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AUTONOMOUS NAVIGATION SYSTEM FOR THE NEW GENERATION OF MILITARY HELICOPTERS AND ASSOCIATED FLIGHT TESTS

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1. Summary

The paper describes an integrated autonomous strapdown inertial navigator, augmented by a doppler velocity sensor and a magnetometer for helicopter application. To obtain height above ground. a radar altimeter is integrated into the navigation system. Accurate weapon delivery requirements and flight safety aspects while operating the helicopter under adverse weather conditions and at night demand the accurate determination of TAS throughout the entire speed regime.

Next to position, velocity and attitude, the strapdown system provides all signals required for stability augmentation and to support autopilot functions. The system communicates with the other avionics on board the helicopter through a dual MIL-STD 1553B bus and for redundancy purpose through an ARINC 429 interface with the AFCS directly.

Various flight trials using three different types of helicopters have been performed to demonstrate the navigation capability and performance of a hybrid strapdown navigator, a new analytical true air speed system for the low speed regime and the performance of a strapdown magnetometer.

2. Introduction

Modern military helicopters as e.g. the planned German-French PAH-2/HAP/HAC-3G and the NH-90/MH-90/SAR rotorcrafts require an autonomous precise and lightweight navigation system for enroute and highly dynamically NOE[1] flying.

The integration of GPS[2] into the navigation system should be anticipated as an option.

A cost effective solution to the autonomous 3D-navigation requirement for the motion envelope of a modern combat helicopter is in our opinion the combination of a medium accurate velocity and heading augmented IRU[3] using a barometer and a radar altimeter for inertial vertical velocity and height above ground determination.

As weight is much more important for rotorcrafts than for any other airborne vehicle it is quite obvious that all the information required for stability augmentation and autopilot functions should be provided by the navigation system as well. The IRU must therefore be mechanized in strap down technology using small and lightweight two degree of freedom mechanical gyros and force rebalanced accelerometers. With a dual IRU installation a very high integrity for the flight safety critical portion of the system could be achieved.

Alternate configurations as e.g. doppler augmented IRS[4] / SD-AHRS or doppler augmented

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[1] Nap Of the Earth

[2] Global Positioning System

[3] Inertial Reference Unit

[4] Inertial Reference System

[5] Ring Laser Gyro

RLG[5] SD-AHRS together with VG/DG[6] and rate gyros do not provide optimal solutions in terms of

- ⊙ integrity for stability augmentation
- ⊙ back up mode navigation accuracy
- ⊙ minimum alignment time
- ⊙ weight
- ⊙ cost

Normal mode navigation accuracy enhancement above the optimal configuration can only be achieved by a very low drift IRS. For the heading drift the following applies:

$$\varepsilon < \frac{K}{\frac{1}{\Omega\cos\phi} + t}$$

with:

Ω = 15.04 °/h ϕ = latitude of alignment t = duration of flight
K = heading error[7] achieved with proper calibrated magnetometer ($K \leq 0.25°$ 1σ)

The penalty for a possible navigation accuracy enhancement is weight, cost and at the most duplex redundant stability augmentation signal provisioning only.

Adverse weather, day and night operation and accurate weapon delivery requires the determination of TAS throughout the entire speed regime of the helicopter. As conventional pressure difference based methods are not applicable in the low speed regime (below 20 m/s) due to limited resolution of the available pressure differential measurement probes and the downwash, an analytical method[8] for the low speed regime has been designed and flight tested[9].

A system beeing able to suit the requirements listed above could be composed out of the following equipments:

- ⊙ 2 Strap down IRU's
- ⊙ 1 Doppler Velocity Sensor DVS
- ⊙ 1 Radar Altimeter (RAM)
- ⊙ 1 Magnetic Sensing Unit (MSU)
- ⊙ 1 TAS system for the low speed regime
- ⊙ 1 TAS system for the high speed regime

The performance required by such a strapdown hybrid navigator is listed in table 2-1 below

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6 Vertical Gyro / Directional Gyro

7 latitude independent

8 patent applied

9 LAASH (LITEF Analytical Air Data System for Helicopters)

Parameter		Range	Refresh-rate [Hz]	Accuracy (95 %) Requirement
Pitch	Θ	$-30 \div 45°$	50	.5°
Roll	Φ	$\pm$ 90°	50	.5°
Heading	Ψ_M	360°	50	.5°
True Heading	Ψ	360°	50	.5°
Velocity along	v_x	$-60 \div +400$km/h	50	.5%+.25kt
Velocity across	v_y	$\pm$50km/h	50	.5%+.25kt
Velocity vertical	v_z	$\pm$15m/s	50	.6%+.2 kt
geographic vertical	v_v	$\pm$15m/s	50	.6%+.2 kt
Ground speed	v_g	$-60 \div +400$km/h	50	.5%+.25kt
Acceleration	a_x	$\pm$.5g	50	.01g
Acceleration	a_y	$\pm$.5g	50	.01g
Acceleration	a_z	$-.5g \div +3.5g$	50	.01g
Angu-	p	100°/s	50	.25°/s
lar	q	60°/s	50	.25°/s
rates	r	100°/s	50	.25°/s
Position(Enroute)	p.p		6.25	2%
Position(NOE)	p.p		6.25	300m/1/4 h
Drift	δ	$\pm$90°	6.25	1°
Wind	v_W	$0 \div +150$km/h	6.25	1.2m/s
Direction	Ψ_W	$\pm$90°	6.25	1°
TAS	u	$-25 \div +100$m/s	12.5	2m/s
	v	$\pm$14m/s	12.5	2m/s
	w	$\pm$15m/s	12.5	1m/s
Temperature static	T_o	$-45 \div +70$°C	6.25	2°C+$\lvert T_s/100 \rvert$
Static pressure	p_o	$480 \div 1100$mb	6.25	3mb
Height above ground	z_{rs}	$0 \div 2500$ft	50	.5m o.5%
Target	WPT	$\pm$90°/$\pm$180°	12.5	0.5nm
Desired Track	DTK	$0 \div 360°$	6.25	1°
XTrack	XTK	$\pm$50km/h	6.25	1km
Track Angle Error	TKE	$\pm$100°	6.25	1°
Roll commanded	ϕ_c	$\pm$30°	6.25	0.1°
Turnrate	$d\psi/dt$	10°/s	12.5	0.6°/s

Table 2-1 Performance Requirements

Furthermore it is very much advisable to reduce the cost of ownership. This leads to highly reliable equipments and last but not least to a minimum use of special to type test equipment.

As normally magnetic sensors require a turntable for calibration and annual update of local magnetic variation, a calibration routine using a strapdown magnetometer has been designed[10] and flight tested, which eliminates calibration test equipment at all and logistic efforts for the annual update of magnetic variation.

An integrated helicopter navigator able to comply with the requirements listed above is described below. Its name is LHNS (Litef Helicopter Navigation System).

3. LHNS Description

The LHNS is a heading- and velocity augmented SD-IRU, providing 3-D navigation information in conjunction with a radar altimeter and calculates the wind vector by means of a TAS system for the entire speed regime of the helicopter. The latitude range is ±80° (UTM range).

The on ground alignment time is

- fixed base alignment time ≤ 2 min
- moving base alignment time approx. 5 min

Angular rates and linear acceleration in the body frame coordinate system for flight control and weapon delivery purposes are supplied by the SD-IRU. The autopilot functions are supported by the following signals:

- Radar altitude	h_R	- Inertial altitude	h_i	- Attitude	Φ, Θ
- Magnetic heading	Ψ_M	- True heading	Ψ	- Body velocities	v_x, v_y, v_z
- Doppler vertical velocity	v_{vD}	- Inertial vertical velocity	v_i	- Velocities in the navigation frame	v_E, v_N, v_v

[10] patent applied

Besides calculating the present position coordinates the following navigation functions are available:

- Bearing and Distance to the selected Waypoint
- Time to Go to this Waypoint based on the momentary speed
- Optimal steering information to the selected Waypoint
- Targets of Opportunity
- Position Update by flying over known landmarks whereby the position coordinates of these landmarks

  ⊙ are already stored

  ⊙ are read from the map and manually inserted after 'freezing' the position flown over

  ⊙ are gathered and inserted by means of a map-display after 'freezing' the position flown over

The position is calculated in geographical coordinates and will be distributed either in geographical or UTM coordinates depending on the crews request.

Coordinate insertion e.g. initial position coordinates and/or Waypoints could be accomplished in UTM or geographical coordinates as well.

Position coordinates calculated whilst landing are stored in an EEPROM and used as initial position coordinates prior to take off provided these coordinates

⊙ are not manually overwritten

⊙ are not automatically overwritten by GPS P-Code position

⊙ are not approximately identical with a stored waypoint

The LITEF designation of the SD-IRU is LHN-85, using two two degree of freedom DTG's[11] K-273 and three dry force balanced accelerometers B-280 together with the necessary instrument electronics and processing capacity to perform the strapdown and TAS algorithms, BITE, I/O handling, mode processing etc.

With the two LHN-85 SD-IRU's in the LHNS the following features can be achieved:

⊙ triplex configuration for p and q

⊙ duplex configuration for r and a_i

⊙ probability of two flight critical axis simultaneously simplex below 10^{-5}

⊙ duplex navigation capability

A comprehensive already successfully flight proven BIT takes care for the high failure detection rate.

The programme proposed by LITEF to calculate true heading from magnetic heading measured through the proposed magnetometer is an improved version of the "MAG VAR" software already successfully in service with the close air support version of the ALPHA JET.

However the method to compensate for the rotation dependent and constant error sources which otherwise will very much reduce the accuracy of the heading determination differs considerably from the method used in the ALPHA JET programme. With this new method it is no longer necessary to centrally update for the annual change in magnetic variation (approximately 0.2° pa in middle europe).

The calibration method[12] proposed can be carried out by the average army/navy pilot in the field without any additional test equipment. Furthermore it is not necessary any more to carefully align optically the DVS and/or the MSU. This is valid for the first installation and any subsequent possibly required exchange in the field.

This method is advantageous because

- there is no logistic effort for the annual update of the local magnetic variation
- there is no equipment required to optically align MSU and/or DVS
- there is no workload for the optical alignment of MSU and/or DVS

The land- and ship based operation of helicopters will require different calibration methods due to the larger iron masses aboard of ships. The calibration software in the

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[11] Dry Tuned Gyroscope

[12] Patent applied

LHNS could be made common for both versions.

In order to suppress high frequency emission which could cause premature detection both the RAM and the DVS will have the "RADAR SILENT" mode.[13]

The figures 3-1 ÷ 3-3 and the table 3-1 show the LHNS block diagram, the LHNS in- and output parameters, the LHNS interfaces and the most important installation parameters.

Figure 3-1 shows the LHNS as it will be proposed for the PAH-2/HAP/HAC-3G programme.

Figure 3-2 shows the modified LHNS with a GPS receiver and figure 3-3 shows a possible avionics architecture with the GPS receiver communicating with the helicopter avionics through the MIL-STD-1553B bus.

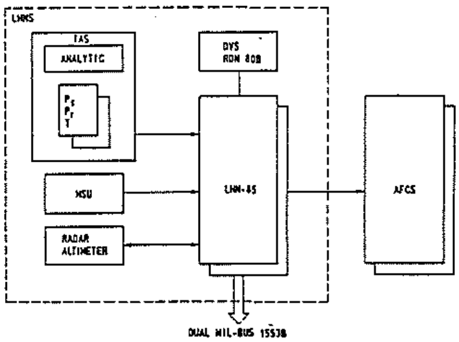

Figure 3-1 LHNS Block Diagram

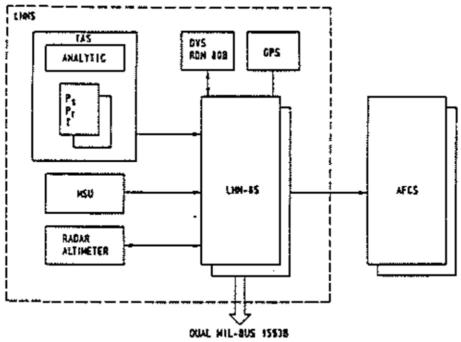

Figure 3-2 LHNS modified Block Diagram

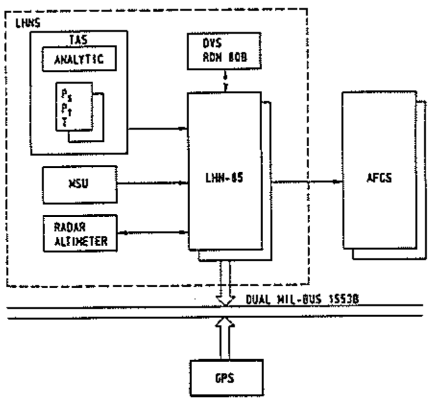

Figure 3-3 Block Diagram Avionics Architecture LHNS + GPS

Figure 3-4 displays the LHNS in- and output Parameters as intended to be proposed for the PAH-2/HAP/HAC-3G programme and figure 3-5 adds the GPS receiver as an input to the LHN-85 SD-IRU.

Map display and control- & display unit/functions are not part of the LHNS as to our understanding these functions are to be integrated into the multifunction display/keyboard equipment in the cockpit.

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[13] this mode can be entered manually and/or automatically under software control

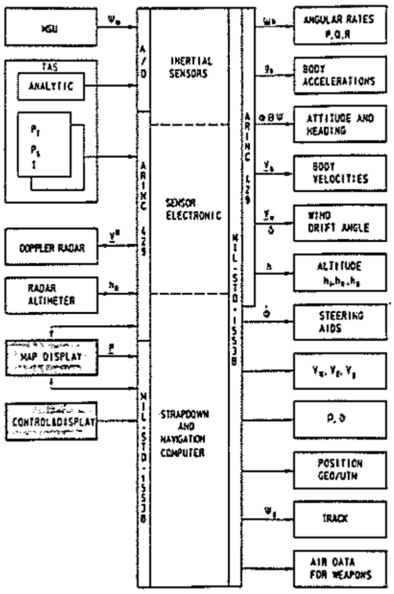

Figure 3-4 LHNS In- and Output Parameters

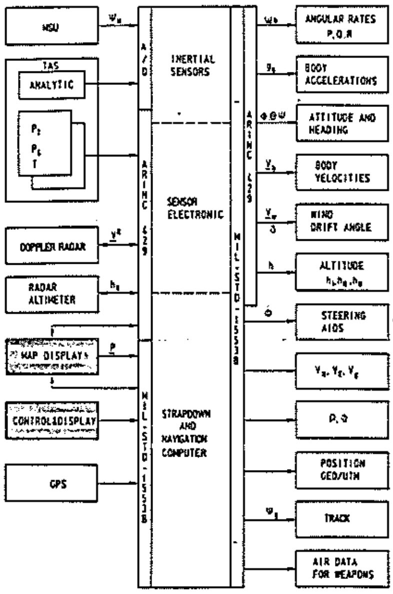

Figure 3-5 LHNS + GPS In- and Output Parameters

Avionic		LHNS						Avionic
		LHN-85 #1		MSU		LHN-85 #2		
		ANALOG	←	ANALOG	→	ANALOG		
		A/D	←	# 1	→	A/D		
		A/D	←	# 2	→	A/D		
		A/D	←	# 3	→	A/D		
				TAS				
				v<20m/s				
				Synchro				
		S/D	←	# 1	→	S/D		
		S/D	←	# 2	→	S/D		
		S/D	←	# 3	→	S/D		
		400 Hz	→	Exit.	←	400 Hz		
		ARINC		DVS		ARINC		
				ARINC				
		429 L	→	429 L	←	429 L		
		429 L	←	429 L	→	429 L		
		ARINC		RAM		ARINC		
				ARINC				
		429 L	→	429 L	←	429 L		
		429 L	←	429 L	→	429 L		
AFCS		ARINC				ARINC		AFCS
# 1	←	429 H		TAS		429 H	→	# 1
# 2	←	429 H		v>20m/s		429 H	→	# 2
		ARINC		ARINC		ARINC		
		429 L	←	429 L	→	429 L		
		ARINC		ARINC		ARINC		
		429 L	←	429 L	→	429 L		
		429 L	→	429 L	←	429 L		
		RTU		Map-		RTU		
MIL-BUS		MIL-BUS		display		MIL-BUS		MIL-BUS
BUS A	→	BUS A		(not		BUS A	→	BUS A
BUS A	←	BUS		part		BUS A	←	BUS
BUS B	→	BUS B		of		BUS B	→	BUS B
BUS B	←	BUS B		LHNS)		BUS B	←	BUS B

Figure 3-6 LHNS Interface Diagram

The interfaces of figure 3-6 show the flow of data, it is not an interwiring diagram.

Figure 3-6 does not show the interface to the GPS receiver which could be in accordance with MIL-STD-1553B or ARINC 429 or it could be fully integrated within the SD-IRU's.

The housings of the LHN-85 and the conventional air data equipment are supposed to be in accordance with ARINC 600 using the relevant rear rack and panel connector as this installation concept will be highly recommended for the PAH-2/HAP/HAC-3G programme.

Equipment/ Function	Designation	Housing (L,W,H)	Qty.	Mass [kg]	Power [W]
SD-IRU Mtg.prov.	LHN-85	4 MCU TBD	2 2	2x7,2 2x1,4	2x80
DVS	RDN 80 B	416x390x82	1	8,5	30
RAM	TBD	TBD	1	1,5	40
MSU	TBD	TBD	1	0,26	0,9
TAS v<20m/s	LAASH	na	1	0,16	≤ 1
TAS v>20m/s	TBD	2 MCU	1	3,2[14]	≤ 500[15]
Σ				30,82	

Table 3-1 LHNS Installation Parameters

The position of the LHN-85 in the helicopter is defined by the appropriate coding of four connector pins. This is necessary for the leverarm correction and the definition of the master IRU.

Reliability is very important and with the strap down technology a large and unexpected improvement was possible. Table 3-2 shows the reliability and the probability of failure for the individual equipments. These numbers are calculated in accordance with MIL-HDBK-217, but it should be mentioned, that the LTR-81 ARINC 705 strap down AHRS using the inertial instruments to be used in the LHN-85 SD-IRU has experienced a MTBF of more than 10.000 h within more than 400.000 equipment flying hours with the K-273 DTG's MTBF exceeding 139.000 hours.

Equipm./ Function	Des.	QTY	Reliability	Probability of Failure
SD-IRU Mtg.prov.	LHN-85	2 2	.99999986 na	1.38×10^{-7} na
DVS	RDN 80 B	1	.99984	1.6×10^{-4}
RAM	TBD	1	.99972	2.85×10^{-4}
MSU	TBD	1	.99998	2×10^{-5}
TAS v<20m/s	LAASH	1	.999931	6.9×10^{-5}
TAS v>20m/s	TBD	1	.999875	1.25×10^{-4}

Table 3-2 LHNS Reliability Figures

Using the reliability figures listed above the probability of failure for the different modes of operation as navigation, stability augmentation and autopilot functions has been calculated and is listed in table 3-3 below.

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14 2 Pitot-Static Tubes

15 De icing Pitot-Static Tube

Function	Param.	Probability of failure
Navigation	pp(ϕ,λ)	1.8×10^{-4}
Stab.Augmentation	r	1.38×10^{-7}
	p,q	1×10^{-11}
Auto pilot	Φ,Θ	1.5×10^{-7}
	$\underline{a}$	1.4×10^{-7}
	h_i	7×10^{-5}
	v_i	7×10^{-5}
	Ψ	2×10^{-5}

Table 3-3 Probability of Failure

3.1. Performance Parameters

Parameter		Range	Refresh-rate [Hz]	Accuracy (95 %) Requirement	LHNS
Pitch	Θ	-30 ÷ 45°	50	.5°	.25°
Roll	Φ	± 90°	50	.5°	.25°
Heading	Ψ_M	360°	50	.5°	.5°
True Heading	Ψ	360°	50	.5°	.5°
Velocity along	v_x	-60÷+400km/h	50	.5%+.25kt	.5%+.2kt
Velocity across	v_y	±50km/h	50	.5%+.25kt	.5%+.2kt
Velocity vertical	v_z	±15m/s	50	.6%+.2 kt	.2%+.1kt
geographik vertical	v_v	±15m/s	50	.6%+.2 kt	TBD
Ground speed	v_g	-60÷+400km/h	50	.5%+.25kt	.5%+.25kt
Acceleration	a_x	±.5g	50	.01g	.01g
Acceleration	a_y	±.5g	50	.01g	.01g
Acceleration	a_z	-.5g÷+3.5g	50	.01g	.01g
Angu-	p	100°/s	50	.25°/s	.2°/s
lar	q	60°/s	50	.25°/s	.2°/s
rates	r	100°/s	50	.25°/s	.2°/s
Position(Enroute)	p.p		6.25	2%	1.5%
Position(NOE)	p.p		6.25	300m/1/4 h	250m/1/4h
Drift	δ	±90°	6.25	1°	.5°
Wind	v_W	0÷+150km/h	6.25	1.2m/s	1.2m/s
Direction	Ψ_W	±90°	6.25	1°	1°
TAS	u	-25÷+100m/s	12.5	2m/s	2m/s
	v	±14m/s	12.5	2m/s	2m/s
	w	±15m/s	12.5	1m/s	1m/s
Temperature static	T_o	-45÷+70°C	6.25	2°C+¦T_s/100¦	2°C+¦T_s/100¦
Static pressure	p_o	480÷1100mb	6.25	3mb	3mb
Height above ground	z_{rs}	0÷2500ft	50	.5m o.5%	.5m o.5%
Target	WPT	±90°/±180°	12.5	0.5nm	0.5nm
Desired Track	DTK	0 ÷ 360°	6.25	1°	1°
XTrack	XTK	±50km/h	6.25	1km	1km
Track Angle Error	TKE	±100°	6.25	1°	1°
Roll commanded	ϕ_c	±30°	6.25	0.1°	0.1°
Turnrate	dψ/dt	10°/s	12.5	0.6°/s	0.6°/s

Table 3.1-1 Performance Parameters

The navigation performance displayed in table 3.1-1 is based on the LHNS without GPS. Using GPS the position error will be limited to the GPS position accuracy depending on the code used.

3.2. LHN-85

The LHN-85 SD-IRU uses two K-273 DTG's and three dry force rebalanced B-280 accelerometers. The main features are:

- 28 VDC input 80 Watts
- Duplex MIL-STD 1553B RTU
- Arinc 429 I/O
- A/D converter to accept magnetometer- and aircraft controls input for heading augmentation and low air speed determination
- MC 68000 family microprocessors
- 4 MCU housing with ARINC 600 mounting provisions

Figure 3.2-1 shows the LHN-85 Prototype

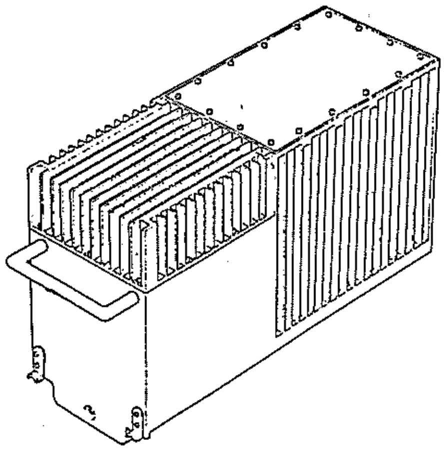

Figure 3.2-1 LHN-85

3.3. Control- & Display Unit

Modern military helicopters will have the control- and display functions required to operate the LHNS integrated into the MFD and MFK[16] of the cockpit. It is anticipated, that a map display is integrated as well.

3.4. LAASH

LAASH[17] is based on the experience that collective pitch represents the horizontal true airspeed of a helicopter in the low speed regime. This has been proven in many flight test hours with a BO-105[18]. Proper designed algorithms using along and across cyclic pitch information allow the determination of along and across TAS at an accuracy of approximately 2 m/s 95 % probability in the low speed regime up to 20 m/s.

To our knowledge these are worldwide the first flight tests with an analytical system of the accuracy class of 2 m/s 95 % probability. The VIMI system has not been designed to meet this accuracy requirement.

3.5. Doppler Velocity Sensor

The RDN 80 B is a three beam janus type FM/CW doppler velocity sensor manufactured by ESD. This DVS is widely used by the french armed forces[19] in most of their helicopters.

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[16] MFD Multi Funktion Display / MFK Multi Funktion Keyboard

[17] patent applied

[18] These flight tests have been performed at the flight test center of the DFVLR (Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt) in Braunschweig

[19] for navy application this DVS has a very high proven "false lock on" detection capability over calm water

This DVS has already demonstrated an in service MTBF of more than 6.500 h in the military helicopter environment.

Figure 3.5-1 shows the RDN 80 B DVS

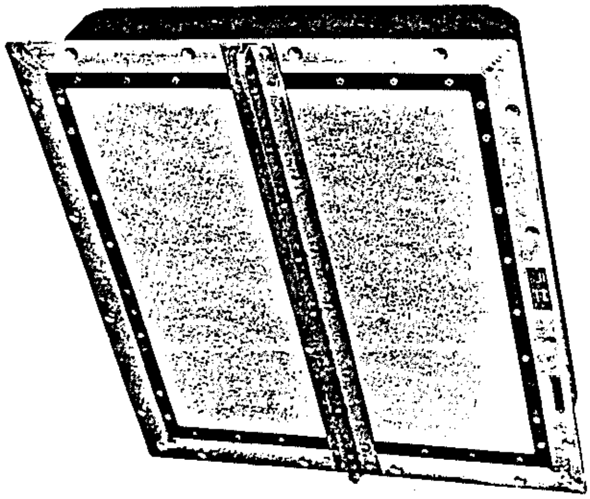

Figure 3.5-1 RDN 80 B Doppler Velocity Sensor

3.6. Conventional Air Data System

At speeds above 20 m/s conventional air data sensors as pitot-static tubes and temperature probes can be used.

There are several manufacturers which have excellent experience in that field.

3.7. Radar Altimeter

Determination of "Height above Ground" requires the use of a radar altimeter. Frequency- and pulse modulated equipments are available on the market. These equipments operate in the C-band and the J-band as well. Generally the beam is a 40° cone.

Equipment selection will be based on price, performance and production experience.

3.8. Magnetometer

A three axes strapdown magnetometer[20] is proposed because the use of this device enables the customer to accomplish the instrument calibration without expensive test equipment and costly logistic provisions for the necessary annual update of the change in magnetic variation.

As there are many experienced suppliers available the best in price and quality can be selected.

4. Flight Tests

Flight tests have been performed to demonstrate

- Navigation performance

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[20] The required accuracy can be accomplished with a flux valve as well. See the flight test results.

- Low air speed system performance (LAASH)
- Strap down magnetometer inflight calibration procedures

In order to perform these flight tests, a LHN-81[21] was developed by modifying the software of the LTR-81 AHRU[22] (Attitude Heading Reference Unit) and subjected to three independent flight tests together with a DVS, a MSU and a Control- and Display Unit in accordance with ARINC 561. The tables 4-1 and 4-2 provides information about general flight test data and test results.

Helicopter		Location	Organisation	Test Purpose	Time Span
BO-105	(2.4t)	Braunschweig	DFVLR	Nav.	Sept.÷Oct.1984
BO-105	(2.4t)	Braunschweig	DFVLR	LAASH	Feb.÷March1985
BO-105	(2.4t)	Braunschweig	DFVLR	LAASH	Sept.÷Oct.1985
BO-105	(2.4t)	Braunschweig	DFVLR	LAASH/ Magnetom.Nav.	May ÷June 1986
CH-53	(15t)	Manching	Erp.St.61	Nav.	Aug.÷Sept.1985
Gazelle	(1.9t)	Brètigny	C.E.V.	Nav.	Oct.÷ Nov.1985

Table 4-1 Flight Test Overview

Test Vehicle		BO-105	CH-53	Gazelle
Equipment under Test	SD-IRU	LHN-81 +	LHN-81 +	LHN-81 +
	DVS	AN/ASN 128 +	AN/ASN 128 +	RDN 80 B +
	MSU	Sperry P/N 658620	KEMS 802-1	KEMS 802-1
Testparameter				
Navigation	Enroute	1.3%[23]	1.01%[24]	1.58%[25]
	NOE	100m	299m	190m[26]
Attitude	Pitch	0.14°		
	Roll	0.29°		
Heading		1.05°	0.47°	0.89°
Velocity		1.18m/s		

Table 4-2 LHN-81 Navigation Flight Test Results[27]

As it could be seen the navigation requirements of table 3-1 are easily met by the equipment under test consisting out of the SD-IRU LHN-81 prototype, the DVS RDN 80 B or AN/ASN 128 and the MSU. During the entire flight test of more than 100 flight hours the equipment operated successfully without any complaints.

4.1. Navigation Performance

The navigation performance of the LHN-81 has been tested in three different helicopters at three test centres (see table 4-1). At the DFVLR in Braunschweig and at Erp.St.61 in Manching the navigation system under test consisted out of the LHN-81, a Doppler

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[21] the LTR-81 hardware was kept unchanged

[22] designed for commercial airline use

[23] calculated without assuming a normal distribution

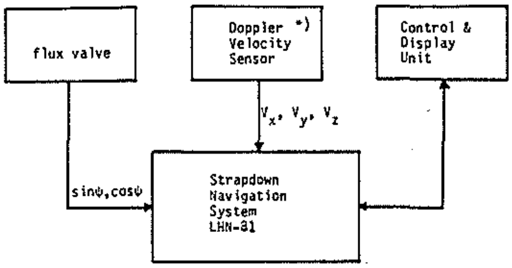
[24] calculated according to STANAG 4278 (assuming a normal distribution)

[25] calculated without assuming a normal distribution

[26] related to 15 min duration

[27] all values 95 % probability

velocity sensor type AN/ASN 128 from Singer Kearfoot produced under license at SEL, and a flux valve. The tests at C.E.V. in Brétigny (France) were carried out using a Doppler velocity sensor RDN 80 B from E.S.D. Figure 4.1-1 demonstrates the interconnection of the individual devices including the control and display unit.



*) - at DFVLR and Erpr.St. 61: LDNS AN/ASN-128 (SEL)
- at C.E.V.: RDN 80 B (ESD)

Figure 4.1-1 System under Test Interconnection

The helicopters used are a BO-105, a CH-53, and a Gazelle. Figures 4.1-2, 4.1-3, 4.1-4, 4.1-5 and 4.1-6 are showing the different helicopters and the appropriate installations of the LHN-81 SD-IRU.

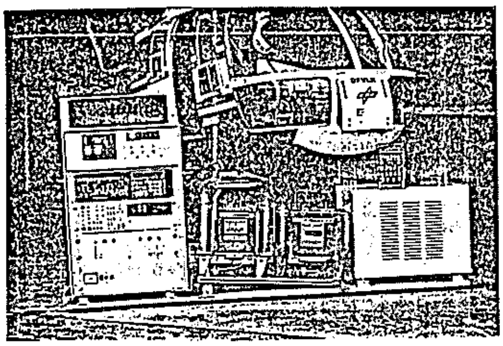


Figure 4.1-2 Flight Test Equipment in Front of the BO-105 used at DFVLR in Braunschweig

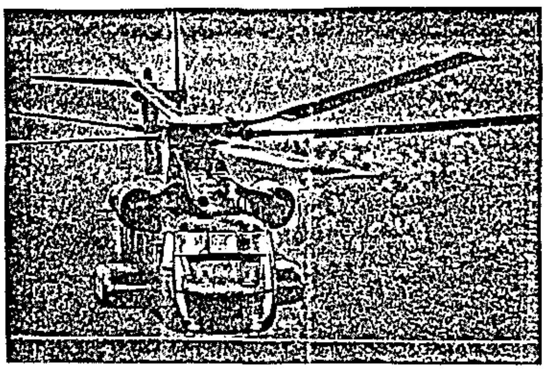


Figure 4.1-3 Helicopter CH-53 used at Erpr.St.61 in Manching

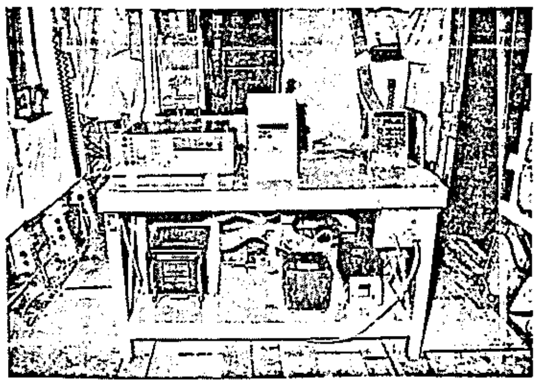


Figure 4.1-4 Installation of Flight Test Equipment in the CH-53

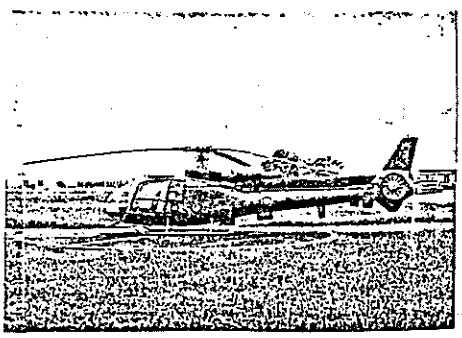


Figure 4.1-5 Helicopter Gazelle used at C.E.V. in Brètigny

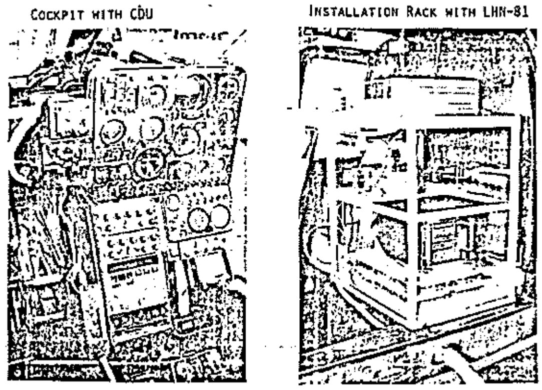


Figure 4.1-6 Installation of the Flight Test Equipment in the Gazelle

Due to the different helicopters in respect to their dynamic capabilities and their weights the LHN-81 had to be adapted to the various flight conditions. The necessary software changes mainly concerning the calibration, the cut-off-logic of the flux valve and the corresponding time constants. In Manching and in Brètigny a new flux valve calibration procedure, especially developed for an inflight calibration of a three axis strapdown magnetometer had been applied successfully. Most of the adaptation parameters have been derived from the results of a few test flights.

The purpose of the flight tests mentioned above was to demonstrate the navigation performance during cross country and high dynamic flights (NOE). The accuracies at Erp.St.61 and at C.E.V. were derived from the comparison of the position coordinates provided from the hybrid navigator LHN-81 + DVS + MSU compared with the known coordinates of reference points flown over. The accuracies of the reference positions are declared to 20m up to 30m. At DFVLR the inertial laser gyro navigation system LTN-90 was used as a reference. At DFVLR the LHN-81 and the LTN-90 data were recorded with a frequency of 10 Hz by the MUDAS[28]. The accuracies of the LTN-90 position have been improved by post-flight filtering by a kalman filter algorithm using the velocities before take-off and after landing thus achieving a position accuracy of 50 m. Additionally the velocities, rates, heading and euler attitude angles have been recorded. The advantage of this data acquisition method is the large quantitiy of comparable data in contrast to the few values of the flight tests at Erp.St.61 and C.E.V., see table 4.1-1 below.

Therefore the statistical results particularly the result of the NOE-flights had to be treated very carefully.

Furthermore the statistical methods used by Erp.St.61 and by C.E.V. are quite different.

Thus the computation of the 95% values at Erp.St.61 are based upon a hypothetically assumed two dimensional normal distribution[29] of the postion errors whereas at DFVLR and at C.E.V. the overall results are independent of an a priori assumed error distribution. To get comparable results the values accomplished at Erp.St.61 and C.E.V. have been computed according to both methods.

test center	navigation		tactical flight	
	no. of flights	no. of comp. data	no. of flights	no. of comp. data
DFVLR	8	190800	1	8400
Erp.St.61	8	29	4	4
C.E.V.	5	37(44*)	4	8
*): including outliers				

Table 4.1-1: Number of Test Flights and Comparable Data

28 Modular Data Aquisition System

29 see STANAG 4278

4.1.1. Performance during Cross Country Flights

The navigation performance of the hybrid system is expressed in terms of position error relative to the distance travelled.

At DFVLR in Braunschweig additionally the accuracies of the heading and attitude angles as well as of the velocity could be computed. These values (95% probability) flown in 8 navigation flights are listed in table 4.1.1-1. Summarizing the individual results, relative navigation accuracies of 1.3% of the distance travelled, a heading accuracy of 1.05°, and a velocity accuracy of 1.18 m/s are observed. The corresponding graphs are displayed in figures 4.1.1-1, 4.1.1-2 and 4.1.1-3.

flight no.	heading accuracy [°]	pitch angle accuracy [°]	roll angle accuracy [°]	velocity accuracy [m/s]	rel. position accuracy [%]
21	0.64	0.14	0.33	1.07	0.85
22	1.49	0.13	0.28	1.16	1.74
23	1.09	0.13	0.26	1.08	0.91
24	1.30	0.11	0.27	1.58	0.79
26	0.75	0.13	0.25	1.05	0.84
27	0.89	0.15	0.29	1.19	1.40
28	1.05	0.13	0.29	1.36	1.03
30	0.74	0.17	0.32	1.01	1.20
overall	1.05	0.14	0.29	1.18	1.30

Table 4.1.1-1: Accuracies (95% probability) of the Cross Country Flight Test at DFVLR

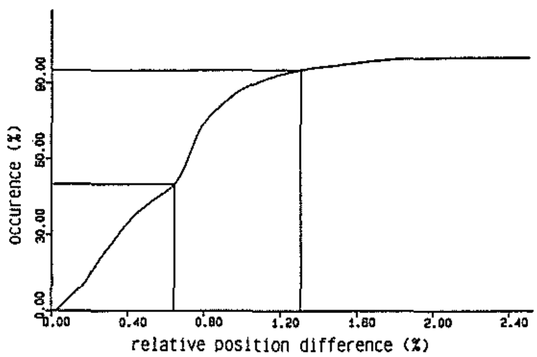


Figure 4.1.1-1 Distribution of the Relative Position Differences (Cross Country Flights at DFLVR)

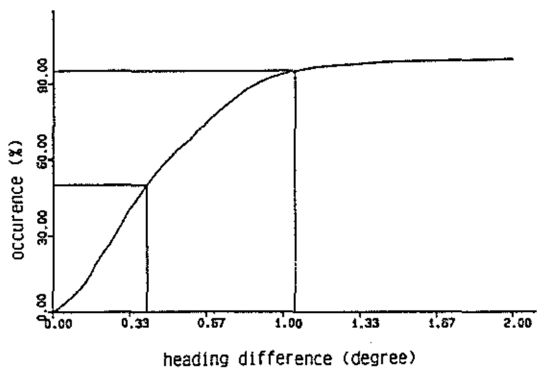


Figure 4.1.1-2 Distribution of the Heading Differences (Cross Country Flights at DFVLR)

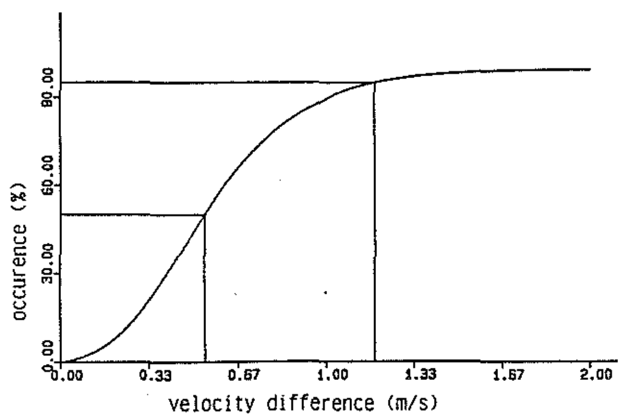


Figure 4.1.1-3 Distribution of the Velocity Differences (Cross Country Flights at DFVLR)

At Erp.St.61 in Manching the navigation accuracy of the LHN-81 has been demonstrated during 8 navigation flights. 4 of them are obtained flying a small triangle of approximately 150 km total length and 4 of them flying a large triangle of ~ 500 km total length.
The 29 individual results computed from the position differences at the reference points of the triangles are listed in table 4.1.1-2. The relative position differences are seperated in an along and an across track error.

Flight No. Date	Section	Distance [km]	Along Track Error [%]	Across Track Error [%]	Rel. [%]
11	1	57.8	0.034	-0.396	0.397
9.9.85	2	56.6	-0.190	-0.701	0.726
	3	32.9	-0.057	0.801	0.803
13	1	32.9	0.183	0.797	0.818
10.9.85	2	56.6	-0.074	-0.311	0.320
	3	57.8	-0.051	-0.462	0.465
15	1	57.8	-0.091	0.245	0.262
11.9.85	2	56.6	0.059	0.605	0.608
	3	32.9	0.088	0.343	0.354
17	1	32.9	0.070	0.696	0.699
11.9.85	2	56.6	-0.004	-0.269	0.269
	3	57.8	0.145	-0.280	0.315
21	1	57.8	0.027	-0.033	0.043
	2	115.5	-0.045	-0;138	0.146
16.9.85	3	106.5	0.042	0.060	0.073
	4	141.0	-0.078	-0.206	0.220
	5	57.7	0.008	-0.231	0.232
22	3	106.5	-0.035	-0.598	0.599
17.9.85	4	115.5	0.080	-0.700	0.705
	5	57.8	0.022	-1.067	1.068
24	1	57.8	0.102	-0.553	0.563
	2	115.5	0.006	-0.148	0.149
18.9.85	3	106.5	0.075	0.052	0.091
	4	141.0	-0.066	-0.285	0.292
	5	57.8	-0.038	-0.237	0.240
25	2	141.0	0.059	0.601	0.604
	3	106.5	0.177	-0.825	0.844
19.9.85	4	115.5	0.055	-0.287	0.293
	5	57.8	0.041	0.735	0.736

Table 4.1.1-2 Individual Results of the Cross Country Flights at Erp.St.61

The across track error can additionally be used for indirectly computing the heading error. As mentioned above the quantity of 29 individual results is quite a small number to compute statistical reliable values. Using the method of Erp.St.61 assuming a normal distribution, a relative position accuracy during cross country flights of 1.01% (95% probability) is obtained. With contrast to this method the individual results are summarized in figure 4.1.1-4. The application of this method free of a priori assumptions yields in a relative navigation accuracy of 0.83% thus showing the a priori assumption not beeing valid. The corresponding heading accuracy derived from the across track errors amounts to 0.47° (95% probability) including a systematic heading error of only -0.05°, and demonstrates the successfully employed flux valve calibration method. The accompanying graph is given in figure 4.1.1-5.

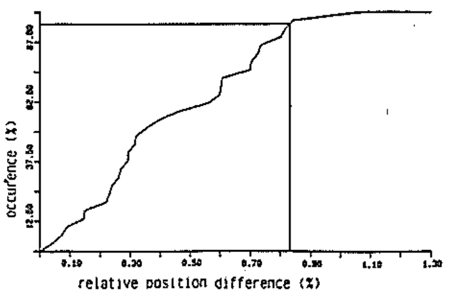


Figure 4.1.1-4 Distribution of the Relative Position Differences (Cross Country Flights at Erp.St.61)

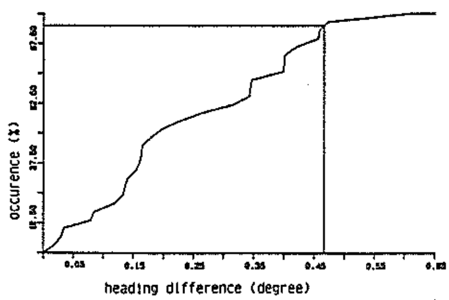


Figure 4.1.1-5 Distribution of the Heading Differences (Cross Country Flights at Erp.St.61)

The navigation accuracy of the LHN-81 was tested at C.E.V. in Brêtigny using an east-west-profile consisting of 6 reference points (total length: 127 km), a north-south-profile consisting of 6 reference points (total length: 124 km) and a circle course including 5 reference points (total length: 126 km).

Due to light weight (1.9 t) and the high dynamic range of the helicopter used, the cut-out-logic and the filter constants of the flux valve disturbed evidently by the dynamics, had to be importantly modified.

Flight No. Date	Section and Direction	Distance	Along Track Error [%]	Across Track Error [%]	Rel. Error [%]
9	1 E -> W	26.0	-0.412	-0.477	0.628
13.11.85	2 E -> W	32.8	-0.186	0.210	0.282
East-	3 E -> W	24.8	-0.367	0.585	0.689
West-	4 E -> W	43.4	-0.445	0.394	0.594
East	4 W -> E	43.4	-0.433	0.864	0.965*
	3 W -> E	24.8	-0.294	1.560	1.585*
	2 W -> E	32.8	-0.262	1.552	1.573*
	1 W -> E	26.0	-0.527	1.039	1.164
10	1 N -> S	33.9	-0.018	0.693	0.694
13.11.85	2 N -> S	33.5	-0.051	0.516	0.519
North-	3 N -> S	25.2	0.119	0.226	0.256
South-	4 N -> S	31.5	-0.248	1.168	1.196*
North	4 S -> N	31.5	0.016	1.737	1.738*
	3 S -> N	25.2	-0.230	2.333	2.347*
	2 S -> N	33.5	0.069	1.012	1.014
	1 S -> N	33.9	-0.230	0.086	0.246
16	1 E -> W	26.0	-0.300	1.104	1.140
22.11.85	2 E -> W	32.8	-0.327	0.466	0.570
East-	3 E -> W	24.8	-0.145	-0.081	0.167
West-	4 E -> W	43.4	-0.394	0.138	0.417
East	4 W -> E	43.4	-0.150	0.813	0.827*
	3 W -> E	24.8	-0.226	0.891	0.917*
	2 W -> E	32.8	-0.198	1.482	1.494*
	1 W -> E	26.0	-0.538	1.262	1.368*
11	1 ccw	24.7	-0.150	-0.798	0.813
14.11.85	2 ccw	33.0	-0.142	0.939	0.949
Rund-	3 ccw	22.0	-0.059	0.832	0.834
kurs	4 ccw	23.1	-0.420	0.545	0.689
	5 ccw	23.4	-0.145	-0.376	0.405
	5 cw	23.4	-0.013	0.603	0.603
	4 cw	23.1	-0.329	0.238	0.407
	3 cw	22.0	-0.123	-0.795	0.806
	2 cw	33.0	-0.161	0.255	0.300
	1 cw	24.7	-0.255	1.008	1.043
12	1 ccw	24.7	0.053	-0.073	0.091
14.11.85	2 ccw	33.0	-0.106	0.470	0.481
Rund-	3 ccw	22.0	0.377	-0.345	0.512
kurs	4 ccw	23.1	-0.294	0.134	0.324
	5 ccw	23.4	-0.239	-0.419	0.481
	5 cw	23.4	-0.141	-0.192	0.239
	4 cw	23.1	-0.238	-0.069	0.250
	3 cw	22.0	-0.023	-0.145	0.146
	2 cw	33.0	-0.106	1.185	1.190
	1 cw	24.7	-0.231	1.053	1.080
ccw: counter clockwise, cw: clockwise, *: outliers					

Table 4.1.1-3 Individual Results of the Cross Country Flights at C.E.V.

The 44 individual results of the navigation flights at C.E.V. are listed in table 4.1.1-3. Assuming a normal error distribution relative navigation error of 1.38% to the mean and 1.75% to zero are obtained. The assumption free value amounts to 1.58%. The discrepancies between these values are cuased by systematic errors of the navigation system. Regarding the individual values a significant deterioration of the across track errors can be observed after the turns at the north-south and the east-west flights. A detailed examination has shown that the cut-out-logic of the flux valve was not active which leads to an important heading error. Due to the time constant in the flux valve augmented navigation system this error did not effect immediately the heading of the navigation system.

By eliminating the so caused outliers, a navigation accuracy of 1.15% is obtained. This value corresponds to the value of 1.18% calculated by assuming a normal distribution. The heading accuracy amounts to 0.64° including a systematic heading error of only 0.15°. The graphs showing the navigation results at C.E.V. are displayed in Figure 4.1.1-6 and Figure 4.1.1-7.

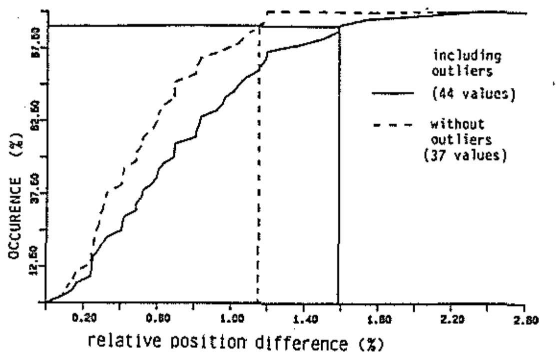


Figure 4.1.1-6 Distribution of the Relative Position Differences (Cross Country Flights at C.E.V.)

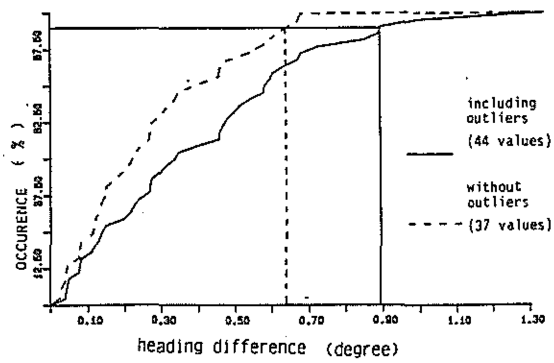


Figure 4.1.1-7 Distribution of the Heading Differences (Cross Country Flights at C.E.V.)

4.1.2. Tactical Flight

The 2nd purpose of the flight trials was to demonstrate the performance of the navigation system during a high dynamic tactical flight (NOE).

With contrast to the navigation flights, here the absolute position differences after a 15 min tactical flight was the essential evaluation criteria. At DFVLR and at Erp.St.61 the tactical flights exactly ended after 15 min while the tactical flights at C.E.V. differed in their duration. Each tactical flight at C.E.V. consisted of a tactical approach to a known waypoint from which the target point had been attacked.
The individual results of the tactical flights at DFVLR, at Erp.St.61 and at C.E.V. are listed in table 4.1.2-1. The time dependent values are summarized to a mean 15 min-value assuming a primary time dependent error model. The mean accuracies are 100m at DFVLR, 298m at Erp.St.61 and 190m at C.E.V. after a 15 min tactical flight.

	DFVLR Braunschweig	E61 Manching	C.E.V. Bretigny
individual results (after 15 min)	100 m	24 m 39 m 56 m 88 m ($14^m 06^s$)	83 m ($19^m 30^s$) 299 m 135 m ($15^m 00^s$) 56m ($29^m 46^s$) 124 m ($28^m 00^s$) 61 m ($15^m 28^s$) 312 m ($35^m 49^s$)
CEP 95%	100 m	298 m	190 m 1)
1) related to 15 min duration			

Table 4.1.2-1: Results of the Tactical Flights

4.2. Low Air Speed System Performance

As conventional pressure and temperature based air data systems are not usable to the low speed regime of helicopters (|v| < 20 m/s), new measurement techniques had to be developed.

It was decided to investigate whether an analytical method based on the helicopter control signals collective and longitudinal and lateral cyclic pitch can be designed to comply with the accuracy requirement of 2 m/s 95 % probability.

In order to get a suitable data base to carry out the investigation in mind, an appropriate flight test was designed to collect the data shown in figure 4.2-1.

LITEF - DFVLR - FLIGHT - TESTS (FEB. 1985)

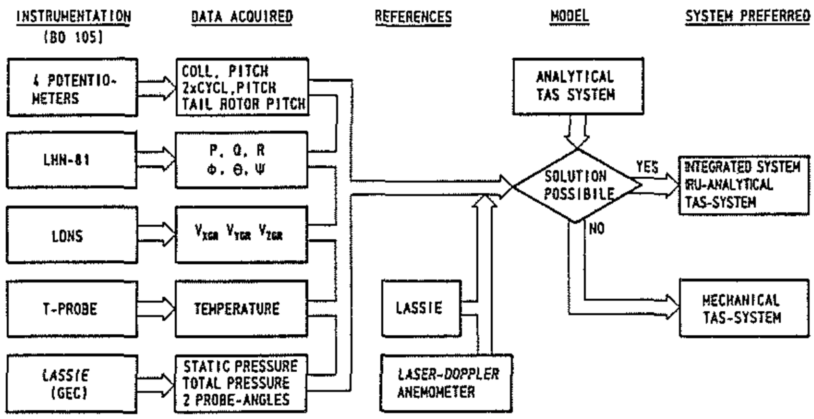


Figure 4.2-1 Block Diagram Data Collection

This flight test was performed during February/March 1985 at DFVLR in Braunschweig utilising their BO-105 with the data recording system already described.

After having analyzed the data gathered during this flight test, it was found that an analytical low air speed system could be mechanized to fulfill the accuracy requirements mentioned above. In order to verify the algorithms used a specific calibration procedure to the type of helicopter used had to be designed.

This calibration procedure was applied to the BO-105 of DFVLR in September/ October 1985.

The next step in the design of LAASH was the implementation of the LAASH algorithms into a LHN-81 SD-IRU and to perform appropriate flight tests for the necessary verification. This flight test was carried out during May/June 1986 at DFVLR using their BO-105 again. As of the time writing this paper the test data has not been fully analyzed. Preliminary analysis indicate satisfactory results.

4.3. Flux Valve Calibration

As the navigation flight test results of the hybrid navigator LHN-81 + DVS + MSU have shown that the navigation accuracy mainly depends on the accuracy of the heading sensor used for augmentation.

During the flight tests at DFVLR, Erp.St.61 and C.E.V. a standard flux valve[30] was used. Like any magnetic field detector, the flux valve had to be compensated for magnetic materials in the airborne vehicle causing constant and cyclic heading errors.

Due to the sensitivity of the flux valve in respect to vibration and dynamics the compensation has to be made on ground.

The magnetic or geographic reference directions used were reference lines on the ground (at DFVLR and Erp.St.61) or a compass integrated in a theodolite (at C.E.V.).

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[30] horizontal magnetic field only

The reference direction was transferred via plumbing or via a theodolite to the center line of the helicopter.

The flux valve corrections were carried out per software using the calibration function

$$\psi_{cor} = \psi + A + B \cdot \sin(\psi+\rho_1) + C \cdot \sin(2\psi+\rho_2).$$

The first flight test at DFVLR has shown that after such a compensation a constant heading error of about 1° remained in the navigation results. This effect is caused by mounting errors of the flux valve and of the doppler velocity sensor around the yaw axis of the helicopter.

As true north was required in the navigation equations, additional error sources are incorrect tables for magnetic variation or local and temporary anomalies of magnetic variation.

Therefore a new flux valve calibration procedure developed for a three axis strapdown magnetometer has been employed in the following flight tests at Erp.St.61 and at C.E.V.

In a first step the new procedure only compensates for the cyclic errors of the flux valve as usual. In a second step the constant heading error is calculated from the across track position differences measured during a calibration flight with the navigation system.

For optimal accuracy it is very much advisable to take redundant measurements by flying along a large enough triangle clockwise and counterclockwise to find the constant correction term from the differences at the corner points of that very reference triangle.

Using this procedure the constant heading errors could be reduced from about 1° to -0.054° at Erp.St.61 and to 0.15° at C.E.V.

In the same way the heading error (95% probability) has decreased from 1.05° to 0.47° at Erp.St.61 and 0.64° at C.E.V. The excellent result at Erp.St.61 is additionally influenced by the low dynamics of the CH-53 helicopter because the percentage augmentation time of the flux valve during the calibration and navigation flights was higher than in the highly dynamic helicopters Gazelle and BO-105.

4.4. Three Axes Strapdown Magnetometer

As can be seen on the results of the LHN-81 flight tests a well calibrated flux valve is able to reduce the heading errors to 0.5° (95% probability).

The disadvantages of the standard flux valve are:

- no inflight-calibration capability
- high noise
- requires specific adaptation to the type of helicopter
- highly sensitive to dynamics
- very little relative augmentation due to dynamics

A three axes strapdown magnetometer eliminating the a.m. disadvantages of a flux valve will be used in further applications.

Preliminary results with a three axes strapdown magnetometer have been obtained during laboratory and flight test in May 1986 at DFVLR in Braunschweig.

The goal of the magnetometer flight test was to develop a suitable inflight-calibration procedure and to test the accuracy of a magnetometer calibrated accordingly. The tests have been performed with two magnetometers which were installed at the tail of a BO-105. As reference a LTN-90 laser gyro inertial navigation system was used.

A three axes strapdown magnetometer measures the earth magnetic field in the fixed body coordinate frame of the vehicle. These components need to be transformed via the attitude angles in the horizontal coordinate system so that an attitude reference system yielding roll and pitch angles becomes necessary. The horizontal components ($\sin\psi$, $\cos\psi$) then will be used for the heading computation.

Furthermore besides the cyclic heading-dependent errors, the roll and pitch-dependent errors need to be compensated for. This is done in accordance with a specific LITEF procedure by the calibration functions which eliminate the most important magnetometer errors

$$T_i^{cal} = T_i+A_i+B_i\cdot\sin\psi+C_i\cdot\cos\psi+D_i\cdot\phi+E_i\cdot\phi^2+F_i\cdot\theta+G_i\cdot\theta^2$$

$$i = X, Y, Z.$$

where

ψ: Heading ϕ: roll angle θ: pitch angle

The calibration coefficients are calculated during a special calibration manoeuvre of the helicopter.

At the magnetometer flight test several calibration manoeuvres have been examined. For these purposes the magnetometer signals have been recorded via the MUDAS with a frequency of 20 Hz.

The necessary roll and pitch angles as well as the reference heading was provided in the same way from the LTN-90. First noise examinations of the magnetometer signals have shown that the inflight noise is mainly caused by the helicopter dynamics and vibrations:

Brand x: 70 n Tesla (≙ 0.2° in respect to heading)

Brand y: 100 n Tesla (≙ 0.4° in respect to heading)

(based upon a horizontal magnetic field intensity of 20.000 n Tesla).

The noise can be decreased to less than 35 n Tesla (≙ 0.1°) by appropriate filtering.

A suitable calibration function is a circular flight clockwise and counter clockwise with different bank angles and with additional pitch manoeuvres.

Due to dynamic effects and roll and pitch angle errors the measurement range of a magnetometer should not exceed 20° attitude angle respectively angular rates of 5°/s.

With the above mentioned manoeuvres the primarily uncompensated heading error (1σ) of the magnetometers could be reduced from 2.6° (brand x) and 1.3° (brand y) to 0.26° (brand x) and 0.39° (brand y). The corresponding 95% probability values are 0.41° (brand x) and 0.61° (brand y). The inflight calibration time was approximately 14 minutes.

In a second step the calculated calibration coefficients are used to correct the magnetometer signal during

- a navigation flight (enroute)
- a Nap of the Earth flight (NOE)
- a procedure turn clockwise and counter clockwise.

The results achieved with the calibrated magnetometers are listed in table 4.4-1. The cut-off limits of the magnetometer signals were set to angular rates of 5°/s. The important result is that the magnetometer augmentation can also be used during NOE-flight (percentage augmentation ~70%) and a procedure turn (~82%) where a conventional pendulous flux valve cannot be used for augmentation during these manoevres at all. The accuracy can be improved by additional filtering and a different setting of the cut-off limits. The preliminary analysis shows that a heading accuracy of 0.5° (95% probability) can easily be achieved with a properly calibrated magnetometer utilizing a suitable inflight calibration procedure.

	enroute flight	NOE flight	procedure turn
elapsed time	45 min	53 min	13.5 min
perc.augmentation	85%	70%	82%
$\delta\psi$ (brand x) 1σ bef.cal.	2.4°	2.1°	3.0°
$\delta\psi$ (brand x) 1σ after cal.	0.33°	0.47°	0.53°
$\delta\psi$ (brand x) 95% after cal.	0.55°	0.69°	0.84°
$\delta\psi$ (brand y) 1σ bef.cal.	1.15°	1.52°	1.3°
$\delta\psi$ (brand y) 1σ after cal.	0.33°	0.38°	0.36°
$\delta\psi$ (brand y) 95% after cal.	0.56°	0.59°	0.64°

Table 4.4-1: Heading Errors ($\delta\psi$) before and after Magnetometer Calibration

5. Conclusions

An autonomous hybrid navigation system for modern rotorcrafts has been described. During various flight trials the performance and accuracy of such a system has been demonstrated together with a new analytical low speed TAS determination method and inflight calibration methods for strapdown magnetometers.

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