition to the automatic navigation data, all data of the received radio navigation aids are stored on the tapes. For example, if DME signals are available on left, right, forward, and behind the grid path, all these signals can be correlated with each other and the reference position of the aircraft. Processing these stored data off-line on digital computers, error data of the DME stations can be evaluated. This makes it possible to decide whether or not the station performs as required. It is sufficient to have DME stations located in opposite directions; therefore, it is not necessary to receive data from all four main directions. These are limitations for the selection of SAFI grid paths. The same evaluation can be done for the VOR and TACAN data. The receivers are tuned to the proper channels at appropriate points along the track. For special events, the operator can manually tune the receivers and these events are registered on the tape as well.

For the SAFI inspection, a total of 759 flight hours have to be evaluated off-line each year. That is, of course, a lot of data; but on the other hand 1537 VOR, DME, and TACAN facilities have to be flight inspected in the United States.

8.1.2 Automatic Flight Inspection System (AFIS)

In addition to the SAFI, the Automatic Flight Inspection System has been fully operational since 1993. This system is now a totally digital system and is installed in the Beechcraft Super King Air 300, Sabreliner, and BAe 125-800. This system incorporates the latest technology available for aircraft systems and sensors. The aircraft are equipped with the latest flight instrumentation and this has reduced technician interface (with the entire system) to keyboard functions only. The main new systems are a navigational computer unit, a control and display unit, and a laser-inertial reference unit from the Honeywell company. The missions done with this system are equivalent to those done with the SAFI system; however, a lot of flight inspections could be done simultaneously because much more data can be recorded and analysed by the system itself or by the flight inspection personnel. Therefore, the AFIS uses the same procedures as the SAFI but with a "better" hardware.

8.2 Flight Inspection in Europe

The flight inspection work is a governmental job. Therefore, each country tries to form a unique flight inspection group. However, some of the countries are very small and have only a few installed radio navigation aids. Each state has its own policy for the flight inspection. As examples, short descriptions of the flight inspection in France, Great Britain, the Netherlands, and Germany follows.

8.2.1 French Flight Inspection

The flight inspection in France is divided in two parts: the military and civil. The military part is named DGA (Délégation Générale pour l'Armement) and is situated in Bretigny-sur-orge, Cazaux, and Istres. For the flight testing they have two turboprop CASA test aircraft equipped with a self-developed system. For high accuracy navigation tests, a so-called BEARN radar-system or the STRADA laser radar system is used. The evaluation of the data and references is done off-line after the flight test. This test group examines the new radio navigation systems before they are bought by the ministry of defence and they are installed in military aircraft or at military aerodromes. For the French Navy, the DGA must inspect the radio navigation systems--for example MLS and GPS--on their aircraft carriers.

The calibration and inspection of radio navigation systems is done by the army.

The civil part for flight inspection in France is done by the STNA (Service Technique de la Navigation Aérienne) which is part of the DGAC (Direction Generale de l'Aviation Civile). This flight inspection group uses aircraft of type ATR 42 equipped with various flight inspection systems. These commercial systems are built by the French company SFIM. Nowadays a reference system based on multi-DME or GPS and an inertial navigation system is used sometimes together with a MINILIR infrared tracker, but in the future the SFIM inspection system CARNAC 21 will be installed. The multi-DME system has an accuracy of about 200 m while the GPS based system reaches 100 m. The MINILIR system has to be used for high accuracy ILS inspection, but the weather conditions influence the availability. The new flight inspection system with the VPDGPS (Very high precise differential global positioning system) will have an accuracy of about 10 cm and is independent of the weather conditions. As always, the influences to the transmitting frequencies and the errors of multipath in the vicinity of aerodromes have to be evaluated and checked.

The STNA has to inspect about 100 ILS systems--25 with CAT III--and about 100 VOR, Doppler VOR, DME/VOR systems. Until the year 2015 the ILS systems have to be inspected. For the ILS inspection, one ground maintenance inspector is responsible for seven to ten stations for ILS ground test and once a year an ILS flight inspection test takes place. For the other radio navigation systems, the STNA uses a high level GRID inspection flight as described for the US flight inspection. For this part the test aircraft is equipped with 6 VOR receivers that can receive 12 VOR stations by multiplexing the channels. For the whole country, five flights with approximately seven or eight flight hours per each of the five flights have to be flown. The MLS program stopped in 1994; therefore, only one MLS system at the military part in Bretegny is working.

The STNA also inspects overseas radio navigation systems such as those at the airdromes Pointe-à-Pitre, Fort-de-France, Papeete, and Saint-Denis-de-La Réunion. Additional flight inspection is done for Cuba and Egypt. In Egypt, a new flight inspection group for the Middle East has been installed--named ASIGMA--which is supported by the French STNA and SFIM.

After each inspection, documentation is written by the Division Controle en Vol (DCV) (part of the DGAC). In this inspection paper, the inspected systems are outlined as well as the limitations of the inspected systems. In addition to the described situation of the radio navigation system, all curves, graphs, and error documentation are part of the paperwork. So the owner of the radio navigation aid can see the antenna diagram, special influences to the range, or angle information, etc.

This documentation is very helpful for discussion about failures, the installation of new navigation systems, influences of buildings, etc.

8.2.2 The Flight Inspection in the United Kingdom

In Great Britain, as in most other countries, the flight inspection is split into military and civil parts. The military flight inspection group is in Boscombe Down near Salisbury. They only test the military radio navigation systems, ground installations, and aircraft systems. For the inspection and testing work they use special equipment adapted to the required accuracy. All military aircraft are cleared to CAT III ILS. For the future landing system, the MLS and DGPS systems would be tested. The main interest for the military groups are the TACAN radio navigation systems because they are also used for tanker aircraft. For this usage electromagnetic influences have been evaluated and removed. As described for the French military inspection group, in Great Britain carriers must be flight inspected also.

The civil flight inspection group has its base at Teesside airport and is named CAA (Civil Aviation Authority). Since 1992 this group has been the only civil organization approved to carry out flight tests on radio navigation aids in the United Kingdom.

Presently the CAA delivers their service to each customer needing flight inspection. The CAA uses two HS 748 Series 2A Model 238 turboprop flight calibration aircraft. The inspection equipment was defined by the CAA itself at 1969 and a first redefinition took place at 1987. In 1990 the new system starts working and uses a Hewlett Packard HP9000 computer for the calculation work. A console and a graphical display are the main input and output devices for the system together with a printer, an optical disk, and a 32-channel analog recorder. The radio navigation receivers transmit their data to the main computer via an RDE (remote data exchange) and a CDE (central data exchange). Each RDE can collect 52 parameters in parallel with the aircraft equipment. Additional radio navigation receivers are installed for the inspection system. Because the general aviation uses mainly two different ILS/VOR receivers (BENDIX RNA 3 AF and COLLINS S /RV4), these receivers are also installed in the inspection aircraft to evaluate possible differences between these receivers. The inspection aircraft is also equipped with all other radio navigation receivers as well as with two MLS receivers. For MLS inspection a BENDIX ML301 receiver is installed. The reason for installing a MARCONI CMA2000 receiver relates to special problems during the inspection of the London City Airport.

To calculate a high accuracy flight path, an infrared tracking system MINILIR has to be installed at the inspected airfield. With this radar and a link to the onboard system, the position-fixing equipment can fix the position to within 23 cm and 0.003 degrees angular displacement. They can also simulate all inspection flights on their ground system, which is equal to the airborne inspection system. Therefore special effects and errors can be analysed on ground.

The CAA has checked ILS, VOR, DVOR, DME, MLS, DMLS, MADGE, TACAN, NDB, SSR, MSSR, SRA, ADSEL, and DABS. Naturally they are also involved in the use and inspection of GPS and DGPS. In the UK, the ILS has to be flight inspected twice a year and about 52 DME and VOR stations must be flight inspected as well. The CAA does flight inspection for the UK and Ireland.

The CAA transferred its flight calibration service, assets, and staff to Flight Precision Ltd (FP)--a joint venture between FR Aviation Ltd and Aerodata GmbH. FP announced this change in October 1996 and now comprises four flight inspection aircraft carrying out work for the Royal Airforce, National Air Traffic Services Ltd, UK regional airports, and the Irish Aviation Authority.

8.2.3 The Flight Inspection in the Netherlands

The flight inspection department in the Netherlands is only a small group within the Netherlands Department of Civil Aviation (RLD now LVB). But as in the other nations, the civil flight inspection group only inspects civil radio navigation systems--with the exception of flight inspection for the Netherlands Navy. The Air Force has their own flight inspection group.

Starting in 1977, the RLD used a flight inspection system first developed in 1976. This system was based on an inertial navigation system LTN76 within a multi-DME update to get higher accuracy navigation information. The system itself was built by SIERRA and was equipped with a ROLM computer. Since 1997 the flight inspection work has been done by the NLR (National Lucht- en Ruimtevaartlaboratorium, National Aerospace

Laboratory). The NLR uses an AERODATA system for flight inspection in their Fairchild Metro II aircraft. About 180 flying hours are estimated for the inspection of ILS and 120 hours for the inspections of VOR, DME, VDF, and NDB. The contract for flight inspection has been made for seven years because the government assumed that after this period a change from ILS to a new landing system based on MLS or DGPS would be made.

The main work of flight inspection in the Netherlands is done for the Amsterdam Schiphol airport with its five ILS CAT IIIb runways. A complete ILS inspection has a duration of about 3 to 4.5 hours. At Schiphol, an MLS is installed on one runway (01R) where the ILS antenna looks over the MLS antenna; therefore, the influence between these two landing systems can be determined. The DME/VOR stations are flight checked twice a year and the total amount of flight hours for the inspection of all radio navigation systems is less than 350 hours. The calibration of the radio navigation systems is done by the LVB ground maintenance department and no in-flight calibration is required. The data from the flight inspection is put into a test report. The basic inspection data are calculated and evaluated off-line after the flight.

8.2.4 German Flight Inspection

Until 1993 the German civil flight inspection service was done by the GmFS at the German Air Force field at Lechfeld. In March 1993 a future flight inspection organization was presented to the DFS (**D**eutsche **F**lugsicherung), and in 1994 the new DFMG (**D**eutsche **F**lugmessgesellschaft) was founded. This private company is a Joint Venture between the DFS and AERODATA. The aim for this cooperation was to reduce the costs for flight inspection in Germany and to increase the efficiency.

The operating base for the flight inspection company changes from Lechfeld to Braunschweig where the AERODATA, the German Federal Aviation Authority, a pilot pool, and 24-hour service of a relatively small--but efficiently operated--airport are situated. The aircraft type changed from a HS748 to a King Air 350. In 1995, the new flight inspection system (FIS) produced by AERODATA, and using GPS as a reference system, was installed into the two King Air aircraft. The instrumentation and installation of the flight inspection system--as well as the procedures for flight inspection--were changed to improve the efficiency and accuracy of the whole system. Meanwhile, Kuwait, Jemen, Macao, Macedonia, Lithuania, Kew, Usbekistan, and Italy belong to their field of operation.

This company was the first one where a new private flight inspection group sells flight inspection service. For the government, the costs for flight inspection decrease and, especially for small countries, flight inspection can be done at a higher level and with high accuracy.

9. FLIGHT INSPECTION AIRCRAFT

For the flight inspection, special items have to take into consideration when selecting test aircraft. The aircraft must have a cabin size where all equipment can be installed--as well as have seats for the inspection personnel that can be easily adjusted. Besides the normal inspection equipment, one has to take into consideration that the systems and cabin need cooling air and sufficient electrical power. Certain hot regions, such as the Near East, require more power for cooling. This infers that generators are required with sufficient electrical power both at 115 Volt AC, 400 Hz and for various DC power supplies. Additionally, standby power equipment has to be installed in order to make it feasible to shut down the inspection system or to terminate the flight inspection at a defined point if the normal power breaks down.

Another point of concern for the system development is the aircraft skin, because a lot of antennas have to be mounted outside the aircraft and these must not be influenced by each other. The cable-channels for the antenna cable, as well as the power and signal cables, have to be separated sufficiently. This normally implies a total separation of aircraft basic instrumentation and flight test instrumentation--which cannot be done completely because some receiver antennas cannot be mounted twice on the aircraft.

The aircraft engines may influence the antennas, computers, or other flight inspection instrumentation in terms of both electromagnetic interference and vibration. The aircraft itself must be able to reach altitudes up to 10 000 feet at undetermined velocities.

Operation in extreme weather conditions is normally not a basis for selecting an aircraft, but inspecting radio navigation systems in countries near the equator or in very hot and moist or humid areas need special equipment; including, for example, water for the inspection personnel. In the arctic zone, the equipment must work under very cold weather conditions.

The different types of flight inspections--periodic inspection, site evaluation, commissioning, reconfiguration, etc.--have naturally different requirements for the aircraft type and workload. In addition, the type of radio navigation system that has to be checked determines the type of equipment required onboard the aircraft. The number of radio navigation systems that must be flight inspected for a country is another decision basis on which to select one or more aircraft for the flight inspection. As noted previously, some countries do not have their own flight inspection aircraft and crew. These countries have agreements with, for example, the United States to perform the flight inspection.

Table 9.1 shows the types of aircraft used for flight inspection in the different countries:

Country	Type of aircraft
United States	Convair 580, Sabreliner 80, Sabreliner 40, Beechcraft F-90, Beechcraft BE-300, British Aerospace BAe-125-800.
France	ATR 42-300
United Kingdom	HS 748 Series 2A Model 238
Netherlands	Fairchild Metro II
Germany	Beechcraft Super King Air 350

Table 9.1: Types of aircraft in different countries.

This is only a small list of countries and aircraft used for flight inspection.

10. CONCLUSION

This report was written over a period of time while in the flight navigation and inspection world a lot has changed.

The improvements on satellite navigation systems like GPS and GLONASS with regard to coverage, accuracy and reliability have cut down on the further development and implementation of the new Microwave Landing System MLS. But the application of global navigation systems as the only means of navigation to long range, terminal area and landing is still not yet completely solved. Among other potential risks the most problematic potential risk is that because of intentional interference. [16] So most of the conventional navigation systems like INS, VOR, DME and ILS will endure for quite a while.

In this report the function of conventional radio navigation systems and the problems for testing these systems are described. Especially the different error sources for the enroute and terminal area navigation systems are discussed. One chapter shows the main radio frequency problems: coverage and multipath and the different measurement methods for these errors. A description of the flight test procedures and flight test methods shows the state of the art for the flight inspection of the actual generation of radio navigation systems. As well, the flight inspection systems and the flight inspection aircrafts of the different countries used for the testing of radio navigation systems are outlined. Flight inspection policy changes in a lot of countries, so in this report the authors can only describe their known actual situation of flight inspection policy as a snapshot.

"Flight inspection in a world of change" was the title of the ninth flight inspection symposium and this title characterizes very precisely the problems of flight inspection. Up till replacement the different radio navigation systems like DME, VOR, TACAN, OMEGA, LORAN-C, ILS, MLS etc. have to be inspected. In the future more and more of these systems will be replaced by the GPS system. Therefore this report describes the function and problems of the GPS and the add-ons like DGPS, LADGPS, WAAS etc.. The satellite navigation systems also enable considerable improvements to the flight inspection systems. New systems equipped with differential mode GPS using carrier-phase positioning achieve real-time on-line flight path measurements with errors below 20 cm only. For measurement purposes the mentioned risks of the GNS are of no significance. If interference occurs the measurements can easily be repeated.

Modern flight inspection systems have reached a high standard regarding accuracy and automation. So only small improvements can be expected in the near future.

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13. LIST OF SYMBOLS

δ	error part
$\varepsilon_{N,E,D}$	angle error in north, east and down direction
λ	wavelength
λ	longitude
σ	standard deviation
σ_0	standard deviation of the pseudo range
$\sigma_{\mathrm{N,E,D}}$	standard deviation in north, east or vertical direction
σ_{h}	standard deviation of the height
σ_{t}	standard deviation of the time
φ	latitude
ψ	heading or azimuth angle
ω_0	earth rotation ($15\ °/h$)
ω	rotation frequency
Θ	roll angle
θ	azimuth angle in figure 4.6
ϕ	pitch angle
Φ	transition matrix
Ω	carrier frequency
Δd	distance
Δs	spatial resolution
Δt	time delay or time difference
$a_{N,E,D}$	north, east or down acceleration
c_0	velocity of light
$\mathbf{C}_{(\mathrm{n,b})}$	transformation matrix (b=body to n=geographical coordinate system)
$\mathbf{C}^T$	transposed transformation matrix
$D_{N,E,D}$	north, east or down drift error
E	earth radius (calculating with respect to the reference ellipsoid)
f_d	Doppler shift
f_T	oscillator (carrier) frequency
$\mathbf{F}$	model matrix
F	frequency
$\vec{g}$	gravity vector
$\mathbf{H}$	measurement matrix
$\mathbf{K}$	Kalman gain matrix
$\mathbf{P}$	covariance matrix
$\mathbf{Q}$	covariance matrix of the state vector
$\mathbf{R}$	covariance matrix of the measurement vector
R_i	pseudo range of the i-th satellite
s	distance
$S_{N,Ei}$	north or east position
$t,\ T$	time
U_e	Voltage
v	motion speed of oscillator
$v_{N,E,D}$	north, east or down velocity
$\vec{v}_n$	velocity vector in the geographical coordinate system
$\vec{v}_b$	velocity vector in the body coordinate system
$\vec{x}_k$	system state vector
x	aircraft horizontal x-position
x_{R_i}	horizontal x-position of the satellite i
Δx	difference of the horizontal x-position
y	aircraft horizontal y-position
y_{R_i}	horizontal y-position of the satellite i
Δy	difference of the horizontal y-position
z	aircraft vertical (z-) position
$\vec{z}$	z-axis
$\vec{z}_k$	measurement vector
z_{R_i}	vertical (z-) position of the satellite i
Δz	difference of the vertical position

14. ABBREVIATIONS

AAIM	Aircraft Autonomous Integrity Monitoring
ADC	Air Data Computer
ADF	Automatic Direction Finding
AFIS	Automatic Flight Inspection System
AGC	Automatic Gain Control
AHRS	Attitude and Heading Reference System
AM	amplitude modulation
ATC	Air Traffic Control
ATIS	Air Traffic Information System
BPSK	Binary Phase Shift Keying
CAA	Civil Aviation Authority
c/a code	course/aquisition code
CAID	Carrier Aided Receiver
CDU	Control and Display Unit
CSOC	Consolidated Satellite Operations Center
DCV	Division Controle en Vol
CAID	carrier aided receiver
DDM	Difference in Depth of Modulation
CDE	central data exchange
DFMG	Deutsche Flugmessgesellschaft
DFS	Deutsche Flugsicherung
DGA	Délégation Générale pour l'Armement
DGAC	Direction Generale de l'Aviation Civile
DGPS	Differential GPS
DLR	German Flight and Space Research Center
DH	decision heights
DME	Distance Measurement Equipment
DMU	Data Management Unit
DOD	Department of Defense
DOP	Dilution of Precision
D/U	Desired to Undesired signal ratio
DVOR	Doppler-VOR
ECD	Envelope to cycle discrepancy
ED-50	European Data 50
EGNOS	European Global Navigation Overlay Service
EIRP	Equivalent Isotropically Radiated Power

ELAB	Electro-magnetics Laboratory
EMI	Electron-Magnet Influence
ESA	European Space Agency
FAA	Federal Aviation Authority
FAF	Final Approach Fix
FIIS	Flight Inspection Instrumentation Systems
FIS	Flight Inspection System
FOM	Figure of Merit
FM	frequency modulation
GDOP	Geometric Dilution of Precision
GEOS	geostationary communication satellites
GLONASS	lobal Orbiting Navigation Satellite System
GLS	Global Landing System
GMT	Greenwich Mean Time
GNSS	Glabal Navigation Satellite System(s)
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
ICAO	International Civil Aviation Organisation
ILS	Instrument Landing System
INS	Inertial Navigation System
IRS	Inertial Reference System
IRU	Inertial Reference Unit
ISMLS	Interim Standard Microwave Landing System
ITS	Institute for Telecommunication Sciences
KIN	Kinematic Receiver
LAAS	Local Area Augmentation System
LADGPS	Local Area DGPS
LDA	Localizer-Type Directional Aids
LORAN	ong Range Navigation System
MAF	Missed Approach Fix
MAP	Missed Approach Point
M/D	Multipath to Direct signal ratio
MIT	Massachusetts Institute of Technology
MLS	Microwave Landing System
MSL	Mean Sea Level
NCI	Navigation computer or Interface
NCOR	Narrow-Correlator Spacing Receiver
NDB	non directional beacon
NLR	National Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory
NM	Nautical Miles
OBS	omnibearing selector
PAPI	Precision Approach Path Indicator System
PAR	Precision Approach Radar
PDME	Precision Distance Measurement Equipment
PDOP	Position Dilution of Precision
pps	precise positioning service
prn	pseudo random noise
PVGSI	Pulsating Visual Glide Slope Indicator System
RAIM	Receiver Autonomous Integrity Monitoring
RDE	remote data exchange
RLD	Netherlands Department of Civil Aviation
RWY	Runway
sa-code	selective availability code
SAFI	Semi-Automatic Flight Inspection
SAPPHIRE	Satellite and Aircraft Database Programme for System Integrity Research
SatCom	Satellite Communication
SDF	Simplified Directional Facility
SEQ	Sequential Receiver
SID	Standard Instrument Departures
SNR	signal-to-noise ratio
sps	standard positioning service
STAR	Standard Terminal Arrival Routes
STNA	Service Technique de la Navigation Aérienne
SU	Storage Unit
TACAN	Tactical Air Navigation System
TDOP	Time Dilution of Precision
TRSB	Time Reference Scanning Beam
UTC	Universal Time Code
VASI	Visual Approach Slope Indicator System
VPDGPS	very high precise differential global positioning system
VDOP	Vertical Dilution of Precision
VFR	Visual Flight Roules
VGSI	Visual Glide Slope Indicators
VOR	Very high frequency Omnidirectional radio Range
VORTAC	VOR and TACAN
WAAS	Wide Area Augmentation System
WADGPS	Wide Area DGPS
WGS-84	World Geographic coordinate System 1984

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DGPS (Differential Global Positioning System)

14. Abstract

Civil as well as military aviation relies on a number of radio navigation systems including satellite systems in space. As new systems are developed extensive flight testing is needed to ensure that the design parameters are met. The approval of every new installation is dependent on flight tests. Moreover all installations require flight inspection in well-defined time periods. The development and application of cost effective flight test techniques and instrumentation systems including the test aircraft are presented. Room is given also to the adverse effects of radio wave propagation like multipath.

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