Integrated Navigation, Communication, and Surveillance Systems Based on Standard Distance Measuring Equipment

A. Becker*
Deutsche Forschungs-und Versuchsanstalt für Luft- und Raumfahrt e.V. Braunschweig, Federal Republic of Germany

Distance measuring equipment (DME) is an approved means of short-range navigation in international civil aviation. Because, in most applications, it utilizes the inherent capacity of the system to a relatively small degree, additional functions can be integrated into the system, i.e., data links, ground-derived slant range measurement equipment, and direction finders (growth potential). Thus, the DME can be extended to an integrated navigation, communication, and surveillance system. For technical, as well as economic and operational, reasons, such a system may be superior to conventional solutions that use separate systems for the different functions. Integrated systems can be composed in different ways using different sets of the DME growth elements. Two promising sets are described and applied to a scenario of helicopter operations to oil rigs. The key elements of the system will be realized in the hardware and flight tested at DFVLR in Braunschweig.

Nomenclature

A/G-SDL	= air-to-ground selective data link
ATC	= air traffic control
DAS	= DME-based azimuth system
DLS	= DME-based landing system
DME	= distance measuring equipment
DME/P	= precision DME
G/A-BDL	= ground-to-air broadcast data link
G/A-SDL	= ground-to-air selective data link
ILS	= instrument landing system
INCS	= integrated navigation, communication, and surveillance system
MLS	= microwave landing system
NDB	= nondirectional radio beacon
SSR	= secondary surveillance radar
STW-DME	= scanning three-way DME
TMA	= terminal maneuvering area
TTW-DME	= trilateration three-way DME
TW-DME	= three-way DME
VOR	= vhf omnidirectional radio range

Introduction

THE tasks of navigation, communication, and surveillance in international civil aviation are supported by systems such as VOR, NDB, DME, ILS, and SSR. These systems are standardized by the International Civil Aviation Organization the (ICAO) and are in worldwide use. Such systems as the MLS and DME/P will be introduced in the near future. These systems have been well tested and proved. The high degree of safety in today's civil aviation results from the reliability of the equipment and the knowledge gained in their operation.

However, provision for different systems covering the various phases of a flight cannot be the optimum solution. Each system is useless during some phase(s) of the flight, but still adds weight to the aircraft, takes up space, and consumes power. This is not the case with integrated systems, which use the same components (transmitters, receivers, antennas) for as many functions and in as many flight phases as necessary. Thus, weight, space, and power consumption, as well as cost, can be reduced considerably. For reliability reasons, however, the key components should be built in a redundant configuration in order to prevent a breakdown of the total integrated system when one component fails. Thus, the same or even greater reliability can be obtained with integrated systems as compared to conventional systems.

The advantages of integrated systems are particularly apparent for those applications where international standardization is not mandatory and where amortization of expensive installations already in use is not required. This is the case in large developing countries that want to improve their infrastructure with a national air network. Another potential application is the helicopter traffic with off-shore oil rigs.

Several investigators have proved the DME to be a promising base for an integrated system.[1-5] In this paper, two different concepts of an integrated navigation, communication, and surveillance system are developed using the growth potential of the DME. The expected performance and advantages of integrated systems, as well as the components of the experimental hardware, are discussed.

Growth Potential of the DME

The DME is a well-proved component of air navigation systems that was introduced in 1959 and standardized internationally since then. The standards now are extended to the DME/P, a component of the new MLS. Both the DME and DME/P will be used far beyond the year 2000.

It is well known that in most applications the pulse space of the DME is used to only a small degree. Therefore, additional functions can be integrated into the system by inserting further pulses into the signal format. These pulses can be modulated with the desired information (e.g., by pulse position modulation). Moreover, additional information can be derived from the conventional DME signal in space. These are the azimuth and the elevation angles, respectively, of the received DME interrogation wave on the ground that indicate the direction to the aircraft. All of these additional functions can be obtained without loss of compatibility with the standard DME. The requirements for the pulse shape and rf spectrum[6] are maintained. Some of the these additional functions were already realized with the DLS[1] and DAS.[3]

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*Head, Radio Navigation and Information Processing Branch, Institute for Flight Guidance and Control.

A set of possible DME growth elements is described in Ref. 4. The two configurations of an integrated navigation, communication, and surveillance system (INCS), which will be defined below, make use of the following DME growth elements: three-way DME (TW-DME), air-to-ground selective data link (A/G-SDL), ground-to-air selective data link (G/A-SDL), ground-to-air broadcast data link (G/A-BDL), scanning three-way DME (STW-DME), and trilateration three-way DME (TTW-DME).

Three-Way DME (TW-DME)

The TW-DME is an extension of the standard DME. It provides the slant range information on the aircraft as well as on the ground. The principle is shown by Fig. 1 and the signal format can be taken from Fig. 2.[2]

In Fig. 1, the airborne DME interrogates the ground transponder (route 1). The ground transponder transmits a reply pulse pair back to the aircraft (route 2). Thus, the pulse travel time (which is proportional to the slant range) can be measured onboard the aircraft. This is the basic function of the standard DME. In the case of the TW-DME, however, the reply pulse pair is supplemented by a third pulse, the so-called marking pulse. Simultaneously, a time counter is started on the ground. When the onboard equipment detects the marking pulse, the airborne transmitter sends a further pulse pair (route 3). After detection of this pulse pair at the ground station, the counter is stopped. The slant range information is thus also available on the ground. In order to distinguish between the pulse pairs of routes 1 and 3, the pulse spacing is different. A reply of the transponder to a received pulse pair will be initiated only by the ICAO standardized pulse spacing on route 1. Thus, the compatibility with the standard DME is maintained.

The signal format of the TW-DME can be taken in a simplified form from Fig. 2, where the events on both the aircraft and the ground are indicated. The horizontal axis is the time. The transmitting time 1 of the airborne interrogation is the reference for the onboard pulse travel time measurement (shown in Fig. 2 as a 1 inside a ∇). The pulse pair arrives on the ground after the time interval τ_1. The reference for the travel time measurement on the ground is shown as a 1 inside a Δ. The ground station transmits the reply pulse pair (standardized fixed delays are neglected in Fig. 2) and adds the marking pulse after approximately 50 μs. When the pulse pair arrives, the onboard time measurement is stopped and the slant range information can be read out for further processing and display. After recognition of the marking pulse,† the airborne equipment again transmits a pulse pair. As already explained, this pulse pair must have a larger spacing. When it arrives on the ground, the corresponding time measurement is stopped. The slant range information can be read out for further processing.

In order to assign the reply pulse pairs on route 3 (see Fig. 1) to the right aircraft, a marking dead time must be introduced on the ground. During this dead time, the received interrogations create a reply pulse pair but no further marking pulse, prohibiting a reception of a route 3 pulse pair from another aircraft. The marking dead time of the TW-DME must be at least greater than or equal to $2 \cdot \tau_{1\max}$, which is the pulse travel time at the maximum operational distance of the aircraft. Figure 2 also shows the position of the coding windows of the incorporated data link, which are explained below. Obviously, confusion also occurs when the data pulses of different aircraft are intermixed. Therefore, the marking dead time must be enlarged to $(2 \cdot \tau_{1\max} + \tau_{h0} + \tau_{h\max})$, where τ_{h0} is the relative beginning of the height coding window and $\tau_{h\max}$ the length of this window.

†Obviously, a certain time interval is needed for detection of the marking pulse. Therefore, a fixed time delay must be applied before route 3 can be initiated. This delay is suppressed in Fig. 2 for clarification of the main principle.

The signal format of the TW-DME is compatible with that of the standard DME. That means that an aircraft fitted with a standard onboard DME will get the standard DME service by the TW-DME ground transponder. However, for obtaining the additional surveillance service, TW-DME airborne equipment must be installed.

Obviously, the TW-DME uses the transmitters, receivers, and antennas of the airborne and ground equipment. Only the control logic must be extended. On the ground, the time counter and its associated periphery must be provided. For reasons of hardware minimization, these functions should be integrated into the standard airborne DME and the standard DME ground transponder. With experimental equipment or equipment produced in low quantities, however, the use of supplements to the standard DME is preferrable, as is supposed in Fig. 1 (as well as in Figs. 9-11 below). Then additional hardware must be provided for the supplements in order to minimize interface problems between the units. The standard DME, however, remains as is.

Air-to-Ground Selective Data Link (A/G-SDL)

The A/G-SDL is intended to transmit data from an individual aircraft to the ATC center on the ground. The applied principle and signal format can also be taken from Figs. 1 and 2, respectively. In Fig. 1, the altitude and the identification code of the aircraft are shown to be transmit-

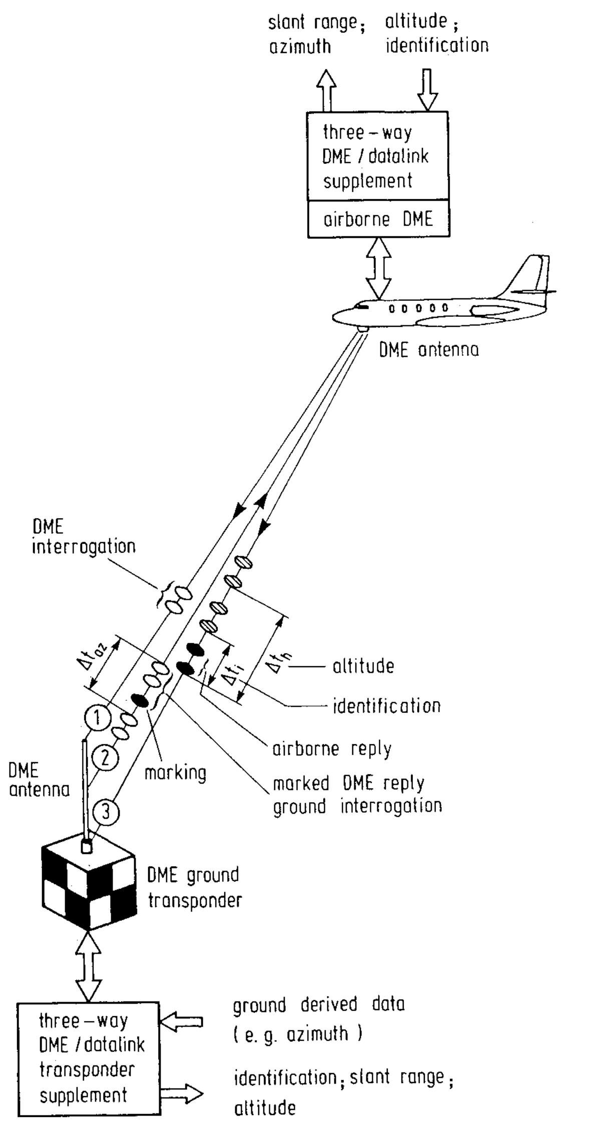

Fig. 1 Principle of the three-way DME with integrated air→ground and ground→air selective data links.

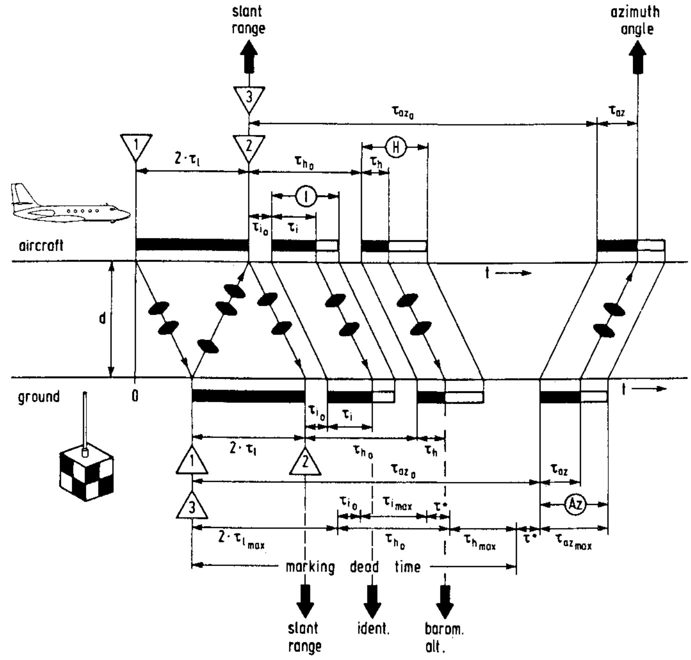

Fig. 2 Signal format for the three-way DME with integrated air→ground and ground→air selective data links.

ted to the ground on route 3 by the pulse position modulation of two additional pulse pairs. The airborne reply of the TW-DME is used as a time reference for the pulse position coding. The signal format is presented in Fig. 2. A coding window I is assigned to the identification and window H to the altitude where 2 is used as the time reference, as noted in the symbol table in Fig. 2. The decoding windows have the same relative position as on the aircraft. The corresponding delays τ_i and τ_h are decoded and represent the identification and altitude, respectively. At those points in time marked in Fig. 2 by a downward pointing arrow, the measured or transmitted data are available on the ground for further processing.

Ground-to-Air Selective Data Link (G/A-SDL)

The G/A-SDL is intended to transmit data from the central station on the ground to an individual aircraft. The principle corresponds to that of the A/G-SDL described above. It is also illustrated by Figs. 1 and 2. In both figures, only one type of information is shown to be transmitted by this data link. This is the azimuth angle, which is calculated from the such ground-derived aircraft position. This position is known from such further growth elements as the scanning three-way DME or trilateration three-way DME (see below). Obviously, the principle of ground-to-air data transmission can be extended to more data if needed.

The encoding principle becomes obvious from Fig. 1. The DME reply of the ground transponder is followed by a further pulse pair. The time delay Δt_{az} carries the azimuth information to be transmitted. The signal format is shown in some more detail in Fig. 2. The coding and decoding windows are referenced to the point in time 3 as noted. The fixed time interval τ_{az0} that determines the beginning of the azimuth coding window must be sufficiently wide. Even at the largest specified slant range, an overlapping with the decoding windows of the A/G-SDL must not occur. The transmitted azimuth angle can be used on board for further processing.

One inherent problem of the G/A-SDL is discussed below. The data pulse pairs are applied to route 2 of the DME or TW-DME. The transponder reply pulse pair is the reference for the pulse position coding. As the ground transponder communicates with a number of aircraft, the association of a received airborne interrogation pulse pair to the interrogating aircraft is not possible without further information. Therefore, the ground data assigned to the interrogating aircraft cannot be identified and coded. With the DLS[1] and DAS,[3] the problem did not exist because the information to be transmitted to the aircraft was developed from the interrogating pulse itself, namely the azimuth angle and the elevation angle of the received rf wave front. This information was available a few milliseconds after reception of the interrogation at the coding windows of the G/A-SDL. Thus, the azimuth and elevation information could be correctly transmitted without the need of identifying the associated aircraft. But other information not physically related to the received interrogation could not be transmitted with those systems. The situation changes, however, when a A/G-SDL is incorporated into the system. From Fig. 2, it can be assumed that the interrogating aircraft is already identified on the ground when the coding window of the G/A-SDL begins. Thus, any data can be transmitted to this aircraft.

Ground-to-Air Broadcast Data Link (G/A-BDL)

The G/A-BDL provides all aircraft served by the ground station (ATC center) with the same set of data (e.g., wind direction and wind speed at the airport, identification of runway in use, status of navigational ground equipment, geographic coordinates of the ground station), each element of the set being identified by a special word. The principle and the signal format of the G/A-BDL is illustrated by Fig. 3. Each piece of information to be transmitted is coded in two data words: identification and information. Both are coded by the position modulation of pulse triplets. By the use of pulse triplets instead of pulse pairs, the pulses can be easily identified on the aircraft as coding elements of the G/A-BDL.

The transmission is started with the time reference triplet. After a short time interval τ_{w0}, the coding window for the identification word begins. Within this window, a second pulse triplet is transmitted, the position of which carries the identification. In order to obtain a reliable decoding of adjacent positions, the coding is performed in relatively coarse steps of 4 μs. Even under noisy conditions, the decoding can be done with a very low error probability. Given a coding window width of 400 μs, 100 different identification words can be resolved. A second coding window is provided for the information contents. The position of a third pulse triplet is placed within this window according to the data value. When the same low error probability shall be obtained, the same

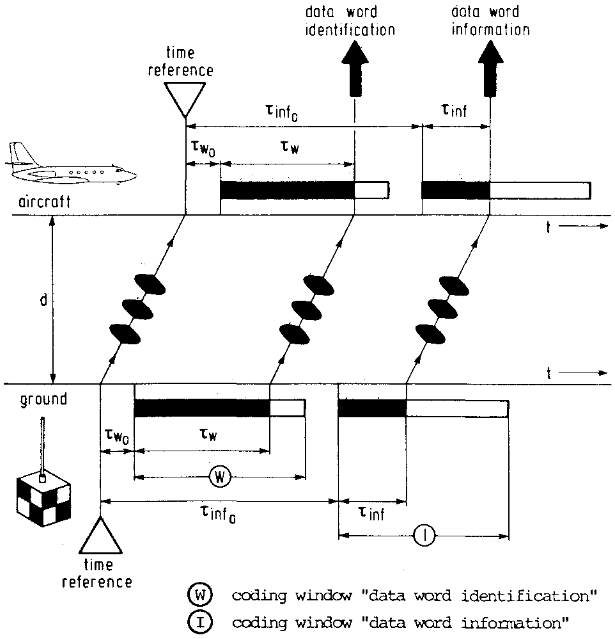

Fig. 3 Signal format for the ground→air broadcast data link.

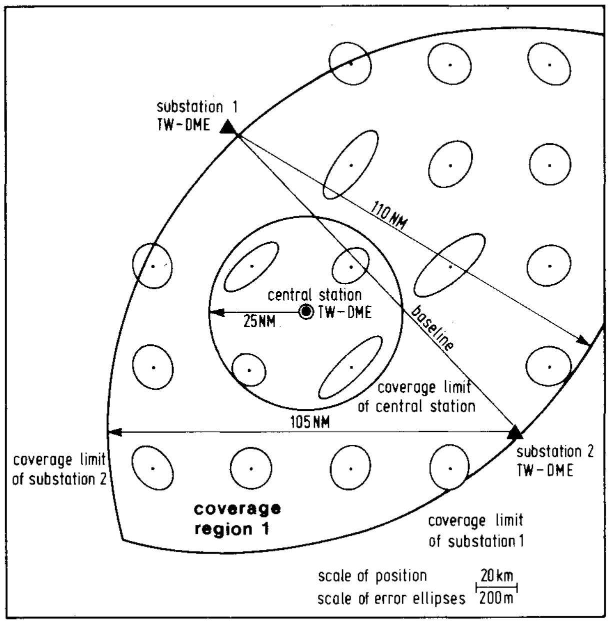

Fig. 5 Error ellipses with STW-DME in the Ekofisk scenario, coverage region 1: barometric altitude 500 m; assumed standard deviation of TW-DME measurements 100 m; and assumed standard deviation of altitude measurements 100 m.

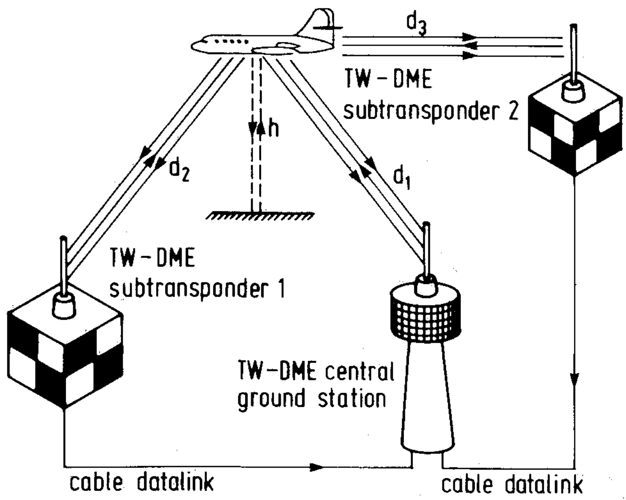

Fig. 4 Principle of the scanning three-way DME (STW-DME).

width of the coding steps must be applied. Thus, a coding window width of another 400 μs allows for 100 information steps. For reasons of hardware simplification, the following regulations for the pulse spacing of the pulse triplets are chosen: the pulses are equally spaced and the spacing corresponds to the mode of the DME channel.[6]

Scanning Three-Way DME (STW-DME)

The STW-DME is an extension of the three-way DME (TW-DME) to a complete position measuring device. The principle is shown in Fig. 4. On the ground, several (at least two) TW-DME ground stations are located about 10 km or more apart. The airborne TW-DME equipment makes use of the well-known scanning principle, i.e., it scans from one frequency channel to the next, thus interrogating the ground stations one after the other. On the aircraft, the measured slant ranges to the ground stations can be processed in the airborne computer or in the flight management system in order to get the position of the aircraft in the same way as with the well-known scanning DME (see also Fig. 9). The height calculation is supported by the barometric altitude measurement available on the aircraft. This is mandatory because of the poor height accuracy of trilateration measurements at low elevation angles of the aircraft with respect to the ground stations.

Each ground station measures the corresponding slant range to the aircraft (see also Fig. 10). Assuming that the TW-DME is supplied with an integrated air-to-ground selective data link (A/G-SDL) (see Figs. 1 and 2), the aircraft's identification and the barometric altitude are also available at each ground station. These data sets can be linked via telephone cables to the central station. Here, the calculation of aircraft's position can be made in the same manner as on board.

At a minimum, two ground stations are needed for the STW-DME. However, the more ground stations used, the higher the accuracy of the position calculation. This is because of the use of the least squares method. On the other hand, obviously the cost of the ground system increases in proportion to the number of ground stations.

With only two ground stations, some drawbacks have to be accepted. To begin with, an ambiguity in the position calculation must be resolved. This is often possible when the coarse position is known from other sources. Further, the accuracy of the position calculation is poor at points close to the baseline between the ground station.[7,8] This can be accepted when this critical area is not used for aircraft operations.

In Fig. 5, the error ellipses of STW-DME are shown for an application that will be discussed later in greater detail. The position of the ground station and their coverage limits are indicated. Within the inner circle having a radius of 25 n.mi., the reception of three TW-DME ground stations is possible. Thus, fairly good accuracy can be obtained, especially in the operationally relevant areas and there is no ambiguity. However, outside the coverage limit of the central station, an ambiguity problem does exists. From the measurements alone, one cannot tell what the real and image positions are. The baseline between substations 1 and 2 is the specular line. However, the real position can easily be identified because the coarse position is known from the unambiguous determinations of the previous positions. Again, a good accuracy can be obtained in the area of operational relevance up to the coverage limits of both substations.

(Operational relevance is given for a flight corridor from Forus ATC center toward the Ekofisk center, see Fig. 6.)

In Fig. 5, the assumed standard deviation (SD) of the TW-DME measurements of 100 m is rather pessimistic for modern equipment. Given a lower SD for the TW-DME, the axis of the error ellipses will decrease proportionally. In Fig. 5, the SD of the TW-DME is assumed to be independent of range. This assumption is essentially true for modern DME equipment using digital signal processing. Near the coverage limit, however, a slight degradation due to the influence of noise may occur. In this area, the error ellipses are somewhat optimistic.

Trilateration Three-Way DME (TTW-DME)

The TTW-DME is another extension of the TW-DME. Like the STW-DME, it has the capability of multiple slant range measurements on the ground and thus the capability of a complete position determination of the aircraft by trilateration. However, it uses only one DME channel, thus saving DME frequencies. Moreover the hardware expense is expected to be lower. On the other hand, a line-of-sight rf connection between the substations and the ground central station is required, thus limiting the base length of the ground system (see below).

The principle can be taken from Fig. 7 (compare with Figs. 9 and 11). The aircraft and the central ground station are linked via a TW-DME. The three routes are indicated by 1, 2, and 3_1. In addition, two substations are positioned at exactly known locations having the distances a_1 and a_2 from the central station. These subsystems consist mainly of DME receivers that are tuned to route 3 of the TW-DME. Thus, the pulse pairs of route 3 not only generate trigger pulses in the central ground station, but also in both substations. These trigger pulses are transmitted by a wide band rf link to the central ground station. The pulse travel time measurements on the ground now can be made via three different paths,

1) Route 2 + route 3_1 (TW-DME)$\rightarrow d_1$.
2) Route 2 + route 3_2 + $a_1 \rightarrow d_2$.
3) Route 2 + route 3_3 + $a_2 \rightarrow d_3$.

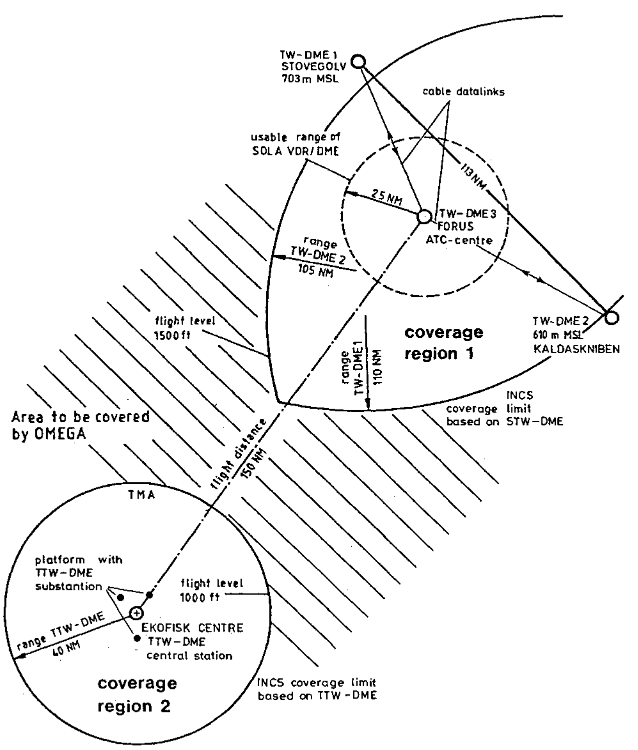

Fig. 6 Off-shore installation Ekofisk with INCS installations on the base of the STW-DME and TTW-DME, respectively.

Measurement 1) provides the slant range d_1. Measurements 2) and 3) can be used for the determination of d_2 and d_3, respectively, by taking into account the known distances a_1 and a_2, as well as the already measured slant range d_1. From these slant ranges, the position of the aircraft is calculated with respect to the central ground station.

Again, the z coordinate of the aircraft at low elevation angles can be obtained with only poor accuracy, as in the case of the STW-DME. Therefore, a direct measurement of the altitude (barometric or radio) is provided on the aircraft. This altitude is transmitted to the ground by an integrated air-to-ground selective data link (A/G-SDL).

Similar to the STW-DME, one central ground station and one substation are needed at a minimum for the TTW-DME. However, the ambiguity problem then has to be solved. Moreover, areas with poor position accuracy have to be accepted. With one further substation (see Fig. 7), the set of position coordinates is already redundant. Thus, the method of least squares can be applied to the position calculation algorithm. For further improvement of the integrity of the system, a third substation can be added. Then, errors caused

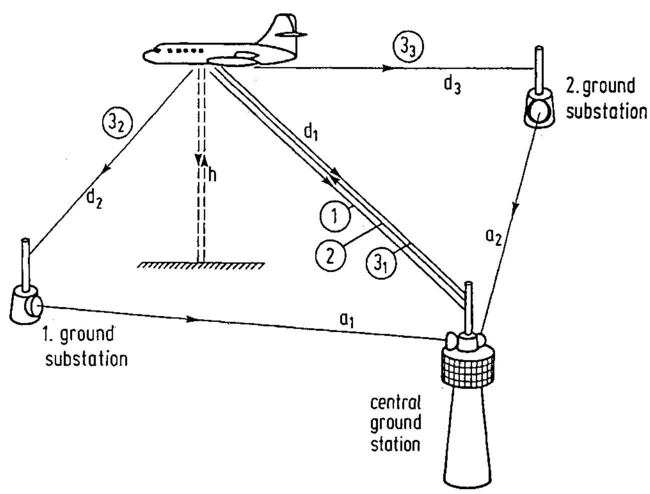

Fig. 7 Principle of the trilateration three-way DME (TTW-DME).

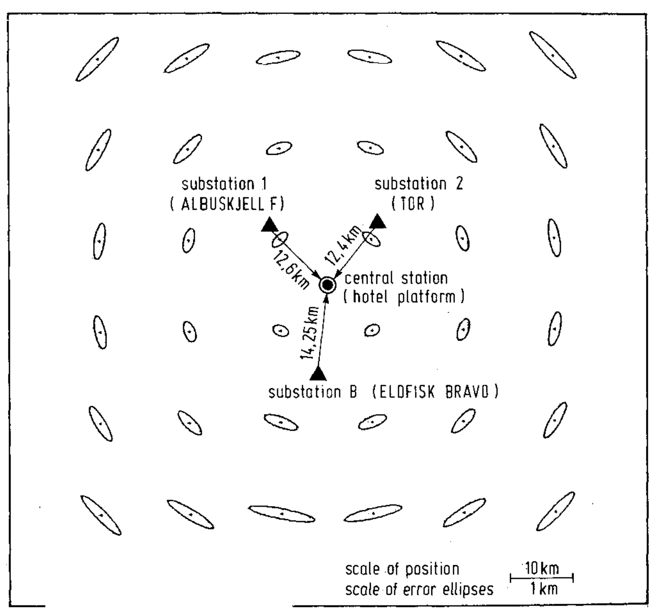

Fig. 8 Error ellipses with TTW-DME in the Ekofisk scenario, coverage region 2: barometric altitude 300 m; assumed standard deviation of TW-DME central station measurements 100 m; assumed standard deviation of slant range measurements via substation 173 m; and assumed standard deviation of altitude measurements 100 m.

by ground antenna shadowing or multipath wave propagation can considerably be reduced. Therefore, in Fig. 6 (coverage region 2) and Fig. 11 below, a configuration utilizing one central station and three substations is chosen.

The error ellipses for a TTW-DME installation with three substations are shown in Fig. 8. This installation is part of a system to be described later. Within the triangle formed by the three substations, the length of the axes of the ellipses are roughly of the order of the standard deviation (SD) of the basic TW-DME measurements. Outside the triangle, the error behavior approaches that of a ρ/ϑ navigation system (e.g., VOR/DME) with respect to the central ground station. The lengths of the smaller axes are slightly smaller than the SD and approach $1/\sqrt{2}$ at large ranges. The larger axes of the error ellipses increase linearly with the range.

The basic assumptions for the error calculation are given by the notes in Fig. 8. It can be shown that the slant range measurement to a substation is less accurate than the direct TW-DME measurement with the central ground station by a factor of $\sqrt{3}$. This is because the algorithm for determining the slant ranges to the substations use the direct slant range measurement with the central ground station. Therefore, the error of the latter measurement adds to the error of the slant range measurement with the substations. The assumed SD of the TW-DME of 100 m is rather pessimistic, as already mentioned for the example illustrated in Fig. 5. With a lower SD, the axes of the error ellipses will decrease in proportion. The conclusions concerning the accuracy degradation of the STW-DME at the limits of coverage are also true for the TTW-DME.

Integrated System Assessment

The conventional systems used for the navigation and the surveillance tasks are the NDB, VOR, DME, and SSR. These systems are in worldwide use and standardized by ICAO. As already outlined in the introduction, however, an integrated navigation, communication, and surveillance system (INCS) offers potential advantages for technical as well as operational and economic reasons.

In the following, two different versions of an INCS are proposed, incorporating different sets of the DME growth elements described above. Both versions offer the following advantages compared to conventional systems:

1) Higher update rate of the surveillance measurements.
2) Higher accuracy because of redundant measurements.
3) Good integrity because of redundant measurements.
4) Only one system in use during the mission; no switching and tuning of different units.
5) Considerable savings of equipment cost and installation cost, on the aircraft as well as the ground.

These advantages should be taken in all cases where ICAO standards are not required. Potential applications are, e.g., domestic air traffic nets in developing countries and helicopter operations with off-shore oil rigs. A proposal is made in the next section for the latter application. An equipment description of the two proposed INCS versions for this application follows (compare also Table 1).

The backbone of both versions is the three-way DME (TW-DME) with integrated air-to-ground (A/G-SDL) and ground-to-air (G/A-SDL) selective data links (see Figs. 1 and 2). The ground-to-air broadcast data link (G/A-BDL) (see Fig. 3) is also integrated into both versions.

The main difference is the method of determining aircraft's position. As version 1, the scanning three-way DME principle using one central ground station and two substations (see Figs. 4, 9, and 10) is proposed, while the trilateration three-way DME using one central ground station and three substations is proposed as version 2 (see Figs. 7, 9, and 11). It should be mentioned that for version 1 the G/A-SDL can be omitted because the slant ranges to all ground stations as well as the altitude are measured directly on the aircraft. Thus, the position of the aircraft can be calculated by the onboard computer. Version 2, however, needs the G/A-SDL for transmission of the ground-derived azimuth angle. Table 1 shows that the information provided on the aircraft as well as on the ground is complete for the tasks of navigation and surveillance. With respect to the system performance, Table 1 is self-explanatory. Obviously,

Table 1 Comparison of INCS versions 1 and 2

Aspect of comparison	Version 1	Version 2
DME growth elements	STW-DME A/G-SDL G/A-BDL	TTW-DME A/G-SDL G/A-SDL G/A-BDL
Information provided on aircraft	Slant range aircraft-central ground station	
	Slant range aircraft substations	Azimuth angle relative to central ground station
	Broadcast ground information	
Information provided on ground	Slant ranges of all aircraft (relative to the central ground station)	
	Slant ranges of all aircraft (relative to the substations)	
	Identifications of all aircraft	
	Barometric altitudes of all aircraft	
Performance coverage	Hemispherical	
accuracy	Proportional to the accuracy of the basic DME (See Fig. 5)	(See Fig. 8)
Degree of redundancy, n		
position determination	0-1	2
A/G-SDL	1-2	3
G/A-SDL	Not applicable	0
G/A-BDL	1-2	0

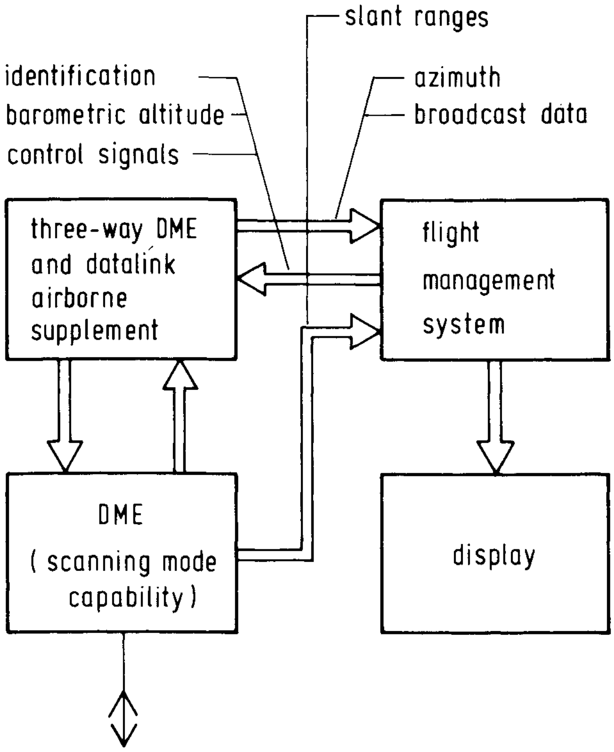

Fig. 9 Block diagram of the INCS airborne installation.

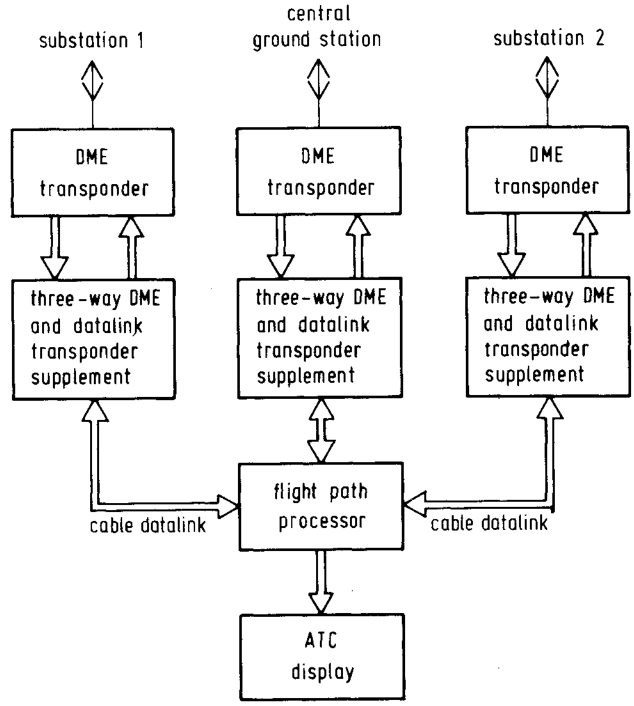

Fig. 10 Block diagram of the INCS ground installation, coverage region 1, based on the STW-DME.

the accuracies, which can be taken from Figs. 5 and 8, respectively, are proportional to the accuracy of the DME that is the basis of the TW-DME. If a precision higher than that assumed in Figs. 5 and 8 is given, the axis of the error ellipses will decrease in proportion (e.g., with DME/P). At the bottom of Table 1, the degree of redundancy of the different functions is noted. Degree n means that n links can fail without loss of the required information. Obviously, version 2 is very protected against transmission errors affecting the surveillance function. On the aircraft, however, the navigation information is not redundant.

An important parameter in an INCS is the update rate of the navigation and surveillance information. It is well known from the DME that at high interrogation rates, i.e., at high traffic load, the reply rate is reduced to a certain extent. This situation is given when a large number of aircraft interrogate the ground station. There are different reasons for this reduction, e.g., dead times in the system and pulse distortion by pulse overlapping.[5,6] Other DME-based systems like DLS[1] and DAS[3] are also subject to this effect. An INCS has to cope with another effect that contributes to the reduction of the sample rate, especially concerning the ground-derived data. Once the slant range measurement on the ground for one specific aircraft is started, a marking dead time follows (see Fig. 2). Interrogations from other aircraft arriving during this time interval will initiate a standard reply pulse pair in most cases, but never a marking pulse. Thus, a slant range measurement on the ground is possible for only one aircraft at a time. This mechanism causes a further reduction of the ground-derived update rate. A system with the signal format of Fig. 2 was investigated in detail,[5] which showed that 20 aircraft were served by the ground station at an average airborne measuring rate of 15/s, and an average measuring rate on the ground of 8.4/s, when an average airborne interrogation rate of 16/s is assumed.

Obviously, the reduction of the airborne update rate is negligible. The ground rate, however, is considerably reduced, but it still remains more than 50% of the airborne interrogation rate. The ground rate is well above the minimum update rate of 5/s required for navigation systems. This limit must be maintained when the navigational information is fed into the automatic flight control system. The situation is even more advantageous with respect to the surveillance function. The rate of 8.4/s is 34 times higher than the low update rate (i.e., 0.25/s) of conventional secondary surveillance radar (SSR), which is the international surveillance system. Therefore, even a quickly maneuvering aircraft can be tracked with sufficient accuracy on the ground.

It should be pointed out that the update rates given above are true for a TW-DME with integrated A/G-SDL and G/A-SDL, the signal format of which is given in Fig. 2. This configuration is the kernel of both INCS versions. The update rate of the different functions of both versions may be somewhat increased with the degree of redundancy (see Table 1).

The block diagrams of both INCS are given in Figs. 9-11. For reasons of system reliability, the installation on the aircraft as well as on the ground will be duplicated in applications where a high reliability of the navigation and the surveillance information is mandatory. Duplication is already common practice with conventional systems. Therefore, it is even more important for an INCS to provide redundant equipment in order to prevent a simultaneous breakdown of the navigation and the surveillance functions due to a single element failure.

Standard DME equipment is used for both installations, airborne as well as ground. In order to realize the additional growth functions, special supplements are provided on the aircraft and on the ground. Supplements should be preferred when only a few systems are needed (i.e., as experimental equipment). Special integrated equipment would be less complex; however, the development cost will pay off only at sufficient production quantities.

Figure 9 shows the block diagram of the INCS airborne installation. This installation can operate with both versions of the INCS ground installation. In the case of version 1, the DME operates in the scanning mode delivering three slant ranges directly to the flight management system (FMS). In the FMS, the barometric altitude information is available. Thus, the position of the aircraft can be evaluated. The result is displayed in conventional form on the display. The FMS provides the TW-DME equipment with the identifica-

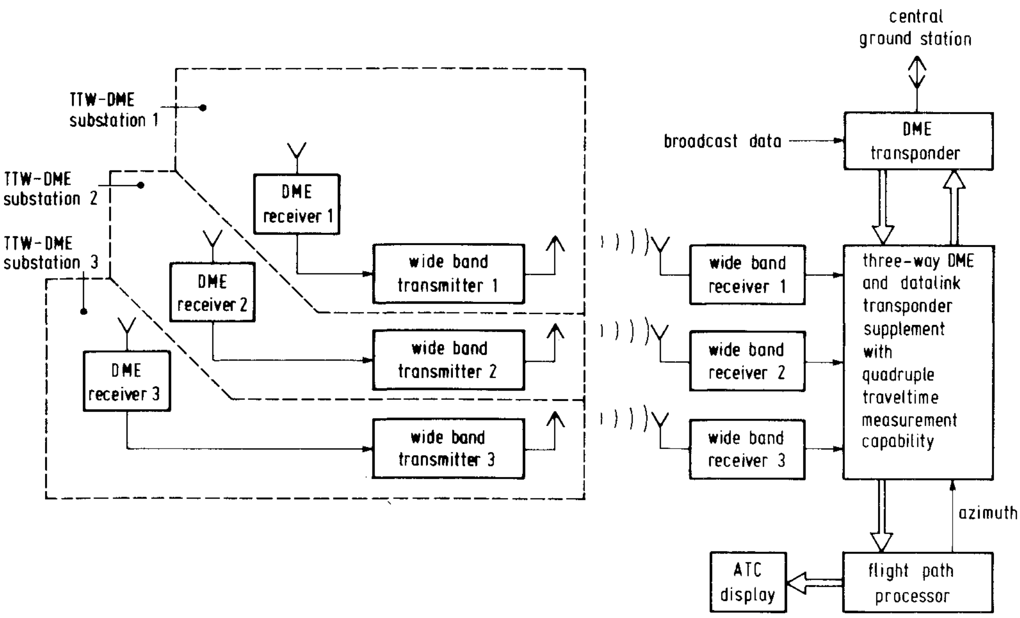

Fig. 11 Block diagram of the UNCS ground installation, coverage region 2, based on the TTW-DME.

tion and barometric altitude to be transmitted to the ground. Moreover, it provides the necessary control signals.

The corresponding ground installation is shown in Fig. 10. Each of the three ground stations is equipped with a conventional DME transponder and a TW-DME and data link transponder supplement. Thus, the corresponding slant ranges and the transmitted onboard data can be decoded. From the substations, these decoded data are transmitted to the central ground station via telephone cables. The flight path processor tracks the flight paths of all aircraft. The last part of each flight path attached with the identification and the flight level labels is displayed on the ATC display. The broadcast data are fed to all supplements and simultaneously transmitted to all aircraft in the coverage region.

In Fig. 11, the ground installation of INCS version 2 is shown. The airborne DME is now tuned to one frequency only, i.e., the frequency of the central ground station. The transponder supplement has the capability of a quadruple travel time measurement. Thus, the travel time can be measured for four different ways (i.e., direct and detours via the three substations) and the flight path processor can be provided with four slant ranges. The same equipment can be used for decoding the air-to-ground data. The evaluated flight path is transferred to the ATC display. In the flight path processor, the azimuth angle of the aircraft with reference to the central ground station is also evaluated and transmitted to the aircraft. Each substation consists of a DME transponder receiver. The trigger pulses at the output are transmitted via a wide-band rf channel to the central ground station. The requirements on this wide-band link are relatively low. Because of the fixed position of transmitter and receiver, antennas with high directivities can be used. Thus, transmitter power and receiver sensitivity can be kept low. Furthermore, no automatic gain control is required in the receiver because of the constant attenuation of the rf carrier wave.

Potential Application of an INCS for Helicopter Operations with Oil Rigs

One promising application of an INCS is serving the helicopter operations with off-shore oil rigs. This application will be demonstrated by the Norwegian Ekofisk field, which is located in the North Sea about 150 n.mi. off shore. The overall situation is shown in Fig. 6.

There are two coverage regions. Region 1 comprehends the flights between the helicopter base Forus on the Norwegian continent and the Ekofisk area, while region 2 covers a terminal maneuvering area (TMA) of 40 n.mi. radius around the central platform of the oil field. Between both coverage regions, a coverage gap must be accepted because of the large distance of 150 n.mi. between the Ekofisk center and the Forus ATC center. The gap must be covered by the long-range navigation system OMEGA. Its poor accuracy can be accepted in this phase of the flight.

The main requirement in coverage region 1 is a large range. Therefore, two ground stations are positioned on mountains near the coast about 110 n.mi. apart. Near the ATC center Forus, a third ground station is located. Obviously, the installation of the wide-band ground-to-ground data channels of a TTW-DME will become difficult because of the large distances between the ground stations. Line-of-sight conditions cannot be expected. Thus, the STW-DME principle is chosen for this region. The accuracy of this system can be derived from Fig. 5. The block diagram of the ground system corresponds to Fig. 10.

In coverage region 2, however, the advantages of the TTW-DME are obvious, especially the lower hardware costs. The positions of the central station and of the three substations are indicated in Fig. 8. The central station is installed on the top of the central platform, which is really a large hotel. Thus, a reliable rf connection to all helicopters within coverage region 2 can be guaranteed. The high degree of redundancy for the ground measurements assures a reliable and accurate position determination on the ground (see Table 1 and Fig. 8), even in the case of transmission interruption of one or even two substations (e.g., because of shadowing by obstructions).

The position accuracy on the helicopter is slightly worse compared to the accuracy on the ground illustrated by Fig. 8. The lateral accuracy corresponding to that of the transmitted azimuth angle is the same as on the ground. The range measurement, however, is performed by the single air-derived measurement of the onboard DME only, while on the ground the measurement is three-fold redundant.

The task of the INCS version 2 is to allow the helicopter to approach the helideck up to 0.5 n.mi. at a minimum height of 200 ft. The final approach and landing procedure will be performed visually. An automatic landing is not required for the near future. If, however, more precise navigation information should be required for the approach close to the helideck, the INCS must be extended accordingly. This could be done by installation of a DME/P on each helideck in combination with azimuth and elevation sensors similar to those used for the DLS.[1] The azimuth and elevation angles measured on the ground will be transmitted to the helicopter via the ground-to-air selective data link. The onboard equipment is the same as for INCS versions 1 and 2; however, the DME must incorporate the DME/P capability. Furthermore, an additional decoding window for the elevation information must be provided.

Hardware Development and Experimental Investigations

Hardware development and experimental investigations are of utmost importance for any new concept. Although basic experience with similar hardware and tests are already available from the DLS[1] program operated in 1974-1978, the main elements of both INCS versions are now being realized in hardware by the DFVLR Institute for Guidance and Control in Braunschweig and by Standard Electric Lorenz (SEL) in Stuttgart. These elements are:

DME/P ground transponder (SEL)
Three-way-DME transponder supplement (DFVLR)
Airborne DME/P (SEL)
Airborne three-way-DME supplement (DFVLR)
Ground-to-air selective data link (SEL)
Air-to-ground selective data link (DFVLR)
Ground-to-air broadcast data link (SEL)
Flight path processor and ATC display (DFVLR)
Special test sets (DFVLR)
Ground and flight tests (DFVLR)

Tests are planned in 1986 at the Braunschweig, FRG, airport using the flight test facilities of DFVLR.

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