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DIGITAL SIMULATION OF AVIONICS NAVIGATION SYSTEMS FOR DIRECTION MEASUREMENTS

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ABSTRACT

Avionics navigation systems for direction measurements have airborne receivers and ground transmitters, which are very expensive equipment. The training of pilots, engineers and technical staffs requires special installation of real equipment with the cooperation of both airborne and ground parts, or it is done through the aircraft simulation system which is special for each aircraft type. These techniques give only the global function training without any details of system hardware or signal processing. This work introduces a digital simulation for some avionics navigation systems of direction measurements as ADF (automatic direction finder) and TACAN (tactical air navigation) for training purposes covering : the system function, the essential processing steps, and the necessary test points. The simulated systems are interfaced with PC to control different modes of operations, and perform the necessary computations for the navigation process. The trainer is implemented using available ICs in the local market, tested, and used as an educational aid for avionics engineering students. It has the flexibility to add other new subsystems. It is of very-low cost when compared with other training facilities. The usual direct step-by-step analog simulation technique is complicated and requires special and expensive ICs as analog multipliers and mixers. The main idea behind this low-cost solution is the application of a versatile function generation using stored digital data and digital to analog conversion. Even the problem of AM (amplitude modulation) simulation process is solved using digital technique.

Keywords :Avionics Navigation Systems, Digital Simulations, ADF.

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I- INTRODUCTION

Avionics navigation system consists of the aircraft electronics subsystems that measure and determine the aircraft position, speed and direction [1,2]. It performs the necessary computations for presentation, guidance, and control. The navigation systems have ground aids such as transmitters and transponders, which communicate with airborne receivers and interrogators. The systems can be classified into two main groups : direction-measuring systems such as ADF, TACAN and VOR, and range-measuring systems such as DME (distance-measuring-equipment) and altimeter, beside autonomous systems (such as Doppler and INS) for dead-reckoning navigation.

This work introduces a proposed navigation trainer that is conceived to serve for introductory presentation for some navigation aids to aviation. This is to be used as an educational aid for avionics students in its integrated computer controlled format or as stand alone modules. It basically comprises simulated functions for the processing blocks for some avionics navigation systems.

The proposed trainer comprises the following :

a-PC-Computer linked with a data show and software developed for presenting the educational material and acquisition as well as control of the navigational modules.

b-Navigational modules simulators of :

- i-Angle measuring systems :
  - -Automatic direction Finder (ADF).
  - -Bearing angle section of TACAN.
- ii-Distance measuring systems :
  - -DME (Distance measuring section of TACAN)
  - -Altimeter
- iii-Air traffic control (ATC)
- iv-Multifunction Display: Head-up Display (HUD).

c-Frequency synthesizer modules :

It delivers the necessary frequencies for different simulation subsystems and ensures the total synchronization of the trainer.

Details of system-functions for the direction measurements of ADF and TACAN systems are analyzed from point-of-view of training the avionics engineering students. Basic relations are given taking into consideration that the minimum number of test points are required. Simplification of each module is done to minimize the hardware implementation and to eliminate redundancy in signal generation.

Analog simulation technique is complicated compared to digital simulation,and requires special and expensive ICs as analog multipliers and mixers with great-care in component selection and realization [3].

The main idea behind this low-cost solution is the application of a versatile function generation using stored digital data and digital to analog conversion. The problem of AM (amplitude modulation) simulation process is solved using digital technique instead of diode/transistor modulators.

The trainer is implemented using available ICs in the local market, tested, and used as an educational aid for avionics engineering students. It has the flexibility to add other new subsystems. It is of very-low cost when compared with other training facilities.

Digital implementation-schemes are designed to minimize the hardware and to use some of test-points for different functions with suitable computer-controls or manual switches [4].

Basic relations and functional diagram of ADF receiver with input signals coming from different directions are given in section II, while details of digital implementation is given in section III. TACAN bearing part is analyzed in section IV and its implementation details are given in section V.Conclusion and future work is given in section VI.

II- FUNCTIONAL DIAGRAM OF ADF SYSTEM

OBJECTIVE:

Provision of the direction measurement in terms of the relative bearing to the station [5] as shown in Fig.1, its receiver diagram is shown in Fig.2

DESCRIPTION AND TECHNICAL SPECIFICATION:

-It is a medium-band navigation system :(100 - 2000) kHz
-It works with a ground-aid as homing-beacon as well as the radio navigation point (RNP) transmitter
-Its Airborne section consists of :
 i-Loop antenna whose pattern is either a single figure of eight (8) or Two-crossed loops (each having two nulls) and a sense antenna (to solve the ambiguity due to the second null so as to obtain only one minimum for moving-type direction measurement).
 ii-Receiver used to amplify and detect the signal from the combined antenna then derive a control signal to orient the loop-minimum to the signal direction in the moving-type system or to process the quadrature signals in pointing-type system [2,3].
 iii-Display subsystem

TEST-POINTS :

From the function diagram of the ADF receiver we select the following test-points :

1-Rod antenna signals (the $\pi/2$ phase-shift is used to compensate the $\pi/2$ phase of the two-loop antennae)

$$U_1(t) = A\cos(wt) \quad (1)$$
$$U_2(t) = A\sin(wt) \quad (2)$$

where w is the medium-band frequency :f = 100 - 2000 kHz

2-Loop-antennae signals :

$$U_3(t) = \alpha A \sin(wt) \sin(\vartheta) \quad (3)$$
$$U_4(t) = \alpha A \sin(wt) \cos(\vartheta) \quad (4)$$

3-Switching signals for internal modulation :

$$U_5(t) = P(t) \quad (5)$$
$$U_6(t) = P(t-T/_4) \quad (6)$$

where P(t) is square-wave signal with period T, with low frequency F in range 30-100 Hz.

4-Switched signals as :

$$U_7(t) = U_3(t) \times U_5(t) = \alpha A P(t) \sin(wt) \sin(\vartheta) \quad (7)$$
$$U_8(t) = U_4(t) \times U_6(t) = \alpha A P(t-T/_4) \sin(wt) \cos(\vartheta) \quad (8)$$

5-The sum of receiver inputs as :

$$U_9(t) = U_2(t) + U_7(t) + U_8(t) = A[1+P(t) \sin(\vartheta) + P(t-T/_4) \cos(\vartheta)] \sin(wt) \quad (9)$$

6-The demodulated (envelope) of receiver output:

$$U_{10}(t) = A[1+P(t) \sin(\vartheta) + P(t-T/_4) \cos(\vartheta)] \quad (10)$$

7-The filtered output as the first harmonic component of $U_{10}(t)$ as :

$$U_{11}(t) = B \sin(\Omega t - \vartheta) \quad (11)$$

8-The output of the shaping circuit is delayed version of P(t) by a delay $\tau = \vartheta/\Omega$ as :

$$U_{12}(t) = P(t-\tau) \quad (12)$$

9-The phase detector output is a rectangular pulse of duration τ as:

$$U_{13}(t) = P_d(t) \quad (13)$$

Fig.3 gives the signal waveforms for different test-points.

III- ADF SIMULATION SCHEME

The straight forward analog simulation requires the generation and processing of the following waveforms and steps :

1-carrier with quadrature phases that simulate the received signals phases from the sense and loop antennae.
2-different weights as **sine** and **cosine** of the signal direction ϑ that simulates the received signals from the two-crossed loop antennae.
3-switching of the two crossed loop antennae-signals with the internal switching square-wave signal.
4-addition of the three antennae-signals to produce the normal AM signal.
5-detection and filteration of receiver-output.
6-digital phase-detection and measurement of the receiver output
7-different changes of the ϑ direction by computer-control

Analog simulation will be very expensive and with complicated circuit design, so the easier way is to use an educational-version of the real receiver with the ground signal simulation adopted for different signal direction.

We have realized a digital simulation of the ADF receiver for training purposes using the conventional digital ICs available in the local market as shown in Fig.4,[4].

The simulation scheme is based on generating different waveforms using Two-ROMs with Two DAC converters and do the necessary functions by proper selection of the ROMs address. This address may be selected through computer controlled interfacing or by manual selections as for stand-alone subsystem. The different directions ϑ are also selected manually or through computer-control [6].

The basic idea of AM simulation using ROM (EPROM or E^2ROM) is realized by storing both the negative and positive envelopes in the ROM circuit in two different places, then switching between these two-places by the carrier frequency as shown in Fig.5.

Parameters selection :

a-frequency selection :

If the phase-measuring counter gives 3 digits for direction in steps of 1°, it requires a clock-signal of frequency f_c = 360 F. So we have three values of frequencies: switching F, clock f_c = 360 F, and carrier f » F. If the carrier frequency f is selected as the reference frequency because it is the highest one, the other frequencies are obtained by suitable division, the carrier itself can be selected in steps to cover the range. The frequency divisions are performed through the frequency-synthesizer modules, the three frequencies are selected as follows :

1-Carrier frequency f:
The carrier frequency in range (200 - 2000) KHz can be selected in two steps 500 KHz, and 250 KHz by division of the 1 MHz by 2 and 4 respectively.

2-Clock frequency f_c: If the switching frequency is low frequency in range 30-100 Hz, then the clock frequency for phase-shift measurement will be of order 11-36 Khz, let it 25 KHz, it is obtained by dividing 1 MHz by 40.

3-Switching frequency F:
It can be obtained by dividing f_c by 360 in steps of $10 \times 6 \times 6$.

b-Quadrature signals :

The two-quadrature carriers and the two-quadrature switching signals may be obtained using two inverted square-wave signals of double the required frequency, division by two of both signals give the two quadrature signals [5].

c-Sampling of analog signals :

The sum of the receiver input $U_9(t)$ gives four different signals at the 4 quadrant of the switching period as follow :

a- $1 + \alpha \sin(\vartheta) + \alpha \cos(\vartheta)$
b- $1 + \alpha \sin(\vartheta) - \alpha \cos(\vartheta)$
c- $1 - \alpha \sin(\vartheta) - \alpha \cos(\vartheta)$
d- $1 - \alpha \sin(\vartheta) + \alpha \cos(\vartheta)$

If the signal is sampled at 2° ,then the total number of sample-points will be 180, this is divided by the 4 quadrants as 45 sample-points in each quadrant.The 180 sample-points require 8 bits address.

d-Addressing :

The 45 points of each quadrant is selected by 6 bit counter decoded to 45 count and reset by 45 decoder using AND circuit, counter addresses the first least significant bit address of the EPROM (A_0 to A_5). Different quadrantsare selected by the two-quadrature switching signals as address bits A_6 and A_7. Changing the phase-shift ϑ is selected as 16 values by 4 bits as A_8 to A_{11}.

e-Mode-selections :

4 different modes are chosen by A_{12} and A_{13} as :
- (00,01) give $\sin(\Omega t-\vartheta)$ from ROM_1 and $\cos(\Omega t-\vartheta)$ from ROM_2
- (10) gives $\sin(\vartheta)$ from ROM_1 and $\cos(\vartheta)$ from ROM_2
- (11) gives $\alpha\ A\ P(t)\ \sin(\vartheta)$ from ROM_1 and $\alpha\ A\ P(t-T/4)\ \cos(\vartheta)$ from ROM_2

The AM modulated signal is obtained by switching the positive and negative envelopes by the carrier signal, it is done by the most significant bit address as A_{14}. This gives the ROM size as 32 KB using 27256 ROM type.

IV- FUNCTIONAL DIAGRAM OF TACAN-BEARING SUBSYSTEM

OBJECTIVE:

Provision of the bearing to the station as shown in Fig.1. The ground transponder (it is considered here as only transmitter for the bearing information only, the transponder action is needed in distance measurement section) and airborne receiver function diagrams are shown in Fig.6 and Fig.7 respectively [7].

TACAN-BEARING SUBSYSTEM DESCRIPTION:

- It operates within 962 to 1213 MHz frequency range.
- The Bearing section operates with a special ground beacon and an airborne receiver outlined briefly in the following

The Ground Transponder :

It is a transmitter with special antenna which produces a space amplitude modulation through its rotation with two modulating frequencies : 15 Hz and 135 Hz .

It transmits special group of reference pulses as (main and auxiliary pulses)

The antenna has two cylinders : inner and outer cylinder , It transmits amplitude modulated signal with 15 Hz ,135 Hz as the variable phase signals.

It transmits the reference groups when the maximum of its antenna (both the inner and the outer) positions to the East.

The transmitted signal is an interrupted carrier with pulse pair of 2700 pps with duration of 3.5 μs which have the reference signals as special groups as main and auxiliary reference pulses at the 15 Hz and 135 Hz respectively, the envelope of the carrier pulses is AM modulated by the variable phase signals.

The Airborne Receiver :

It detects the envelopes of the received carrier pulses to obtain the 15 Hz and the 135 Hz AM (as variable phase signals) and separates them .

It limits the carrier pulses to eliminate the AM modulation, then decodes the pulses to detect the reference signals.

It measures the phase between the variable phase signals and each one and the corresponding reference signals.

The 15 Hz signal is the coarse measurement without ambiguity, while the 135 Hz signal is the fine measurement but with ambiguity of 40 degrees, the coarse one is used to resolve the ambiguity of the fine one.

TEST-POINTS :

The test-points waveforms are shown in Fig.8. for ground-beacon and airborne receiver as follow :

a-Ground-beacon :

-pulse pair of 2700 pps, or 5400 pps with duration 3.5 μs, and pulse separation of 12 μs for mode-X replay as $P_{1x}(t)$ or 30 μs for mode Y replay as $P_{1y}(t)$ (let it $P_1(t)$ with selection for x or y)

-15 Hz main-reference signal as $P_{2x}(t)$ which is 12 group of pulse-pair with separation 12 μs between each pulse pair and 18 μs between groups, or $P_{2y}(t)$ with 13 pulses with separation of 30 μs (let it as $P_2(t)$ with selection for x and y)

-135 Hz auxiliary-reference signal of 12 pulses with separation of 12 μs as $P_{3x}(t)$ or 13 pulses with separation of 15 μs as $P_{3y}(t)$ (let it as $P_3(t)$ with selection for x or y)

-total carrier pulses $P_4(t)$ as :
$$P_4(t) = P_1(t) + P_2(t) + P_3(t) \qquad (14)$$

-15 Hz variable phase signal, for an azimuth ϑ, then $\vartheta_1=\vartheta$ as:
$$U_5(t) = A \sin(\Omega t-\vartheta_1) \qquad (15)$$

-135 Hz variable phase signal will have $\vartheta_2= 9\vartheta$ module 360° as:
$$U_6(t) = \alpha A \sin(9\Omega t-\vartheta_2) \; (\alpha \text{ is the ratio } |U_6|/|U_5|) \qquad (16)$$

-positive envelope of received signal as:
$$U_7(t) = U_5(t) + U_6(t) \qquad (17)$$

-total base-band envelope as :
$$P_8(t) = U_7(t) \times P_4(t) \qquad (18)$$

b-Airborne receiver :

-15 Hz variable phase signal as : $U_9(t) = U_5(t)$ (19)
-135 Hz variable phase signal as : $U_{10}(t) = U_6(t)$ (20)
-15 Hz main-reference signal as : $P_{11}(t) = P_2(t)$ (21)
-135 Hz auxiliary-reference signal as: $P_{12}(t) = P_3(t)$ (22)

-shaped 15 Hz variable phase signal as:
$$P_{13}(t) = P_2(t-\tau_1), \; \tau_1=\vartheta_1/\Omega \qquad (23)$$

-shaped 135 Hz variable phase signal as :
$$P_{14}(t) = P_3(t-\tau_2), \; \tau_2=\vartheta_2/9\Omega \qquad (24)$$

-15 Hz phase-detection pulse as $P_{15}(t)$ of duration τ_1
-135 Hz phase-detection pulse as $P_{16}(t)$ of duration τ_2

Most of the airborne signals already exist in the ground transmitter, the required signals are those of shaped and phase detector outputs.

V- DIGITAL SIMULATION OF TACAN-BEARING SUBSYSTEM

Tacan digital simulation concers only the base-band signal (the interrupted envelope of the UHF carrier) to minimize the cost. The main and auxiliary reference digital signals are generated using one EPROM to simplify the different coding (EPROM type 2732), the analog signals are generated with another EPROM with DAC converter,(EPROM 27512 and DAC 8008 with symmetrical connection with OpAmp LM324), the generation of different timing and selection for addresses of the two EPROMs are done using different dividers for reference signal of 1 MHz, as shown in Fig.9 for the ground section, the airborne section only needs a phase-detector and phase counter to give ϑ_1 and ϑ_2, most of signals are available for ground section so there is no need to draw its simulation scheme.

Parameters selection :

a-Main frequency :
The 3.5 μs interrupted carrier pulse duration is changed to be 4 μs to simplify the total design, it is obtained by dividing a 1 MHz clock f_c by 2 to obtain a square-pulse of duration of 4 μs of frequency 500 KHz.

b-Sampled-points :
If the phase-step for simulation is required to be each 4° sample-points, then for the fine-measurement signal of 9Ω needs 360/4 = 90 points, the coarse-measurement of Ω needs a period 9 times the fine one, it contains 9 x 90 points = 810 sampled-points stored in the memory circuit and selected by 10 bit address. This selection insures periodic change of the complete and non-truncated pattern when addressed sequentially. The change of ϑ is secured by 4 bits (i.e 16 different values), and if the different modes (for different output analog signals) is done by 2 bits, so the total address bits are 16 bits, the memory required is at least of 64 KB, it is 27512 type.

c-The total number of interrupted carrier pulses :
since the number of sampled points is selected as 810 points, the number of selected pulses for the interrupted carrier and different reference signals have to be multiple of 810 to simplify the addressing of the two EPROMs, the suitable number is 4 x 810 = 3240 instead of 5400. The coding EPROM will be of 4 KB size, it is 2732 type.

d-Addressing signal :
The 3420 points sampling is secured by dividing the 500 KHz by 3240 using 14 bit counter as 4020 circuit type (it is aided with 7474 circuit to obtain the second significant bit b_1 from b_o). Division is controlled with an 8 input NAND 7430 circuit to detect the 3240 count for resetting the 14 bit counter. The first 12 bits from b_o to b_{11} is addressing the coding EPROM, while bits from b_2 to b_{11} is chosen for the analog signal EPROM(b_o and b_1 as divide by 4 is eliminated from addresses)

e-The coarse and fine frequencies :
The 15 Hz is not convenient for oscilloscope, so it is recommended to be higher for training purpose, it is selected to be the divider output of 500 KHz signal with the complete counter of sampled data as 500 KHz/ 3240 ≈ 154.3 Hz instead of 15 Hz. Consequently the fine frequency signal will be of 9 times of the low one as 1388.8 Hz instead of 135 Hz.

f-AM modulation :
Switching of the DAC output by the total pulse envelope simulation is done using the switching circuit 4016 that is controlled by the total digital output signal from the EPROM coder circuit.

g-Clock frequency for phase-shift measurements :
It is selected as 360 times the required frequency for

phase-shift of step of 1°. The first one is evaluated as :

$$f_{c1} = ((f_c/2)/3240) \times 360 = f_c/18 = 55.555 \text{ KHz} \quad (25)$$

the second one is 9 times the first one, so it :

$$f_{c2} = 9 \times (f_c/18) = 500 \text{ KHz} \quad (26)$$

h-Mode-selection :

The different modes give 4 different outputs as :

1-coarse-measurement phase-shifted signal
2-fine-measurement phase-shifted signal
3-sum of the phase-shifted signals as carrier envelope
4-interrupted UHF envelope by switching of reference signals

i-Shaped signals :

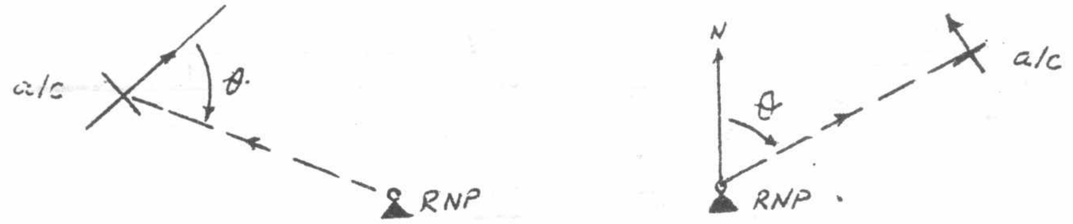
The fine and coarse phase-shifted signals are shaped by schmitt circuit for the digital phase-detector, they may be obtained as the bit change (sign-bit) of MSB bit form the ROM output.

VI- CONCLUSION

Digital implementation for simulation of ADF receiver and TACAN bearing section are given with their analysis from point-of-view of training purposes for avionics engineering students. The trainer covers :the system function, the essential processing steps for each system, and the necessary test-points. The simulated systems are interfaced with PC to control different modes of operations, and performs the necessary computations for the navigation process. The trainer is realized with available ICs in the local market, it is tested and working as an educational aid for avionics lab. The trainer may be expanded to cover new modules for other avionics navigation systems. Necessary simplifications and minimization of system functions and test-points are done to eliminate redundancy in waveform generation. The trainer is deigned with low cost components available in the local market using the idea of a versatile function generation, even the problem of AM modulation is simulated using digital technique instead of analog circuits that require special components with great-care in adjusting performance and selections of parameters.

REFERENCES :

[1] W.R.Fried & M.Kayton," Avionics Navigation Systems ", John Wiley and Sons, New York, 1969.
[2] B.Forssel, "Radionavigation Systems", Printice Hall, New York 1991.
[3] R.P.G. Collinson, "Introduction to avionics ", Chapman & Hall, London, 1996.
[4] D.A.Neamaen, "Electronic circuit analysis and design" IRWIN, Chicago, 1996.
[5] F.Wang et al, "Performance of DF techniques with VHF antenna array", IEEE Trans. on AES Vol. 31, pp.685-694, April,1995
[6] A.Brown, "A low cost vehicle location and tracking system",IEEE Symposium 1992, pp. 516-523.
[7] C.R.Spitzer, "Digital Avionics Systems", McGraw-Hill, New York , 1993.



a- ADF relative bearing

b- TACAN bearing

Fig.1 Direction Measurements

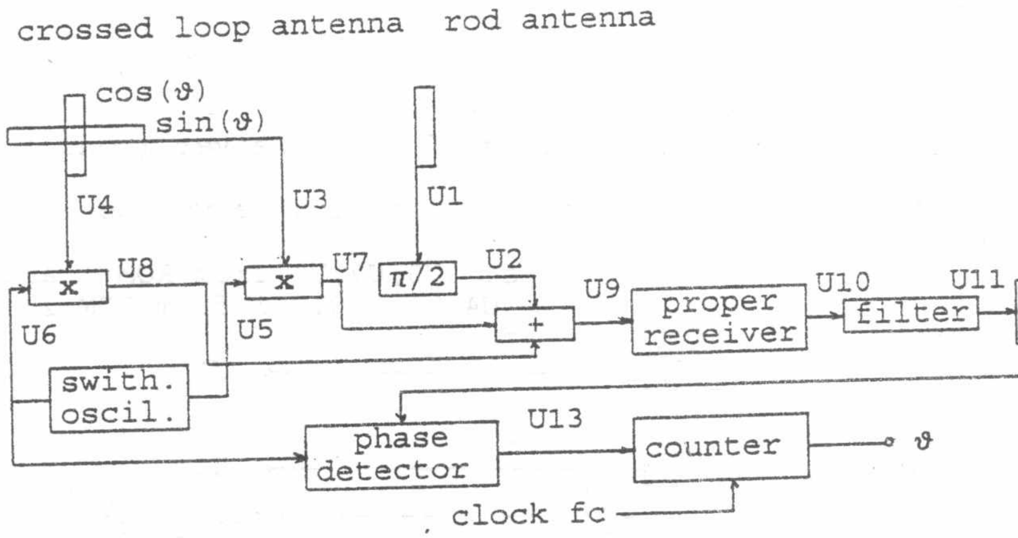


Fig.2 Functional diagram of ADF receiver

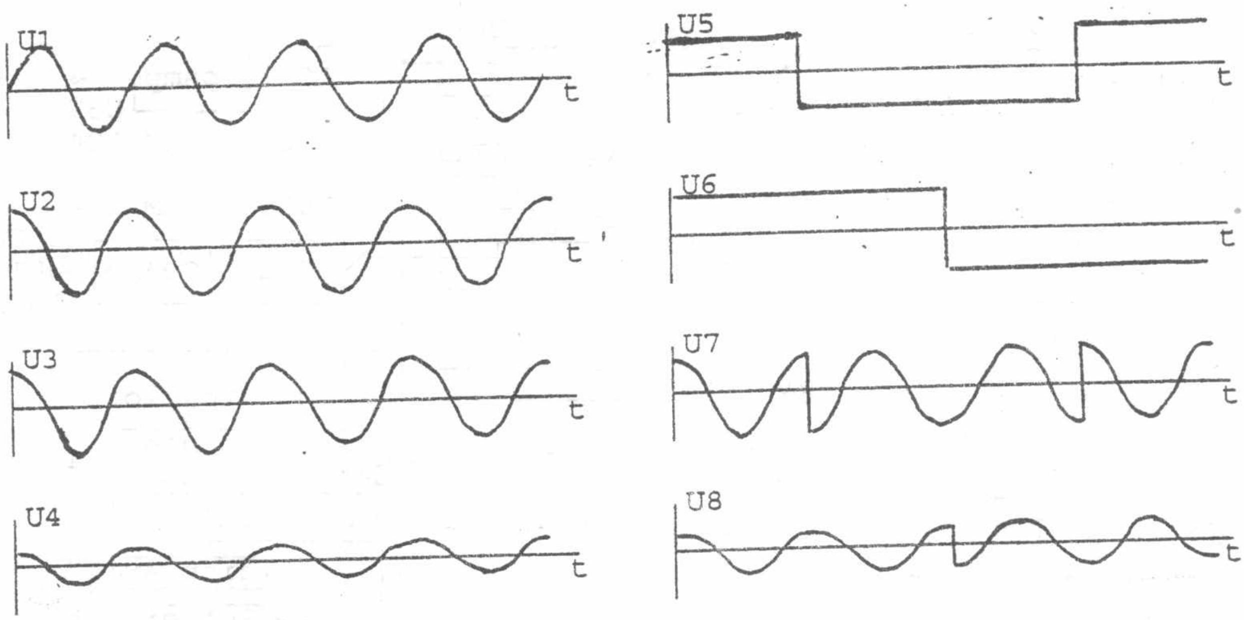


Fig.3 Waveforms at different test-points of ADF receiver

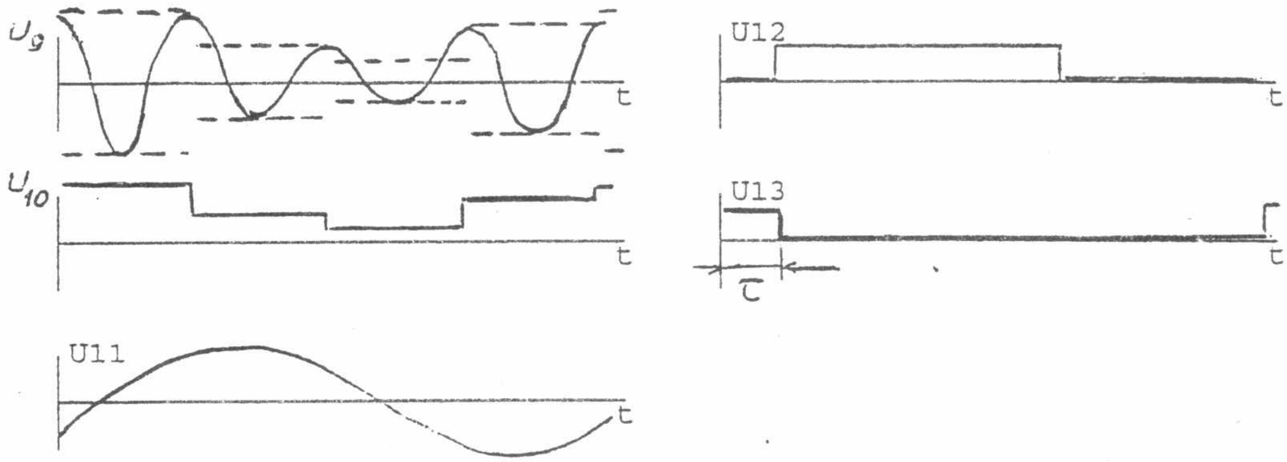


Fig.3 Waveforms at different test-points of ADF receiver (cont.)

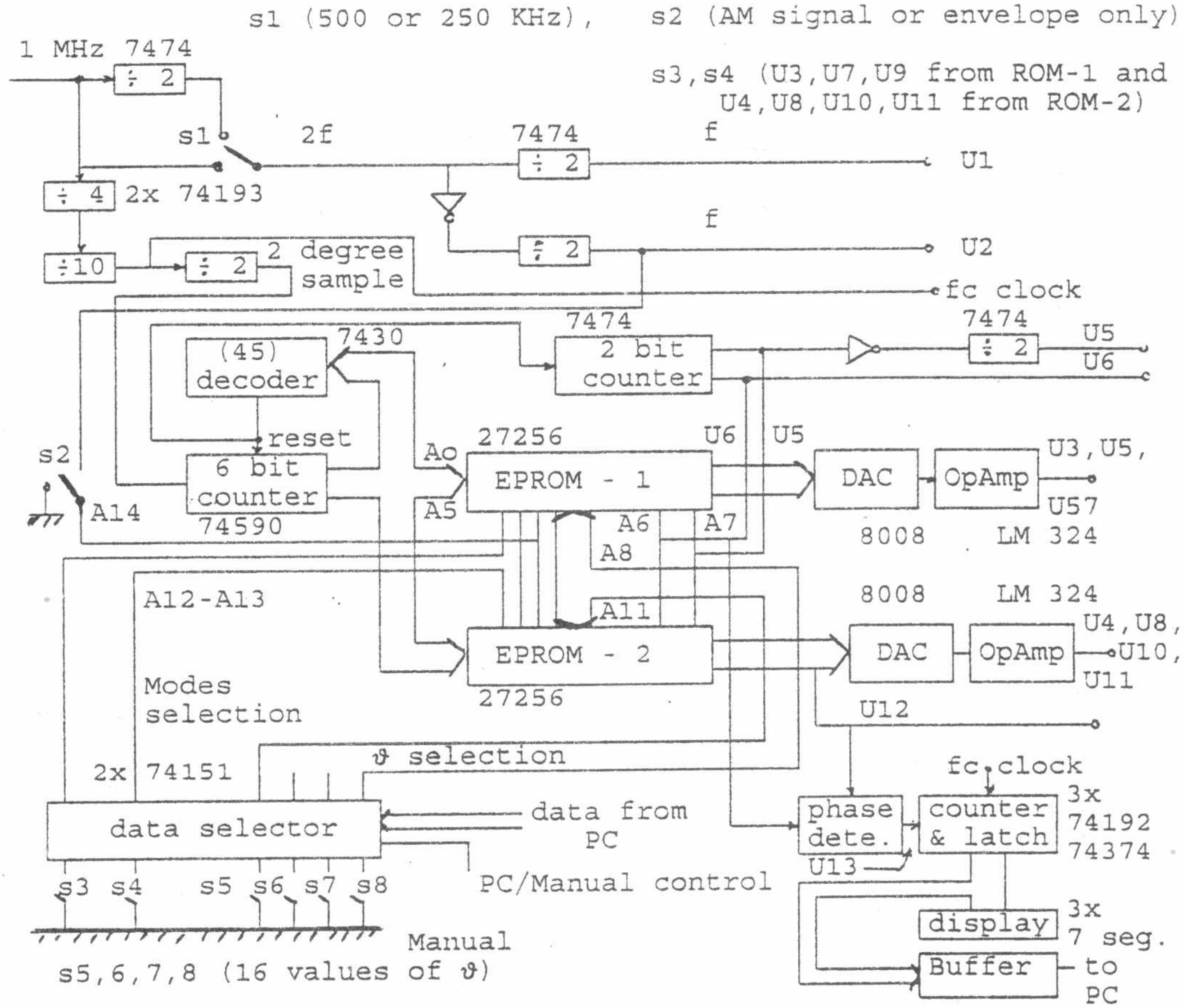


Fig.4 Digital simulation of ADF receiver

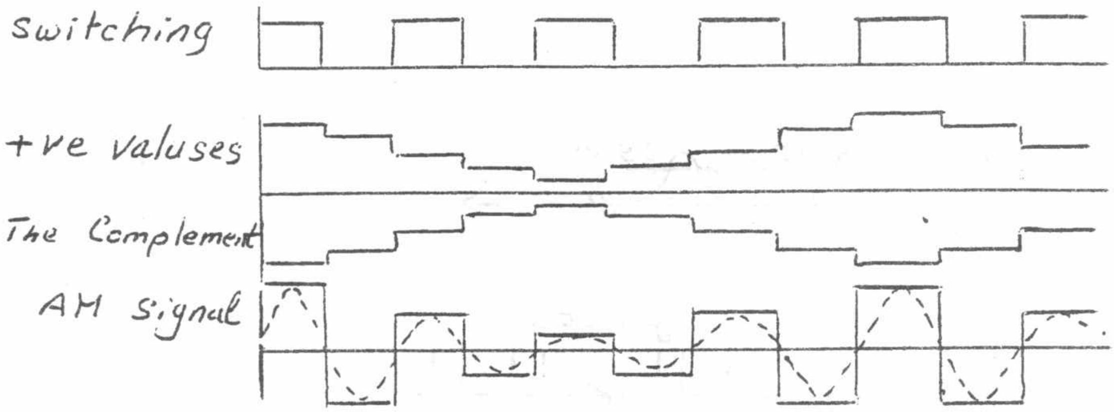


Fig.5 Digital simulation of amplitude-modulated signal

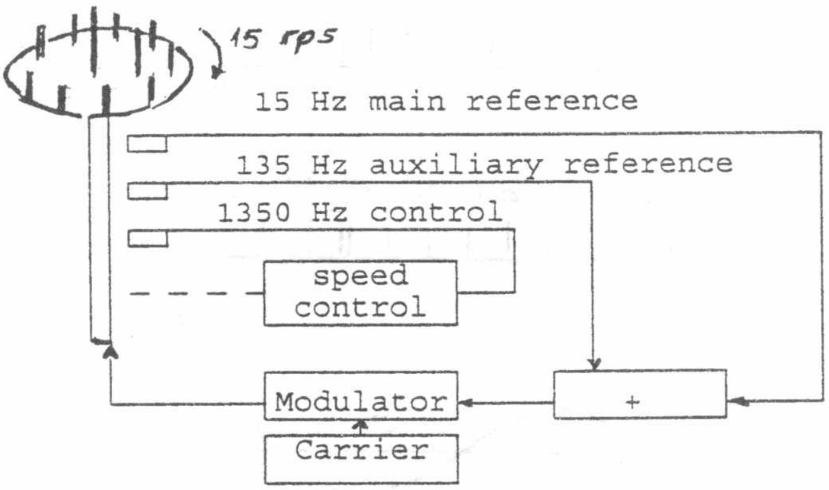


Fig.6 TACAN ground transponder (transmitter) functional diagram

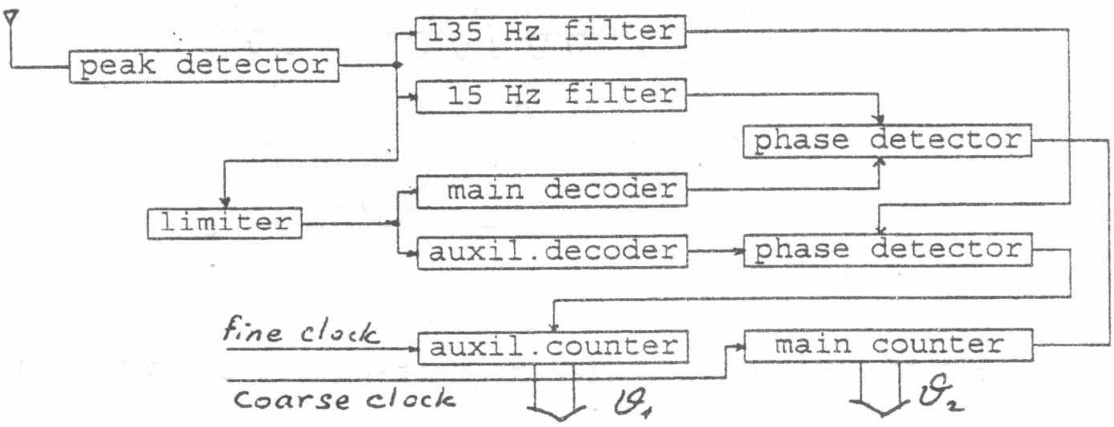


Fig.7 Airborne receiver functional diagram

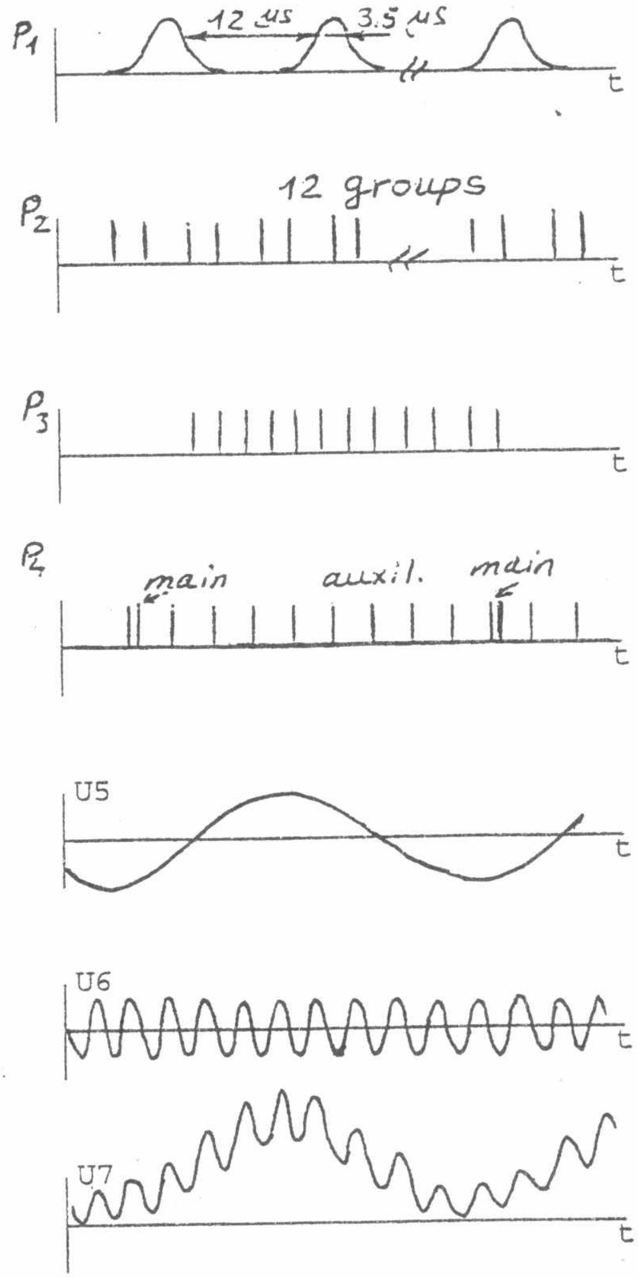


Fig.8 Waveforms at different test-points of TACAN subsystem

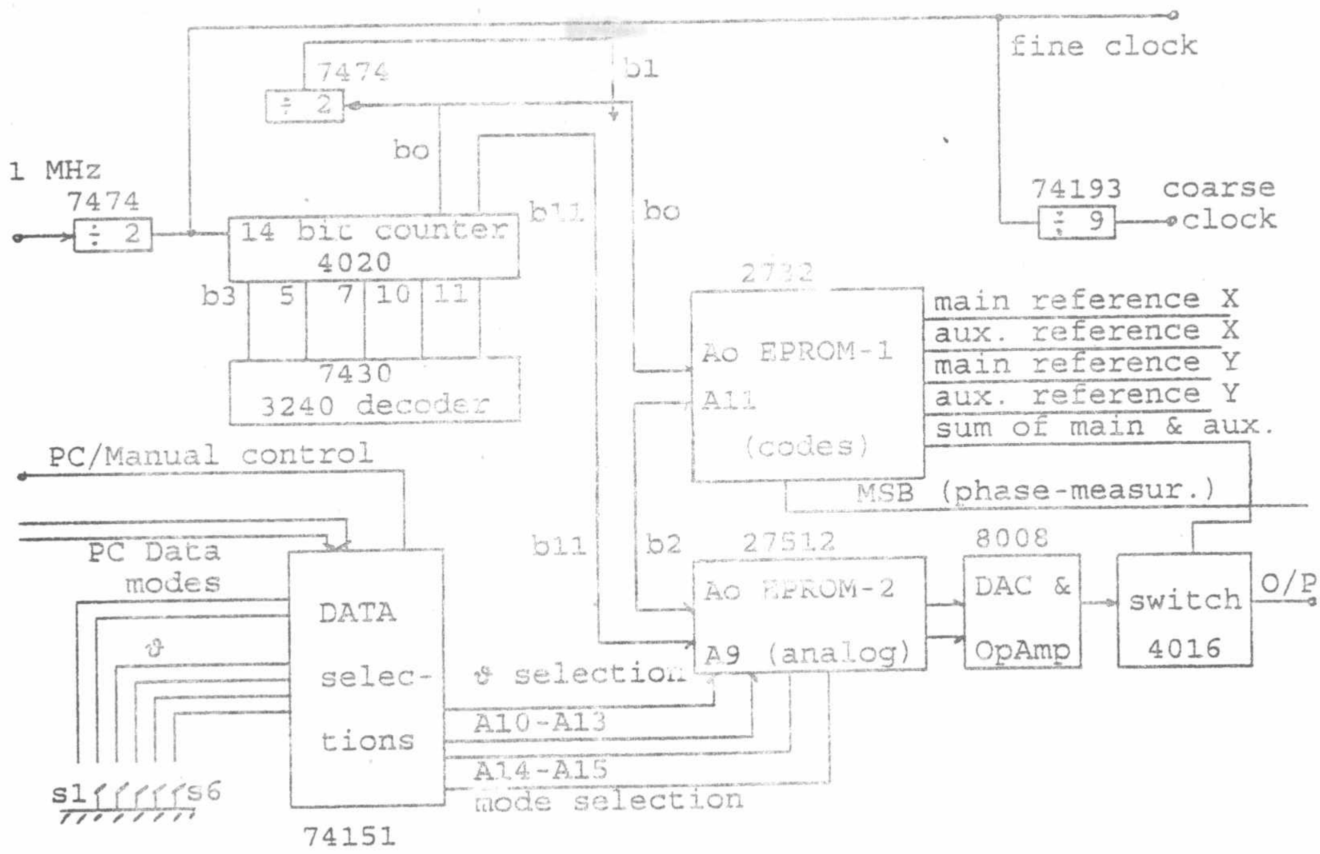


Fig.9 Digital simulation of TACAN bearing subsystem