

Rapport nr. 86.164

NGU TFEM-85

A Time- and Frequency-domain
Electromagnetic System.
Project Research Report



Norges geologiske undersøkelse

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Sammendrag: The report introduces the NGU TFEM-85 time- and frequency-domain electromagnetic system developed at the Geological Survey of Norway. A general description of the system design, and a more specific description of the receiver-coil system, the receiver, the transmitter and the power supply units is given. The report does not include details of the theory, the hardwares and the programs.			
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Instrument			

NGUTFEH-85:

A TIME- & FREQUENCY-DOMAIN ELECTROMAGNETIC SYSTEM

Project Research Report

1986

Geological Survey of Norway

Geophysics Section

PREFACE

This report introduces the NGUTFEM-85 time- & frequency- domain electromagnetic system developed in the Geological Survey of Norway (NGU). This project was started in 1982. From June to October in 1985 it was tested seven times over a near surface conductor at Tempervoll, Trondheim and twice over a deeply buried conductor at Kangsvoll, Hjerlann. During the second test at Kangsvoll, it successfully recorded some smooth anomalies indicating a conductor some 400M under the ground (see Document 6).

The test work of the system is far from enough, and the existing system is only a prototype. A few problems remains to be solved and some suggestions of improvement have been proposed. Unfortunately, all the members of the project have left NGU by now. Therefore, a report has to be written as a preliminary summary, and it is hoped to be helpful for those who would continue the test work with the system or take over to improve it.

Being only a preliminary summary of the project, this report does not include details of the theory, the hardwares and the programs. If any of them are interested, please contact the ex-members of the project or the compiler.

This project was started by Per Eidsvig and Inge Vivaas. Bin Qian joined in the project in May 1983 and Kaare Høy in August 1984 when Vivaas quitted.

Per Eidsvig, the project manager in the first two and half years, was in charge of the whole system. Among other things, he developed the first model transmitter, wrote some calculation and monitoring programs for the receiver, and collaborated with Qian on the receiver-coil system. Inge Vivaas worked on the digital part of the receiver, which includes data storage in a Bubble memory, clock circuit, multiply/divide units, key board and display, and the related programs and computer work, etc. Bin Qian worked on the data acquisition part of the receiver, the related control circuits and the main program and subroutines of the receiver. When Eidsvig quitted in May 1985, Qian took over to adapt Eidsvig and Vivaas's work to the system, and developed the second model transmitter and a switching-type power supply unit, collaborated with Høy. Qian quitted in November 1985. Kaare Høy did most assembling work of the coil system, the receiver and the first-model transmitter, some programing work, and all the hardware work of the power supply unit and the second model transmitter. He also made the spare cards for the system.

The boxes of the instruments, the frame of the coil system, the Helmholtz coil, etc., were made in the workshop of NGU. Many individuals in NGU and NTH helped with the development, field testing and data processing work of the project.

This report is compiled after the compiler has left NGU for a few months. It is mainly based on the program lists, circuit drawings, notebooks, and most important of all, the memory. It is impossible for the compiler to check anything with the system when he felt uncertain about it. There must be some mistakes and omissions through out the report. The compiler would also apologize for his limited knowledge on the project and poor language ability.

Corrections, comments, discussions and advices are warmly welcomed. It is the compiler's hope that this system can work well, and can be developed further.

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(compiler)

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April 1986.

CONTENTS

	Page
I. Introduction	1
1.1 The NGUTFEM-85 system	1
1.2 Important features	2
1.3 Specifications	3
II. Fundamentals of System design	6
2.1 Secondary field signals	6
2.2 Parameters of the primary field waveform	9
2.3 Frequency bandwidth of the receiver system	10
2.4 Higher sensitivity for later channels	13
2.5 Normalization of measured data	13
2.6 Correction of delay time	13
2.7 Channel arrangement	15
2.8 Frequency-domain measurement	17
2.9 Amplifications and dynamic range	17
III. Receiver-coil system	19
3.1 Configuration	19
3.2 Calibration	19
3.3 Preamplifier	20
IV. Receiver	22
4.1 Introduction	22
4.2 Hardware discription	23
4.3 Operation procedures	27
4.4 Main program (SCALK)	28
4.5 Scaling	32
4.6 Overflow handling	33
4.7 Lowering amplifications	34
4.8 Statistic calculation (sub. CAL2)	34
4.9 Monitor (sub. MON)	37
4.10 Explanation of instruction list	38
4.11 Memory map	39
V. Transmitter	40
5.1 Introduction	40
5.2 Hardware discription	40
5.3 Main program	43
5.4 Monitor (sub. MON)	44
VI. Power supply unit	46
VII. Field tests	47
VIII. Problems and suggestions	48
8.1 Receiver	48
8.2 Transmitter	48
8.3 Data processing	49
Appendix. A list of other NGUTFEM-85 documents	50

I. INTRODUCTION

1.1 The NGUTFEM-85 system

The NGUTFEM-85 system is a time- & frequency- domain electromagnetic prospecting system. It consists of seven parts: a transmitter, a power supply unit, a generator, a transmitter loop or grounded cable, a receiver with separated battery pack, a receiver-coil system, and a station computer HP-85. See Document J for the outlooks and inner structures of the instruments and the coil system. The power supply unit converts the 220v AC power from the generator into a DC power as the transmitter power source. The transmitter sends strong current pulses into the large fixed transmitter loop or the grounded cable, and thus sets up an on-off type of primary field as shown in fig.1-1A. Each transmitter pulse has a quickly ended trailing edge. If there is any conductor in the adjacent area of the transmitter loop, an eddy current (fig.1-1B) will be induced in the conductor. The eddy current will further induce secondary field emf's (fig.1-1C) in the receiver-coil system nearby. The receiver samples the primary and secondary field signals by a number of channels and averages the samples over many transmitting cycles to raise the S/N ratio. The measured data are stored in a 1 mega-bit Bubble memory and later transferred to the station computer, HP-85, for mass data storage and data processing.

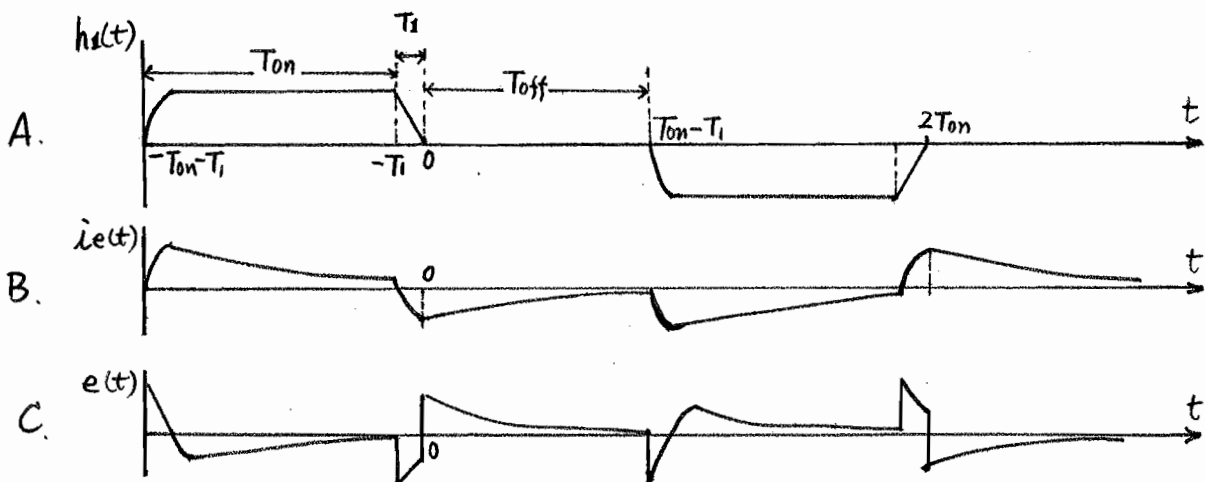


Fig.1-1 A) Primary field waveform. B) Eddy current.
C) Secondary field emf induced in a receiver coil.

The NGUTFEM-85 system measures the primary and secondary fields in both time and frequency domain simultaneously. Primarily it is a TDEM system. As the transmission is pulsed, pure secondary field measurement can be realized at the total absence of the primary field during the transmitter-off time (T_{off} , fig.1-1), thus the influence of the primary field is removed. The investigation depth can be greatly increased by using high transmitter power. This is the essential characteristic of the TDEM measurement using an on-off type of primary field waveform.

Being a periodic signal, the primary field is very rich in harmonics:

$$h_1(t) = \sum_{n=1,3,\dots} C_n \sin(2\pi n f_1 t + p_n)$$

where C_n and p_n are the amplitude and phase of the n -th harmonic component, f_1 is the fundamental frequency of the primary field waveform. For the NGUTFEM-85 system $f_1=25\text{Hz}$. In theory, a TDEM system is equivalent to a multifrequency EM system. It is suitable for detecting a wide variety of conductors. This is another important feature of the TDEM measurement.

If the target conductor has a very long time constant, a TDEM system may fail to detect it (see Sect.2.2). Being also a frequency-domain system, the NGUTFEM-85 has two frequency-domain channels measuring the fundamental-frequency component of the vertical field. This measurement helps to reduce the danger of missing good conductors.

Statistic calculation is carried out during the measurement to estimate the data quality and to suppress strong interferences.

The system measures two spatial magnetic components simultaneously, so as to acquire more information about the geometry of the target in one attempt. Each spatial component is sampled by 8 time-domain (TD) channels.

With only 15 Kg to carry between measurement stations on surface traverses, the receiver-coil system and the receiver were designed to be operated by only a single operator.

1.2 Important features

- A). Real time statistic calculation to ensure the desired quality of data and to speed up the measurement.
- B). Simultaneous measurements in time and frequency domain.
- C). Simultaneous measurements of two spatial components of the magnetic field.
- D). High frequency coils for early channels and high sensitivity coils for later channels.
- E). Full overflow control.
- F). Safe, quick and power-saving data storage in Bubble memory.
- G). Automatic scaling or manual setting of amplification.

- H). Wide dynamic range and high resolution.
- I). Instantaneous monitoring during measurement.
- J). Water-proof and light-weighted receiver and coil system.
- K). PROM selectable sampling arrangement.
- L). Wireless crystal clock synchronization.
- M). Analog output for modelling purpose.

1.3 Specifications

A). Coil system and Receiver

Weight

Receiver	4.2 Kg
Coil system	5.4 Kg
Tripod	1.6 Kg
Battery pack	3.2 Kg
Carrier of receiver and battery	0.8 Kg
Total	15.3Kg

Size

Receiver	28.5x18x24	cm
Battery pack	22x13x8	cm
Coil system	44x44x9	cm
Tripod	78x9x9	cm

Power supply 15v/7AH rechargable battery pack

Power consumption

off (oscillator and counter on)	130 mA
5v on	200 mA
all on	400 mA

Sensitivity of coils

Low frequency coils	3200v/(Tesla.Hz)
High frequency coils	1200v/(Tesla.Hz)

Number of sampling channels

18

16 in time domain and 2 in frequency domain.

Channel width

19.58 us--1250 us.

Amplification

Preamplifiers	x4,x16,x64,x256
Intermediate amplifiers	x1,x4,x16,x64 for TD channels x16,x512 for FD channels
Last amplifiers	x1,x4,x16,x64

Dynamic range

TD channels: 4**9 FD channels: 2*(4**8)

Resolution (nv)

Primary field channels: 74.5
Secondary field channels s1: 37.3 s2: 18.6
s3: 18.6 s4: 9.31
s5: 4.66 s6: 2.33
s7: 1.16
Frequency-domain channels: 0.46 (peak value)

Maximum input 1.25v (peak value)

Temperature range 0 Deg.C.--?

Stacking time at each station: 28+(NH-23)x0.56 sec.
NH:23--65535,selectable via key board. Default value: 200.

Data storage: 128 bytes stored in a 1 mega-bit bubble memory at each station.

Amplification setting

Automatic scaling for all amplifiers in 2 seconds, or
Manual setting via keyboard, or
remaining the previous amplifications.

Synchronization: oven-stabilized crystal oscillators keep synchronization (drift<10 us within 8 hours).

Data output

8-bit parallel interface to computers;
8-character LCD on the panel;
One analog output for laboratory modelling purpose. Channel selectable among V0--V7 via keyboard.

Frequency bandwidth

High frequency channels: 1.6Hz--10KHz;
Low frequency channels: 1.6Hz--3KHz;
Frequency-domain channels: 24-26Hz.

B). Transmitter

Weight 11 Kg
Size 40x36x22 cm
Input voltage AC 220v for operation
DC 10--220v for transmission
Output current 0.1--10 A
Loop size no limit
Loop resistance limit 1--2000 ohm
Pulse width 10 ms

Accuracy of displayed parameters

Current	0.1 A
AC voltage	1 v (RMS)
DC voltage	1 v
Loop resistance	0.1 ohm
Synchronization	1 us
Width of trailing edge	1 us

C). Power supply unit

Weight	18 Kg
Size	40x36x22 cm
Input voltage	AC 220v (+/- 20%), 50-400 Hz
Output voltage	DC 32--212v
Output current	6A (DC); 10A (pulsed; 50% duty cycle)
Output short-circuit protection	
High temperature protection	70 deg.c. on heat sink

II. FUNDAMENTALS OF SYSTEM DESIGN

2.1 Secondary field signals

The first pulse of the primary field waveform shown in fig.1-1A can be expressed as

$$h_1(t) = [1 - \exp(-t'/TL)]U(t') - (t''/T_1)U(t'') + (t/T_1)U(t)$$

where $t' = t + T_{on} + T_1$, $t'' = t + T_1$, T_{on} is the duration of the transmitter on-time, T_1 is the width of the trailing edge of the pulse, TL is the time constant of the transmitter loop, and $U(t+x)$ is a step function started from $t = -x$. The Laplace transformation of $h_1(t)$ is

$$H_1(s) = [1/s - 1/(s+1/TL)] \exp[(T_{on}+T_1)s] - [\exp(T_1*s) - 1]/(T_1*s*s)$$

For convenience of analysis, a single-turn conducting loop model with a self inductance L and a resistance r is used to simulate the target conductor (fig.2-1). Under the excitation of the primary field $h_1(t)$, an eddy current $i_e(t)$ is induced in the model and it further induces a secondary field emf $e(t)$ in the receiver coil. Since the initial amplitude of $h_1(t)$ and consequently that of the eddy current in the model are zero, the secondary field emf induced in a receiver coil can be related to the primary field by

$$E(s) = K*s*s*H_1(s) / [L(s+1/T_c)]$$

where $T_c (=L/r)$ is the time constant of the model, K is a geometrical coefficient. To concentrate on the question that how the resistance of the model affects the behavior of the secondary field, we vary only the resistance of the model and keep all the other parameters of the modeling system (size and shape of the model, geometry of the modeling system, transmitter power, etc.) unchanged, so that both K and L will be constants and can be omitted, and T_c will be inversely proportional to r .

The time function of $E(s)$ is

$$e(t) = [A*\exp(-t'/TL) - B*\exp(-t'/T_c)]U(t') - C*\exp(-t''/T_c)U(t'') + C*\exp(-t/T_c)U(t), \quad T_c \neq TL \quad (2-1)$$

or when $T_c = TL$, it becomes

$$e(t) = D*\exp(-t'/T_c)U(t') - C*\exp(-t''/T_c)U(t'') + C*\exp(-t/T_c)U(t) \quad (2-1a)$$

where $B = 1/(T_c - TL)$, $A = B*T_c/TL$, $C = 1/T_1$ and $D = (1 - t'/T_c)/T_c$. A typical secondary field emf is shown in fig.1-1B. It has a complicated shape in the on-time.

If T_c and/or T_L are comparable with or longer than T_{on} , influence of residuals of the secondary field excited by the preceding primary field pulses should be taken into consideration. Then in the off-time, the secondary field emf will be

$$e(t) = A * F(T_L) \exp(-t'/T_L) - F(T_c) [B * \exp(-t'/T_c) + C * \exp(-t''/T_c) - C * \exp(-t/T_c)], \quad 0 < t < (T_{on} - T_1), \quad T_c \neq T_L \quad (2-2)$$

where $F(x) = 1/[1 + \exp(-2T_{on}/x)]$. In most cases $T_L \ll T_{on}$, and later it will be proved that the system is not suitable for detecting conductors with $T_c > T_{on}$. For the purpose of calculating system parameters, we use a simplified and normalized expression of $e(t)$:

$$e(t) = G * \exp(-t/T_c), \quad 0 < t < (T_{on} - T_1) \quad (2-3)$$

where $G = 1 - \exp(-T_1/T_c)$.

For the induced emf, the coil behaves exactly in the same way as a 2nd-order lowpass (LP) filter. The output of the coil is

$$U(s) = [W_n * W_n / (s^2 + 2d * W_n * s + W_n * W_n)] E(s)$$

where $W_n = 2\pi * f_n$, f_n and d are the natural frequency and the damping coefficient of the coil, $\pi = 3.14159$. Under the condition that $T_L \ll T_{on}$, the time function of $U(s)$ in the transmitter off-time can be expressed as

$$u(t) = H * e(t) + I * \exp(-d * W_n * t) = u_1(t) + u_2(t), \quad 0 < t < (T_{on} - T_1) \quad (2-4)$$

where $u_1(t) = H * e(t)$, $u_2(t) = I * \exp(-d * W_n * t)$, I is a function of time (expression omitted), and

$$H = W_n * W_n / [W_n * W_n + 1 / (T_c * T_c) - 2d * W_n / T_c].$$

There is an AC coupling capacitor in each of the four linear circuit channels of the receiver. This capacitor, together with the input impedance of its following circuit, forms a 1st-order highpass (HP) filter. While considering the HP filter response, we assume that f_n is high enough so that the transfer function of the coil is essentially 1. Then the response of the HP filter is

$$U_h(s) = [s / (s + 2\pi * f_h)] U(s) = [s / (s + 2\pi * f_h)] E(s)$$

where f_h is the lower cut-off frequency of the HP filter. In the off-time, the time function of $U_h(s)$ is

$$u_h(t) = J * e(t) + K * \exp(-2\pi * f_h * t) = u_{h1}(t) + u_{h2}(t), \quad 0 < t < (T_{on} - T_1), \quad (2-5)$$

where $u_{h1}(t) = J * e(t)$, $u_{h2}(t) = K * \exp(-2\pi * f_h * t)$. J and K are functions of T_c , f_h , T_1 and T_{on} (expressions omitted).

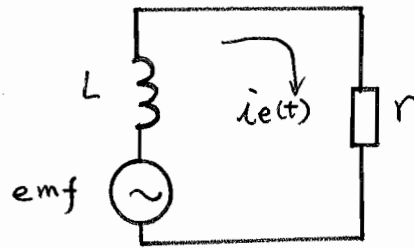


Fig.2-1 Conducting loop model of a conductor.
 emf: induced electromotive force.
 $i_e(t)$: eddy current.

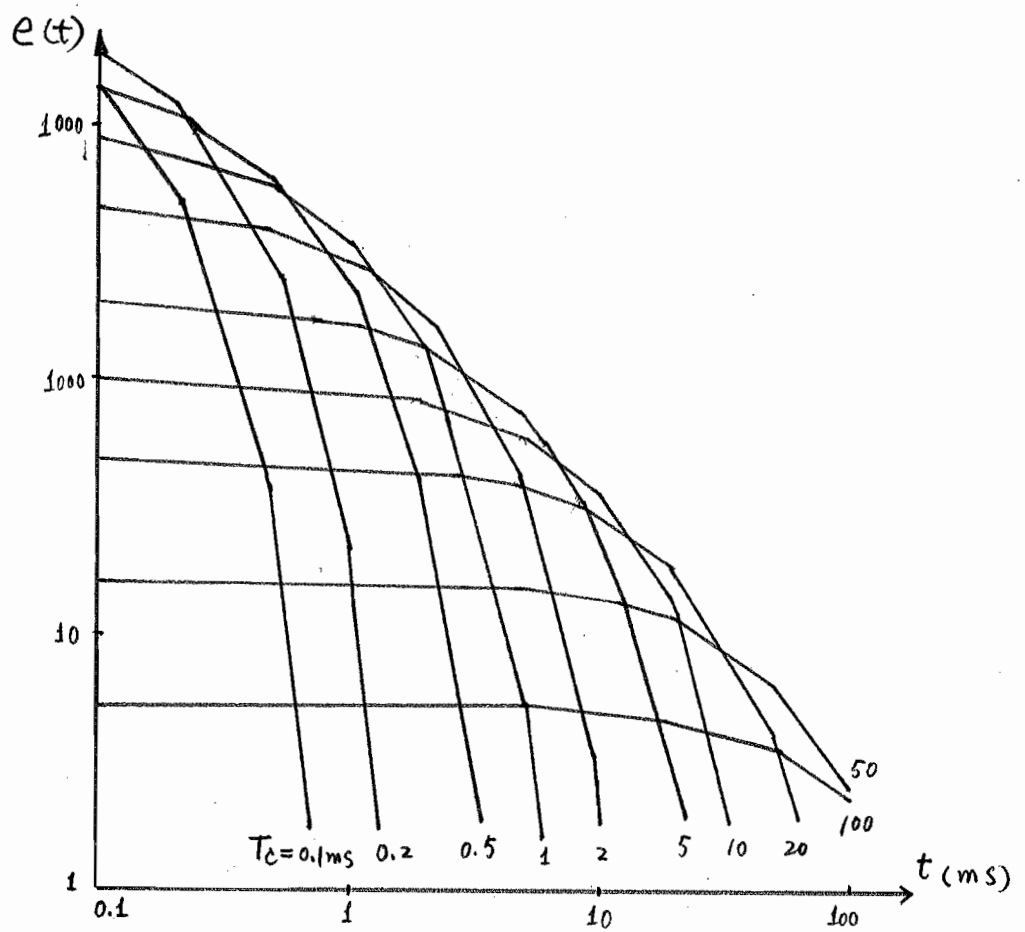


Fig.2-2 Secondary transient emf in the off-time.
 $T_{on}=100ms$, $T_1=0.2ms$.

2.2 Parameters of the Primary field waveform

Primary field waveform as shown in fig.1-1A was adopted by the NGUTFEM-85 because of the following advantages of the waveform: 1, pure secondary field measurement can be realized; 2, this waveform is suitable for exciting a wide range of conductors; 3, it is easy to generate; 4, there is almost no limit on the transmitter loop size and shape; 5, high transmitter power can be conveniently applied.

Once the shape of the waveform is decided, there are only four parameters to be selected: the transmitter on-time (T_{on}), the width of the trailing edge (T_l), the amplitude of current, and the rising rate of the leading edge. The rising rate of the leading edge only depends on the loop inductance and resistance. It has little influence on the measurement. The current is limited to within 10A for the prototype and it can be easily raised in a new design. Selections of T_{on} and T_l are more closely related to the properties of the targets.

Figure 2-2 shows a group of $e(t)$ curves in the off-time computed according to eq.(2-2). Although $e(t)$'s with different T_c 's have different initial amplitudes, there exists a time slot for each $e(t)$ where it is at a maximum relative to all the others. And for any $e(t)$ with a T_c within the range ($T_l, T_{on}-T_l$), its corresponding time slot is located at $t=T_c$. Therefore, $e(t)$'s with their T_c 's within ($T_l, T_{on}-T_l$) will get fairly equal chance to be detected despite of the difference of the initial amplitudes, if the noise level is low enough. On the other hand, conductors with their T_c 's out of this range ($T_l, T_{on}-T_l$) will get little chance to be detected, or in other words, a TDEM system is not suitable for detecting conductors with their T_c 's out of the range ($T_l, T_{on}-T_l$). T_l and T_{on} should be selected deliberately to meet the prospecting purpose.

When selecting T_l , the following factors should be taken into consideration:

A). Conducting overburdens and poor conductors often have short T_c 's. For mapping purpose, T_l may need to be short. While for detecting big and good conductors, T_l should be long enough to suppress the responses from overburdens.

B). Shorter T_l will lead to higher peak value of emf during the trailing edge time, and therefore, wider dynamic range of the receiver is required.

C). The primary field is sampled for about 20 μs during the trailing edge time, so T_l should not be too short.

D). For the NGUTFEM-85 system, the delay time of the first channel from the end of the trailing edge is about 140 μs . T_l needs not to be shorter than this value, not even for the mapping purpose.

E). T_1 should not be longer than 2.5ms, or the last channel S7 will fall into the transmitter on-time.

In practice, a T_1 value in the range (100us, 1000us) is relevant.

T_1 can be found by the approximative formula:

$$T_1 = 2V_t * L / [R(V_t + 2V_z)], \quad V_t < 5V_z$$

where L and R are the inductance and resistance of the transmitter loop, V_t is the transmitting voltage and V_z is the total zener voltage of the zener diodes (D9 and D10, Document D, p.1) in the transmitting network. V_z is about 110v for the presently used diodes. It can be any value between 20v and 200v. When using a grounded cable, an extra air-cored inductance can be put in series with the cable for proper length of T_1 . The real value of T_1 is read from the transmitter during transmission.

For the NGUTFEM-85 system, T_{on} is fixed to 10ms. This was a result of a compromise of the following considerations: target conductors to be detected, suppression to the 50Hz power-line interference, total stacking time needed at each station, etc. T_{on} can be varied by a few changes in receiver and transmitter if necessary.

2.3 Frequency bandwidth of the receiver system

The primary and secondary field signals are periodic pulse sequences which are rich in harmonics. To keep the signals from being seriously distorted, the receiver system, which consists of the receiver coils and the receiver, must have a wide frequency bandwidth. This bandwidth is actually limited by the lower cut-off frequency (f_h) of the 1st-order HP filter in the receiver and the natural frequency (f_n) of the receiver coil.

A). Natural frequency of receiver coils

$u(t)$ defined by eq.(2-4) consists of two parts, $u_1(t)$ and $u_2(t)$. $u_1(t)$ is the forced oscillation of the coil due to $e(t)$ and proportional to $e(t)$, and therefore the signal to be measured. $u_2(t)$ is the free oscillation of the coil, behaving as an interferer. If f_n is high, $u_2(t)$ dies out after a short time, we call it recovery time T_r . But at the beginning of the transient it has strong influence over the measurement of $u_1(t)$. Fig.2-3 shows some curves of $e(t)$ and $u(t)$. $u(t)$ with $f_n=10\text{KHz}$ (curve 3) agrees well with $e(t)$ (curve 1) after a recovery time, T_r , of about 160us. If $f_n=30\text{KHz}$, T_r is only 60us. But if $f_n=3\text{KHz}$, it will be 500us. T_r is actually the time needed for $u_2(t)$ to decay to a negligible level relative to $u_1(t)$, i.e.:

$$u_2(T_r) = E_r * u_1(T_r) \quad (2-6)$$

where E_r is the acceptable relative error.

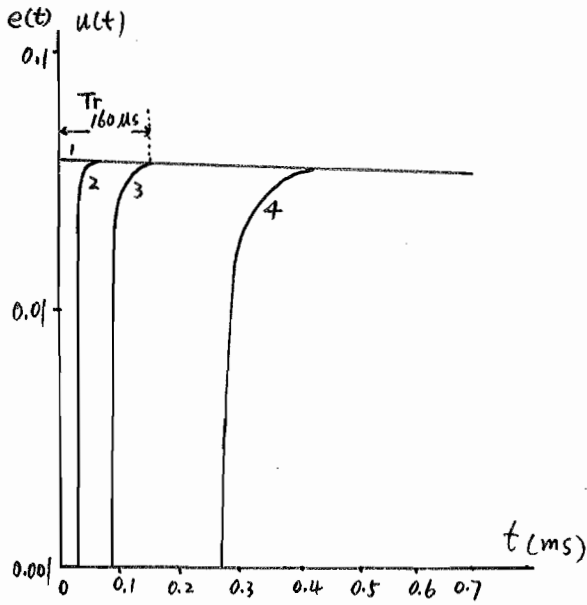


Fig.2-3 $e(t)$ and $u(t)$ curves in the off-time. $T_c=5\text{ms}$.
 1) $e(t)$. 2) $u(t)$, $f_n=30\text{KHz}$.
 3) $u(t)$, $f_n=10\text{KHz}$. 4) $u(t)$, $f_n=3\text{KHz}$.

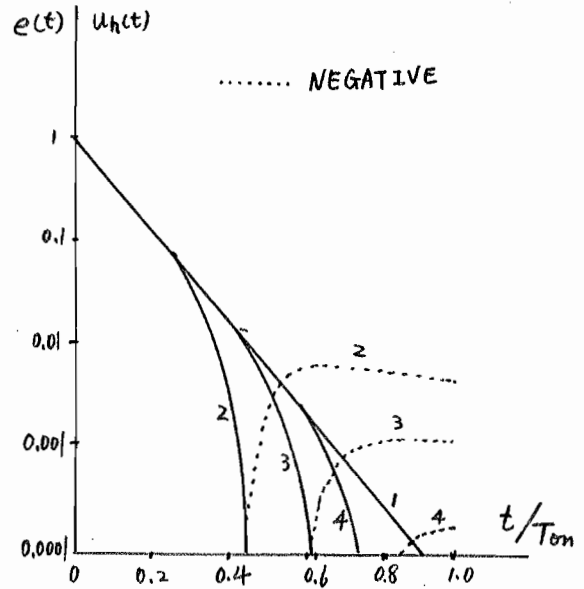


Fig.2-4 $e(t)$ and $u_h(t)$ curves in the off-time. $T_c=0.1T_{on}$.
 1) $e(t)$. 2) $u_h(t)$, $f_h=f_1$.
 3) $u_h(t)$, $f_h=0.5f_1$. 4) $u_h(t)$, $f_h=0.25f_1$. $f_1=(1/4T_{on})=25\text{Hz}$.

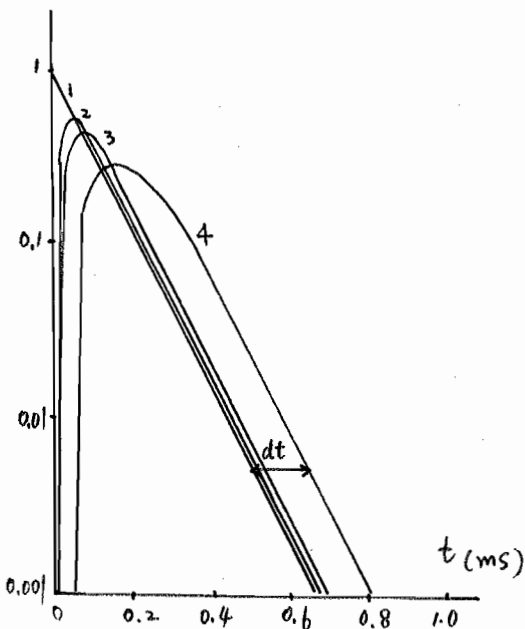


Fig.2-5 $e(t)$ and $u(t)$ curves in the off-time. $T_c=0.1\text{ms}$.
 1) $e(t)$. 2) $u(t)$, $f_n=30\text{KHz}$.
 3) $u(t)$, $f_n=10\text{KHz}$. 4) $u(t)$, $f_n=3\text{KHz}$.

If the receiver starts sampling the transient before the recovery time is passed, a rather erroneous result or false anomaly should be expected.

According to eqs. (2-4) and (2-6), an approximate formula is established:

$$f_n \geq [1 / (2\pi * d)] \{ 1 / T_c - (1 / T_r) \ln [E_r - E_r * \exp(-T_1 / T_c)] \} \quad (2-7)$$

This formula can be used to calculate f_n according to the given conditions and demands for T_1 , T_c , T_r , d and E_r . Here T_r should be replaced by T_s , which is the delay time of the center of the first sampling channel from the end of the trailing edge. For example, if $d=1$, $E_r=3\%$, $T_1=200\mu s$, $T_s=140\mu s$ and T_c ranges from 0.1ms to 5ms, $f_n=7.7\text{KHz}$ is the lowest acceptable value.

As LP filters are used in the receiver as well and they will cause errors in the same way as the receiver coil does, a little higher value of f_n , 10KHz, was selected.

B). Lower cut-off frequency

Similar to $u(t)$, the HP filter response $u_h(t)$ defined by eq. (2-5) also consists of 2 parts, $u_{h1}(t)$ and $u_{h2}(t)$. $u_{h1}(t)$ is the signal to be measured and $u_{h2}(t)$ behaves like an interferer. Fig. 2-4 shows the $e(t)$ and some $u_h(t)$ curves. In the later parts of the $u_h(t)$ curves the polarities were reversed. The maximal amplitudes of the negative values of curves 2 and 3 are approximately 0.6% and 0.12% of the initial amplitude of the transient. They are strong enough to be recorded by the receiver.

It has been proved that IP effects of some ore bodies in TDEM measurements can also result in polarity-reversed transients. Such polarity-reversed transients have similar shapes as those shown in fig. 2-4. So IP effects of ore bodies and the HP filter effect in the receiver can both finally result in polarity-reversed transients in TDEM measurements. But their meanings are completely different. Those caused by IP effects carry important information of the ore bodies, while those by the HP filter effect are false anomalies and could lead to wrong conclusions. Therefore, the lower cut-off frequency of the receiver system should be low enough, so as to ensure that the distortions caused by the HP filter effect would be within some acceptable limits, and the measured data would really represent the true anomaly caused by the target. Calculations show that the maximal negative transient will be within 0.01% of the initial transient amplitude if the inequality

$$f_h < f_1 / 5$$

is satisfied. In case the order of the HP filter is higher than 1, the inequality should be replaced by:

$$f_h < f_1 / (5n)$$

where n is the order of the HP filter.

For the NGUTFEM-85 system, f_h is 1.6Hz ($=0.064f_1$). As the dynamic range of the system is tremendously wide, the polarity-reversed transient still can be observed clearly when a pure exponential calibration signal with a short T_c was fed into the receiver.

2.4 Higher sensitivity for later channels

In Sect.2.3 $f_n=10\text{KHz}$ was selected for a fast frequency response which is necessary for the early sampling channels. For the later ones, however, the frequency response is not so critical. As the transients are much weaker in the later time, higher sensitivity of the coil is more significant. Therefore, another coil with lower natural frequency but higher sensitivity was designed for the later channels (s_4, s_5, s_6 and s_7). The center of s_4 is about 860 μs from the end of the trailing edge. Let $T_s=860\mu\text{s}$, $d=1$, $E_r=3\%$, $T_1=200\mu\text{s}$ and $0.1\text{ms}<T_c<5\text{ms}$, f_n should be higher than 1280Hz according to eq.(2-7). 3KHz was selected considering the possible errors caused by the LP filters in the receiver. This relatively lower f_n means heavier suppression to high frequency interferences like VLF signals, and the sensitivity of the low- f_n coil is 2.6 times of that of the high- f_n one. Both are beneficial to the later channels.

2.5. Normalization of measured data

Since two different coils were used to detect the early and later parts of the transient separately, the measured data must be normalized. This can be done in the data-processing programs in the station computer by multiplying the measured values of the early channels by a factor of 2.6, or by dividing the measured values of the later channels by a factor of 2.6. Neither of these two ways of normalization has been applied to the data stored in the Bubble memory. In the MON(itor) program of the receiver, the former way was adopted when the measured values should be displayed on LCD.

2.6. Correction of delay time

Another thing one should take care of is the delay effect of the coils. Fig.2-5 shows transient signals with $T_c=100\mu\text{s}$. It is quite obvious that the $u(t)$ signals have been delayed by the coils. Now even after a recovery time T_r ($60\mu\text{s}$ for $f_n=30\text{KHz}$ and so on) is passed, $u(t)$ still cannot stand for $e(t)$. As a result of the delay effect, the actually measured values will be larger than what they should be. The relative error caused by the delay effect of the coil is defined as:

$$ER=[u(t)/e(t)-1]*100\%, \quad t>T_r.$$

Some calculated values are given in Table II-1. There we see that to keep the error within 10%, f_n should be higher than 30KHz to measure transients with small time constant. This high f_n will cause two problems: one is that for the same kind of receiver coil, higher natural frequency means lower sensitivity. Another is that higher natural frequency leaves more chances for noises and external interferences, such as VLF broadcasting, static noise, etc. These two factors together will to some extent reduce the signal-to-noise ratio.

Table II-1. Error caused by delay effect of the receiver coil (%)

f_n (KHz)	T_c (ms)			
	0.1	0.2	1.0	5.0
3	320.5	83.0	10.7	-0.2
10	41.4	18.0	3.3	0.6
30	11.5	5.5	1.1	0.2

In fig.2-5, after a necessary recovery time T_r , all the $u(t)$ curves are parallel to the $e(t)$ curve. In other words, when $t > T_r$, the difference between $e(t)$ and $u(t)$ is only a delay time dt . Then we have:

$$u(t) = e(t-dt), \quad t > T_r. \quad (2-8)$$

This equation tells us exactly how to correct the error caused by the delay effect of the coil, that is, to consider a measured value at time t as the $e(t)$ value at time $(t-dt)$. It is simple. No changes in the instrument or coil are needed.

To apply this correction, dt must be estimated. In eq.(2-4), when $t > T_r$, the second part is small enough to be ignored, then:

$$u(t) = H * e(t), \quad t > T_r. \quad (2-9)$$

From eqs.(2-8) and (2-9), we get:

$$dt = 2T_c * \ln(W_n) - T_c * \ln[W_n * W_{n+1} / (T_c * T_c) - 2d * W_n / T_c]. \quad (2-10)$$

To achieve the best correction, the dt value calculated for small T_c should be used because transients with small T_c are more sensitive to time changes. Table II-2 shows the relative errors left after applying the correction of delay time. The error is defined by:

$$ER_c = [u(t) / e(t-dt_{max}) - 1] * 100\%$$

where dt_{max} is the dt value calculated for $T_c = 100\mu s$. For f_n equal to or higher than 10KHz, the correction is exact.

Delay time caused by LP filters in the receiver should also be corrected. The total delay time is a sum of that by the coil and

those by the LP filters:

$$dt = \sum_i dt_i$$

Fourth-order Butterworth LP filter were used in the receiver to suppress the VLF interferences. This filter is actually two 2nd-order LP filters in series with damping coefficients $d_1=0.38$ and $d_2=0.92$. The damping coefficient d is 0.86 for high-fn coils and about 1 for low-fn ones. Eq.(2-10) can be directly used to calculate the individual delay time caused by each of them. The higher cut-off frequency of the LP filter is equal to the natural frequency of the corresponding receiver coil. The total delay time is calculated to be about 70us for the early channels and about 283us for the later channels.

A little big value of dt should be used because the other linear circuits, such as the preamplifiers, also have some delay effect. We take $dt=80\mu s$ for the early channels, and $dt=330\mu s$ for the later channels including the delay time caused by the 5KHz 1st-order LP filter in the low frequency preamplifier (fig.3-2). The last column in Table II-3 shows the centers of the sampling channels after the correction has been applied.

Table II-2. Error left after applying the correction (%)

fn(KHz)	Tc (in ms)			
	0.1	0.2	1.0	5.0
3	-0.2	-13.0	-4.1	-0.9
10	0.0	-0.8	-0.3	0.0
30	0.0	-0.1	0.0	0.0

2.7 Channel arrangement

To find the initial amplitude G and the time constant T_c of a pure exponential transient as expressed by eq.(2-3), two samples of the transient at two different delay times will be enough:

$$T_c = (t_2 - t_1) / [\ln(S_1) - \ln(S_2)] \quad (2-11)$$

$$G = S_1 * ((S_1/S_2) ** [t_1 / (t_2 - t_1)]) \quad (2-12)$$

where $S_1=e(t_1)$ and $S_2=e(t_2)$. Usually, the secondary transient is a combination of many pure exponential transients as follows

$$e(t) = \sum_j e_j(t)$$

To figure the combined transient to details, a big number of samples are obligatory. For each pair of adjacent samples, a pair of apparent time constant and initial amplitude can be found according to eqs.(2-11) and (2-12). Due to practical considerations of data quantity and necessity, the NGUTFEM-85 was

designed to sample the secondary transients in seven time intervals (channels). It also samples the primary field during the trailing edge time of the transmitter pulse. Fig.2-6 shows the eight sampling channels.

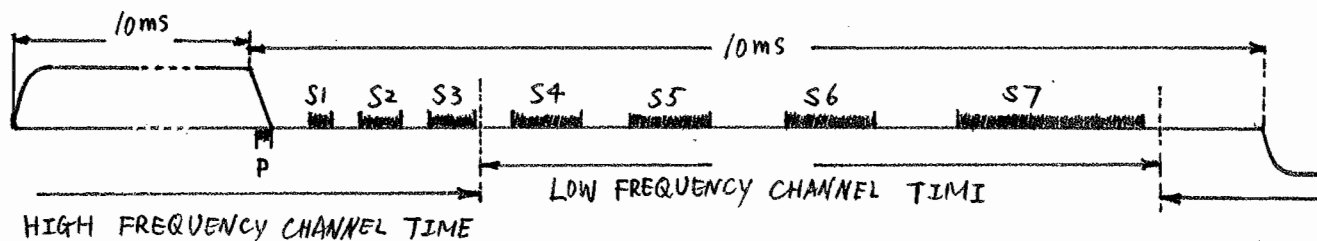


Fig.2-6 Sampling channels (not to the scale). P: primary field channel. S1-S7: secondary field channels.

The system measures two spatial magnetic components in the same time. It has 16 channels working in time-domain. In addition, it has another two time-sharing channels working in frequency domain. Fig.2-7 shows the relations between the channels and the coils, and Table II-3 lists the specifications of the channels. H0/V0 are horizontal/vertical primary channels (P). H1-H7/V1-V7 are horizontal/vertical secondary channels (S1-S7). V8 and V9 are vertical frequency-domain channels. FHH/FLH are high/low fn, horizontal coils and FHV/FLV are high/low fn, vertical coils.

Table II-3. Channel specifications (relative to the end of the primary pulse) (us)

channel	from	to	width	center	center*
H0,V0 (P)	-19.58	0	19.58	-9.79	/
H1,V1 (s1)	116.2	156.3	39.1	136.7	56.7
H2,V2 (s2)	234.4	312.5	78.1	273.5	193.5
H3,V3 (s3)	390.7	468.8	78.1	429.7	349.7
H4,V4 (s4)	781.3	937.5	156.3	859.4	529.4
H5,V5 (s5)	1562.5	1875.0	312.5	1718.8	1388.8
H6,V6 (s6)	3125.0	3750	625	3437.6	3107.6
H7,V7 (s7)	6250	7500	1250	6875	6545
V8,V9	/	/	20000*6	/	/

* Centers of the channels after the correction of delay time is applied.

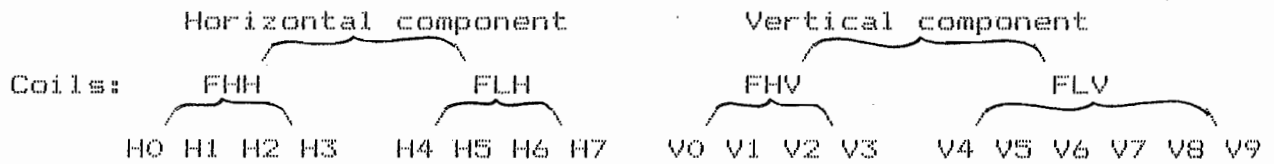


Fig.2-7. Relationship between coils and sampling channels.

2.8 Frequency-domain measurement

From Sect.2.2 we know that a TDEM system may fail to detect a very good conductor (T_c too long). This danger is reduced by the ability of measuring the primary field. In addition to this, the NGUTFEM-85 also measures two quadrature components of the fundamental frequency (25Hz) of the vertical field to ensure that no good conductors will be missed.

The 25Hz signal measurement is accomplished by applying analogue filtering, synchronized detection, multi-cycle averaging and digital "noise-filtering" techniques. The measured values, as can be seen from Documents F and G, were in good quality and highly reliable.

The two components, V8 and V9, are not exactly Re and Im components because the phase will change if the loop configuration varies. In practice, the initial phases of V8 and V9 can be found by measuring close to the loop. These initial phases are taken as references for the later measurements.

V8 is close to the real component and V9 is close to the imaginary component of the fundamental frequency of the primary field.

2.9 Amplification and dynamic range

In order to follow a flat anomaly caused by a deeply buried conductor, the measurement may have to be made from inside the transmitter loop to places kilometers away from it. The TDEM measurement, therefore, implies requirements for a large amplification and wide dynamic range in the instrumentation. A resolution of about 1 nV for the latest channels (H7 and V7) was claimed. To bring this weak signal up to 2.44mV which is the equivalence of one bit of the A/D convertor output, an amplification of more than two million is required.

The integrators I1 and I2 have a gain of 2 for the latest channels, so the total amplification of the amplifiers should be more than one million. This total amplification is realized by three stages of amplifiers: the preamplifier, the intermediate amplifier and the last amplifier, each with a dynamic range of 4×3 . The total dynamic range is 4×9 for the time-domain channels and $2 \times (4 \times 8)$ for the frequency-domain channels. In the field, a proper amplification is selected and distributed to the

three stages by the microprocessor according to the signal and noise level.

As a result of the large amplification and wide dynamic range, the resolution is 1.16nv for the latest channels and 0.46nv for the frequency-domain channels, and the input can be as high as 1.25v (peak value) which means measuring 2 meters away from the transmitter cable carrying a current of 5 A with $T_1=200\mu s$ and $TL \geq T_1$, or 2.6 meters away from a 50Hz power line with a current of 100A flowing through it.

The formulas used are $B=\mu_0 * I / (2\pi * r)$, and $e=B * S / (2\pi * T_1)$ (for transmitter cable) or $e=B * S * f$ (for 50Hz power line), where B is the magnetic induction, I is the current, r is the distance from the cable to the receiver coil, e is the induced emf in the coil, S is the sensitivity of the coil (see the next chapter), and f is the frequency of the current.

III. RECEIVER-COIL SYSTEM

3.1 Configuration

As some of the special features, the NGUTFEM-85 system measures two spatial magnetic components at the same time, and it uses two coils for each spatial component to meet the separate demands for sensitivity and frequency response of the early and late channels. The coil system, therefore, consists of 4 receiver coils, each followed by a preamplifier (Fig.3-1). The coils are ferrite cored. A Faraday shielding layer is attached from the outer surface of the frame which holds the 4 coils rigidly in position. The cores and the shieldings are connected to the common of the receiver to eliminate electrical interferences.

3.2 Calibration

The sensitivities and natural frequencies of the coils were calibrated with the help of a two-turn Helmholtz coil which has a resonance frequency of 5 MHz. At the center of the Helmholtz coil, the magnetic-induction caused by a unit current is

$$K=B/I=8\mu_0/(\sqrt{125}a)=8.992*[10^{**(-7)}] \text{ [Tesla/Ampere]}$$

where $a(=1M)$ is the radius of the Helmholtz coil which equals to the distance between the two layers, $\mu_0=4\pi*10^{**(-7)}$, B is the magnetic induction, I is the current flowing through the Helmholtz coil. K was checked by sending a DC current through the Helmholtz coil and measuring the incremental magnetic field by a magnetometer, the error was within 1%.

An AC current was sent into the Helmholtz coil and the induced emf in the receiver coil placed at the center of the Helmholtz coil and coaxial with it was measured. The sensitivity of the receiver coil was found by the formula

$$S=e/(B*f)=e/(K*I*f) \text{ [v/(Tesla.Hz)]}$$

where e is the emf induced in the coil, f is the frequency of the AC current. For calibration of sensitivity, f should be far lower than the natural frequency f_n of the coil to be calibrated. $f=0.1f_n$ is often adopted.

Normally the receiver coil has a high Q value, so f_n can be found simply by increasing f until the emf induced in the receiver coil reaches its maximum.

The capacitance C_0 of the coil is approximately

$$C_0 \approx 1/(W_n * W_n * L) .$$

The coil must be damped by a resistor to get a flat frequency response around f_n when it is used as a receiver coil. The

damping coefficient of the coil is approximately

$$d = \sqrt{L/C_0} / (2R)$$

where R is the damping resistance in parallel with the coil. It was found that $d \approx 0.9$ is a good damping state for TDEM measurement (derivation omitted).

Parameters of the four receiver coils are given in Table III-1.

Table III-1. Parameters of the receiver coils

Coil	N	S	fn	L	Co	ro	R	d
FHH	7500	1200	10	9.0	28	1.5	330	0.86
FHV	7500	1200	10	9.0	28	1.5	330	0.86
FLH	22500	3200	3	71	40	4.5	680	0.98
FLV	22500	3200	3	73	39	4.6	680	1.01

N: number of turns; S: sensitivity [v/(Tesla.Hz)]; fn: natural frequency (KHz); L: self inductance (Henry); Co: capacitance (pf); ro: copper resistance (K ohm); R: damping resistance (K ohm); d: damping coefficient.

3.3 Preamplifier

The diagram of the preamplifier is shown in fig.3-2. The amplification of the preamplifiers are selected by the receiver according to the signal & noise level. Four steps are available: x4, x16, x64, x256. Operational amplifiers OPA111 are used for the first stage of the preamplifier because they have a low noise coefficient ($8\text{nv}/\sqrt{\text{Hz}}$ at 10 KHz) and high input impedance which is important to keep the damping state stable and to prevent the natural frequency of the coil from being lowered. Low power amplifier OPA 21 is used for the second stage to reduce power consumption.

The accuracy of the amplification is higher than 1% through the four amplification steps. The bandwidth is not narrower than DC-32 KHz for the high frequency preamplifiers and DC-5 KHz for the low frequency ones.

With the input of the OPA111 grounded, the equivalent input noise is 0.80uv(RMS) for the high frequency preamplifiers with its bandwidth limited to DC-10 KHz from outside. The noise for the low frequency preamplifiers were not measured, but in theory it should be $0.8/(\sqrt{2})=0.56\text{uv}$ (RMS)

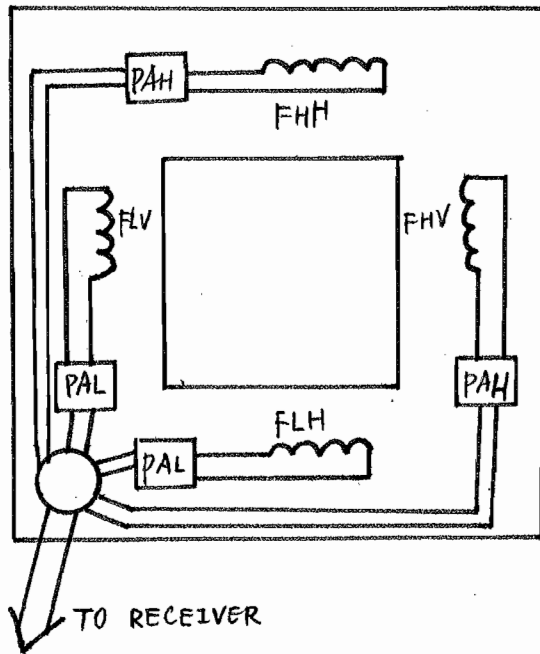


Fig.3-1 Receiver coil system. FHH (FLH): high (low) fn, horizontal coil. FHV (FLV): high (low) fn, vertical coil. PAH (PAL): high (low) frequency preamplifier.

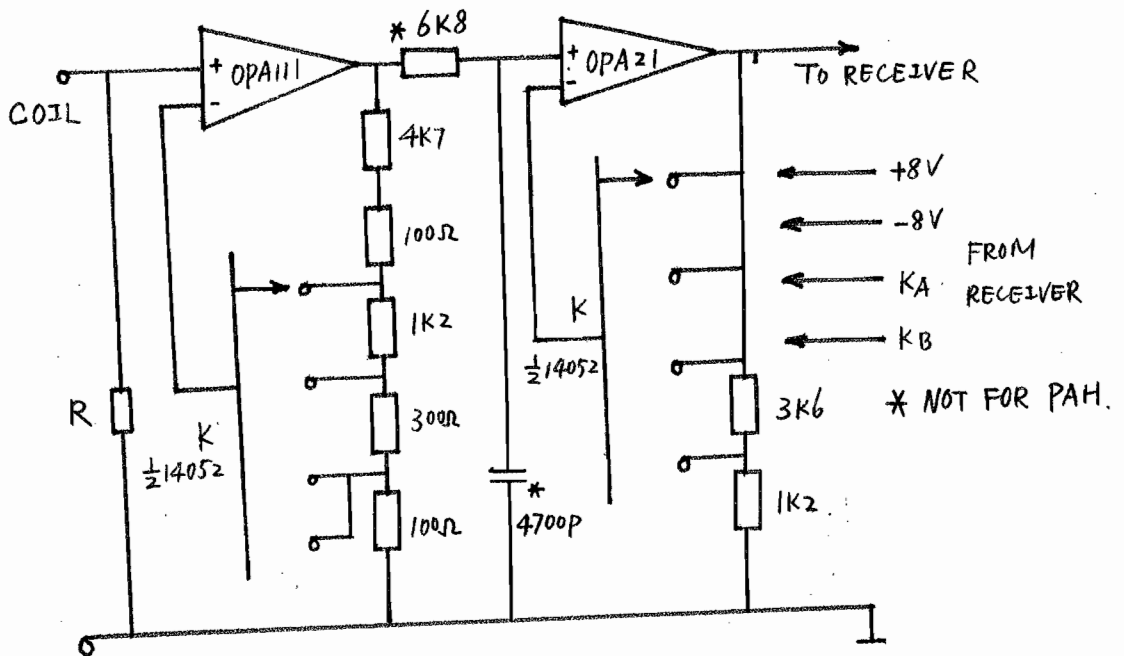


Fig.3-2 Diagram of the preamplifier.
 R=680K for PAL and R=330K for PAH.

IV. RECEIVER

4.1 Introduction

The receiver is a microprocessor-based instrument. It has 16 channels working in time domain and 2 time-sharing channels working in frequency domain. The microprocessor is used to perform the following functions: to set proper amplifications according to the signal level, to control and monitor the measurement, to carry out statistic calculation during measurement, to execute instructions given by the operator, to handle overflows, to store the data into a bubble memory, and to transfer the data to a station computer. The receiver has four inputs, each for a coil. The signals detected by the receiver coils are filtered, amplified, sampled, integrated, A/D converted, averaged and stored at each station.

The measured data are organized in small groups. For each channel, every 14 data form a group (it takes $40 \times 14 = 560$ ms to measure). The mean value and uncertainty of the 14 data are calculated for each group. The uncertainties are used to weight the group mean values when calculating the overall mean value over many groups of measurements.

The uncertainties on the overall mean values are also calculated and stored as a measure of the quality of the data. The demand on the uncertainties can be set via the key board by the operator before or during the measurement. And the operator can choose the uncertainties of some or all of the 16 TD channels to be checked by the microprocessor during measurement. Once the uncertainties of the chosen channels satisfy the demand, the microprocessor will stop the measurement no matter whether the desired number of measuring groups have been finished or not.

At each station, 128 bytes of data are stored in a 128k-byte bubble memory. The data contains information about (see also Document K):

overall mean values of the 18 channels	36 bytes
amplification codes for the 18 channels	18 "
uncertainties of the 18 channels	36 "
control words of uncertainties	6 "
number of measured cycles	6 "
overflow information	6 "
date and time	5 "
coordinates	5 "
transmission parameters	5 "
others	3 "
spare ones	2 "

There is a special program in the receiver which takes care of the overflow problems, so that the relative error caused by overflows will be within $\pm 20\%$ of the measured data in any case. When overflow in a channel happens more than 20% times of N_1 , the receiver will display the channel number and beep to inform the

operator. The operator has the choices of aborting or continuing the measurement. The overflow information are stored in the bubble memory for estimation of the quality of the data later.

High stability crystal oscillators were used to keep the synchronization between the receiver and the transmitter. The drift during 8 hours is less than 10us.

4.2 Hardware discription

See fig.4-1, the block diagram of the receiver, and circuit diagrams of Card 1 and Card 2 in Document C.

A). K22 After automatic scaling is finished and before the receiver actually starts measurement, K22 grounds the 4 inputs of the receiver. The instrument background noise or DC drift is measured for 256 cycles and the mean values of the background noise of the 16 TD channels are stored in RAM (2090H-209FH). Later these noise values will be subtracted from the measured data in every cycle (40ms). After the background noise measurement, K22 connects the coil system to the receiver.

B). LP1--LP4 4th-order LP filters used to eliminate the high-frequency noises such as VLF broadcasting signal. FHV (FLV) means high (low) frequency, vertical component; FHH (FLH) means high (low) frequency, horizontal component. The bandwidth is 1.6Hz--10KHz for high frequency channels and 1.6Hz--3KHz for low frequency channels.

C). K10v, K10h K10v connects A5 to FHV when the receiver is measuring in the high frequency channel time and to FLV when measuring in the low frequency channel time (fig.2-6). K10h does the same for the horizontal compoenet measurement.

D). A5/K11v and A6/K11h A5 (A6) is an amplifier for the vertical (horizontal) component with selectable amplification controlled by software through K11v (K11h). Amplifications for low frequency channels and high frequency ones are separately selected.

E). I1/K1K2K3K4K6 and I2/K1K2K3K4K6 I1 is an active integrator with 8 identical integrating capacitors selected by switches K1-K4 and K6 (see Document C, Card 1, the second diagram). The 8 capacitors are used for the 8 channels, F, S1--S7. K1 is "on" in the 8 sampling time intervals and "off" in the other time. K2 is "off" during the sampling time and when I1 outputs the stored voltages. In the other time, K2 is "on" to keep the feed-back loop "closed". K3 and K4 are used to direct the charging current according to the polarity of the primary field which alters every 20ms, so that the primary/secondary signals will add up in their corresponding channels. K3 and K4 are also used to short-circuit the capacitors to discharge them every 40ms after the integrated voltages have been A/D-converted. K6 (Kc by drawing mistake in the diagram in Document C) is an 8-to-1 switch which selects one

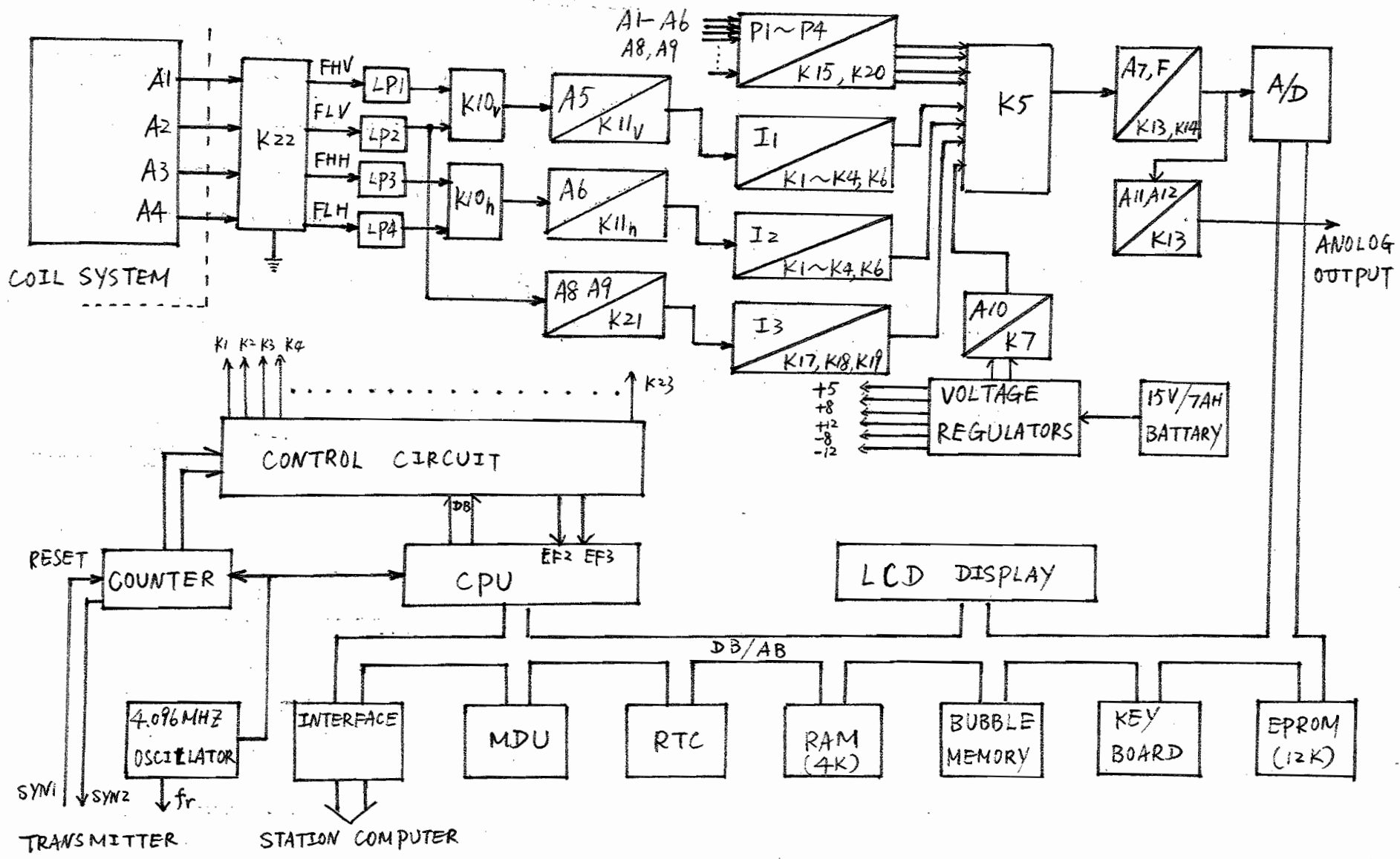


Fig. 4-1 Block diagram of the receiver.

capacitor for each channel. During the "hold" time, all switches except K2 are inhibited to ensure the charges in the capacitors against being discharged. I2/K1K2K3K4K6 are used for the horizontal component.

The time constants of I1 and I2 are identical for all the TD channels and equals to 1.25 ms. Therefore the integrators have different gains, which are proportional to the channel widths, for different channels. The gains are 1/32, 1/16, 1/8, 1/8, 1/4, 1/2, 1 and 2 for channels P, S1, S2...S7 respectively.

F). A8,A9/K21 A8 is a 2nd-order LP filter. A9 is a 2nd-order bandpass filter. The total gain of A8 and A9 for the 25Hz signal is 512. The bandwidth is 2Hz. K21 is used to attenuate the 25Hz signal by a factor of 32 when the signal is too strong.

G) P1--P4/K15,K20 P1--P4 are peak value detectors (Document C, Card 1, second diagram) used to detect and hold the maximum amplitudes of the signal at each amplifiers. These maximum amplitudes are estimated to give appropriate amplification during scaling and checked to see if overflow happens during measurement. K15 is used to select inputs. K20 is used to discharge the capacitors.

H). A10/K7 At each station, the voltages of the battery and the regulated power supplies are checked before measurement. The voltages are selected by K7 and converted by the A/D convertor. The A/D output is compared with the upper and lower limits stored in the EPROM. The output of A10 is scaled so that one bit of the A/D convertor output corresponds to 10mv.

I). K5 8-to-1 switch used to select the input signal for the A/D convertor.

J). A7,F/K13,K14 A7 and F form a high-speed, low-output impedance amplifier with 4 selectable amplifications.

K). A/D 12-bit, high speed A/D convertor AD574 was adopted. 1 bit represents 2.4414mv.

L). A11,A12/K23 A11, A12 and K23 form a sample-hold circuit which samples one of the 7 vertical-channel voltages to provide an analogue output for modelling purpose. The channel to be monitored is chosen via the key board and the default channel is V4.

M). I3/K17K18K19 I3 and the related switches work in a similar way as I1 and its related switches except that a single capacitor is time-shared by two channels, V8 and V9. The integrator integrates for 120ms in every 150ms. During the 120ms, K18 is on and K19 is off, K17-1 and K17-2 reverse the charging direction every 20ms. The integrated voltage is A/D -converted during the next 20ms and then discharged for 10ms. When the second 150ms cycle starts, the phase of integrating has been delayed for 270 degrees for 25Hz signals. In every 600ms, 4 data are collected:

V8, V9, -V8 and -V9.

N). Control circuit The control circuit consists of 5 output ports (out2,3,5,6,7 and some combination circuit to provide control signals to the switches K1--K23. The CPU sends control words to out2 and out3. When the states of the counter match the control words, Gate 18 will be opened and the output of G18 will trigger a combination circuit to yield control signals to K1--K4 and K6 (see Document C, Card 1, first diagram). The sampling sequence is controlled by software, so it is selectable by changing the program in the EPROM. The CPU tests EF3 to get the timing information.

A counter 4024 and a few gates were used to yield the control signals for K17, K18 and K19 for the 25Hz signal measurement (see Document C, Card 1, second diagram). After each cycle (150ms), a feedback signal shifts the timing sequence forwards for 10ms, so that in the next 150ms, the measured component will be 90 degrees out of phase with respect to the previous one.

Other switches are directly controlled by the output ports.

O). Counter The counter consists of 3 components: 4018 (divide by 10), 4040 (divide by $2^{*}9$), and 4024 (divide by $2^{*}5$). The counter is powered on as long as the battery is connected. It is reset at the beginning of the day by a synchronization signal from the transmitter. All the measuring sequences are based on the timing pulses from the counter. The counter keeps the synchronization if only the crystal oscillators are stable enough.

P). 4.096MHz oscillator. An oven-controlled crystal oscillator OCXO is used to provide a very stable clock signal. This oscillator must be powered on at least 2 hours before synchronization with the transmitter.

Q). RAM 4K on-board RAM addressed from 2000H to 2FFFH, see Document K. Every 64 bytes form one page. Two pages of data are stored in the bubble memory for each observation. Bytes from 2000H to 24FFH are used during the measurement. 2600H to 2FFFH are used only for reading back the data stored in the bubble memory (maximum 40 pages each time). Data to be stored in the bubble are kept in the memory from 2000H to 207FH. The contents of the 4K RAM can be seen from the display by keying in a proper instruction.

R). Bubble memory One mega-bit bubble memory is used to store the data for 1023 observations. As the bubble consumes very much power (several hundred mA), it is powered on only when the CPU writes data to or reads data from it.

S). RTC A real time clock 1879 is used to keep the real time during measurement. The real time information is stored in the bubble memory for each observation.

T). MDU Four multiply/divide units are used to carry out 32 bits multiply/divide calculations.

U). Interface An 8-bit parallel output port is built to transfer the data to the computer.

V). CPU 1806 microprocessor.

W). EPROM 12K-byte EPROM used to keep the programs.

4.3 Operation procedures

See also Document A.

A). At the beginning of a day, start transmission first. Then connect the receiver to the transmitter to adjust the frequency of the oscillators (see Document B), and synchronize these two instruments.

B). Before the first measurement, key in the following information: month, date, time, number of traverse, number of the first station, distance between two stations, width and length of the transmitter loop, transmitter current, starting address of data storage in the bubble, demand for the uncertainties, maximum number of groups of measurement at each station, etc.

C). At each station, the receiver will check the voltages of the power supplies and gives warning if any of them is out of its preset limits.

D). The receiver can execute a "scaling" program to choose appropriate amplifications for the amplifiers. The "scaling" procedure takes less than two secs if the amplitude of the signal is no more than 1.25v(p). The scaling program can be executed at each station, or only once at the first station, or at any station at the operator's choice.

E). After "scaling", the inputs of the receiver are grounded to measure the interior back ground noise of the receiver. This takes about 10 secs. These back ground noises are subtracted from the later-measured data.

F). After measuring the back ground noise, the receiver execute dummy measurement for about two secs to pass the transient process yielded by switching K22.

G). The stacking time at each station is selectable between 28 secs and 10 hours in steps of 0.56 sec. During the measurement, the outputs of the amplifiers are monitored against overflow. The error caused by overflows is limited to within 20% of the measured value in the worst case by a "overflow handling" program.

H). The data storage in bubble takes about 1 sec. Then the

receiver will be ready for the next observation. The data can be discarded before being stored if the operator finds something wrong (in noisy environment this instrument occasionally makes mistakes, see Chapter VIII).

I). After a whole day's work, the transmitter and the receiver should be connected together again to check the synchronization. A shift of 10 μ s is allowed for every eight hours.

4.4 Main program (SCALK)

Fig.4-2 is a brief flow chart of the main program SCALK. After being reset, the receiver initialize itself and then ask "INIT?". If the answer is 0, the previous settings, such as the storing address in the bubble, time, coordinates, etc., will be kept. Otherwise, questions like "PAGE 2?", "W=", "L=" have to be answered, as prompted in Document A.

MON1 is an entrance of the program from where a new observation starts. The first thing to do is to check the power supplies. If any of them is out of its limits, its value will be displayed. Then the receiver asks "CHECK?". Key in "1" to continue checking or "0" to branch back to MON1 again.

SCALE is a big part of the main program which estimate the signal level and sets proper amplifications for the amplifiers (see Sect.4.5). After scaling, the receiver measures its own noise and DC drift for 10 secs with the selected amplifications. The mean values of the background noise are stored in the RAM and are subtracted from the measured data later on. If the background noise of any channel exceeds a fixed limit, its value will be displayed.

Two seconds of dummy measurements are carried out to pass the transient process caused by switching the inputs back to the coils. The time constant of the circuit transient is 0.1 sec. After the dummy measurements, CC, N1, N3, N5 and some other bytes are set. CC has 16 bits, each corresponds to one of the 16 TD channels. At the beginning, CC=FFH. When the uncertainty of a channel becomes smaller than the demand D (in 0.1%), the corresponding CC bit will be reset (0). N1, N3 and N5 are the numbers of groups of the TD channels, V8 and V9 respectively.

GPST is the start point of a new group. N2 is the number of the cycles in a group for the TD channels. LK20 is the start point of a new cycle.

MEAS1 is a subroutine which generates the timing pulses for the TD channels. It also does some otherthings in between the sampling time intervals.

CAL2 is a subroutine which calculates the overall mean values and the relative uncertainties. CAL2 takes a maximum of 3.2ms for a single channel. It is put between the ends of S6 and S7, where

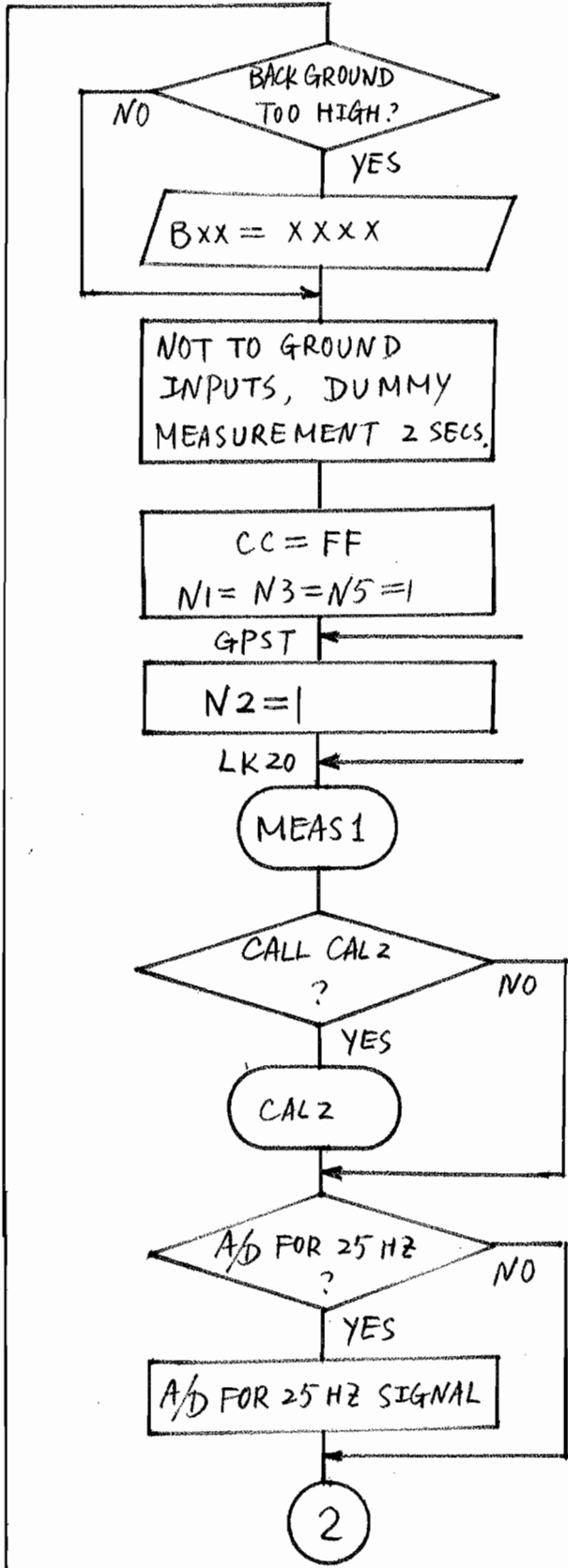
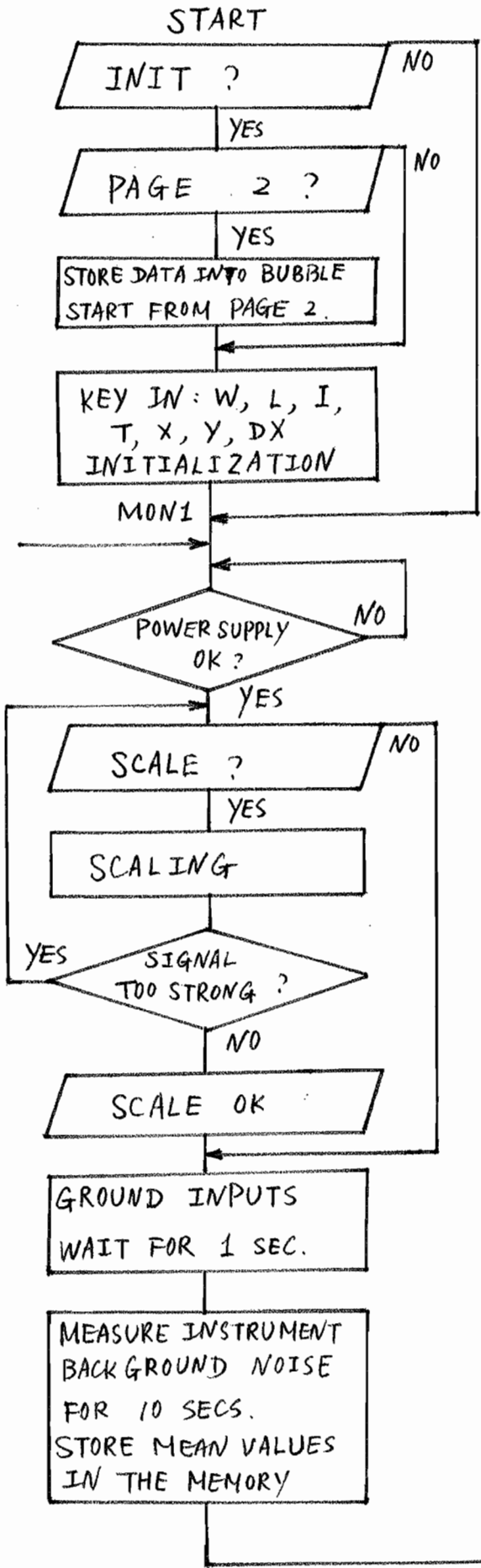


Fig. 4-2 Flow chart of SCAIK.

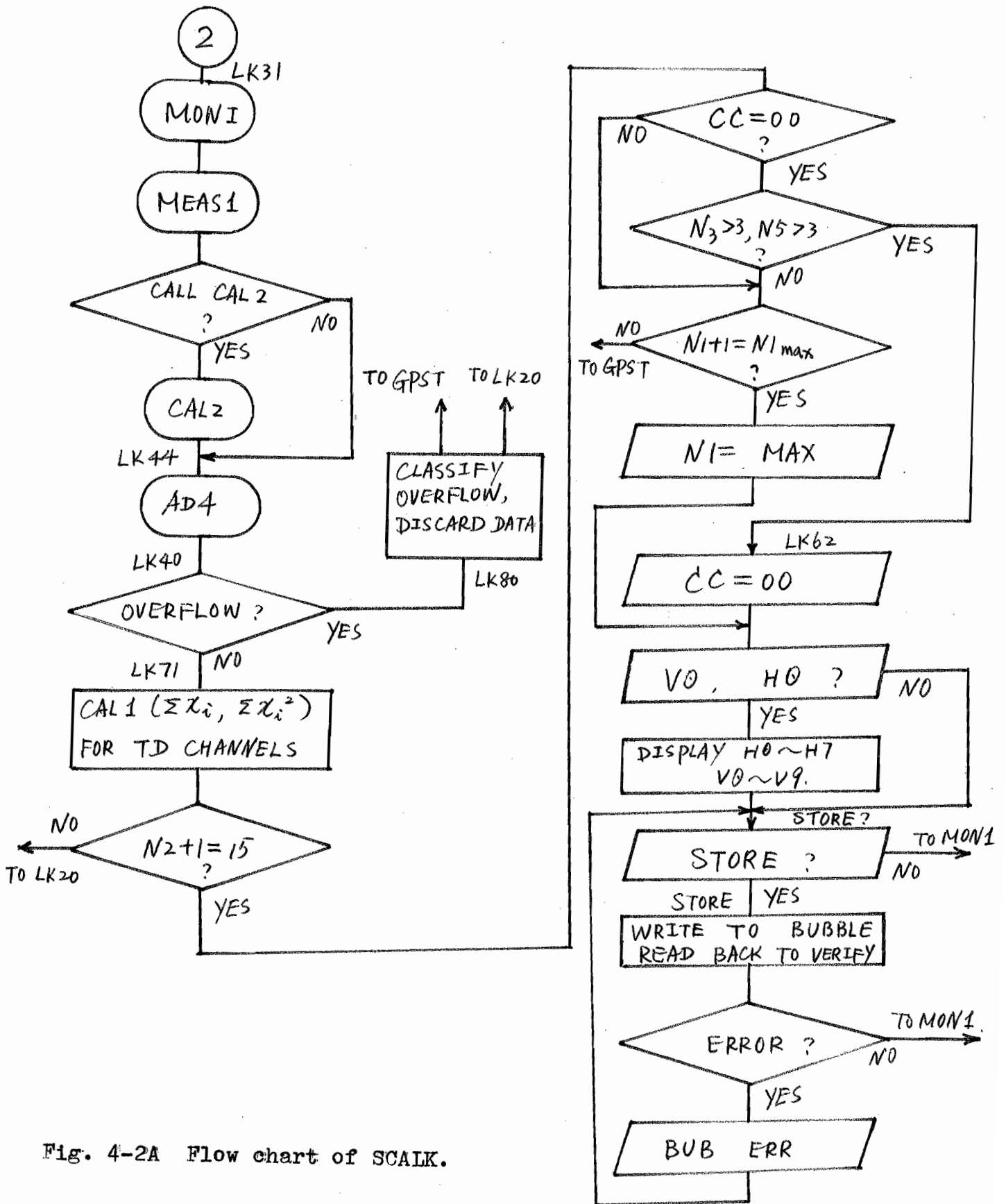


Fig. 4-2A Flow chart of SCALK.

altogether 3.7ms are available. In each group of measurements (0.56 sec), there are 28 such intervals between S6 and S7, and the first 18 intervals are used for calculations of the 18 channels. The calculations are such organized that during the first group of measurements, CAL2 is not executed, and during the second group CAL2 is called to calculate on the data measured during the first group, and so on. At the end of CAL2, the uncertainty of this channel of which the data has been calculated is compared with the demand D. If the uncertainty is smaller than D, the corresponding CC bit is reset. The uncertainties of V8 and V9 are not checked against D. More about CAL2 is given in Sect.4.8.

25Hz signal is converted every 150ms. EF2 is put low when either V8 or V9 is ready for A/D conversion. The CPU tests EF2 every 20ms.

MONI is an entrance of the subroutine MON(itor) during measurement.

Subroutine AD4 is called every 40ms to convert the 16 TD-channel integrated voltages, the outputs of the peak value detectors and the 25Hz signal if it is ready. Then the data are checked to see if any overflow happened during the last 40ms. If it happened, an overflow handling program will be executed which will decide if the single cycle (40ms) or the whole group of 14 cycles (0.56 sec) should be discarded (see Sects. 4.6 and 4.7).

CAL1 is originally a subroutine but now a part of the main program. Each time after the A/D conversion, sums of x_i and $x_i \cdot x_i$ are calculated for the TD channels. When a group is completed, the 16 sums of x_i and 16 sums of $x_i \cdot x_i$ are transferred during the MEAS1 subroutine to a new address for CAL2 to work on.

When a group of 14 cycles are finished, the CPU checks the CC bits. If it is zero, and both N3 and N5 are larger than 3, the stacking will be stopped. The minimum stacking time is 12.6 secs.

If $N1=N1_{max}$ (number of groups to be finished), the stacking will also be stopped. Otherwise, a new group of cycles will be started from GPST.

If the stacking is stopped, either "N1=N1max" or "CC=00" will be displayed depending on which one has been satisfied. Then the receiver will ask "H0 ?" which is an abbreviation of the question "do you want to see the values of H0-H7?". If the question is affirmed (key strike is 1), "H0=xxxxu" will be displayed. "u" means microvolt, it can also be "m"(millivolt) or "n"(nanovolt). The displayed value is the equivalent voltage at the input of the preamplifier. Any following key strike will advance the display to the next channel. After H7 is displayed, "V0 ?" will be asked. Answer "1" to see V0-V7 or "0" to skip them.

The next question "STORE ?" asks if the data should be stored in

the bubble. If "1" is keyed in, it will ask if the X coordinate should be incremented. Answer "1" if DX should be added to X, "2" if DX should be subtracted from X, or "0" if X should remain unchanged.

Writing the data to bubble takes about 1 sec, then the data are read back for verification. In case any error is found, it will be displayed and the program from asking "STORE ?" will be executed again. So far this error has never happened.

4.5 Scaling

As mentioned earlier, the receiver has a wide dynamic range and large amplification. The signal & noise may vary millions of times on the traverse and between channels. As a big part of the main program, the scale program estimates the signal level and set proper amplification for the amplifiers stage by stage.

Before scaling, the amplification of the preamplifiers A1-A4 is set to the second lowest (x16). The peak value detectors P1-P4 are connected to A1-A4 for 120ms. Then the outputs of P1-P4 are A/D converted. The converted values of the high-frequency preamplifiers, A1 and A3, are compared to find the stronger one, and according to which a proper amplification is selected for A1 and A3 so that the peak value of the output of the stronger one will be within and as close as possible to 5v(p). The same is done for A2 and A4.

In the next 120ms, outputs of A5 and A6 are fed to P1 and P3 when A5 and A6 are switched to channels FHH and FHV during the high frequency channel time (from the end of S7 to the end of S3) and fed to P2 and P4 when A5 and A6 are connected to FLH and FLV during the rest time. An amplification is selected for A5 and A6 in the high frequency channel time according to the stronger one of P1 and P3, and similarly another amplification for A5 and A6 in the low frequency channel time according to the stronger one of P2 and P4.

After that, P1-P4 are connected to A8 and A9 to estimate the strength of the 25 Hz signal and to find a proper position of K21. If overflow happens at the output of V8, the selected amplification for A2 and A4 has to be lowered. In the mean time, several cycles of measurements are carried out to find proper amplifications of the last amplifier (A7 and F) for the 18 channels individually. A few more cycles of measurements are also made to check if the selected amplifications are appropriate. If any overflow happened during the scaling time, the corresponding amplification will be lowered.

The selected amplifications are stored in the RAM in a special code form to control the amplifiers during measurement. 18 one-byte amplification codes, each for one of the 18 channels, are stored in the bubble memory for each observation. The amplifications are decoded as follows:

preamplifier	4**(b1b0+1)
intermediate amplifiers for TD channels	4**(b5b4)
intermediate amplifiers for FD channels	16**(32**b6)
last amplifier	4**(b3b2)

A question "SCALE ?" is asked before the scaling program is executed. Four answers are available: "0", not scale but ask again next time; "1", scale and ask again next time; "2", not scale and not ask any more later; "3", scale each time without asking. If "2" or "3" has been answered before but asking becomes necessary again, it can be resumed either by changing the content of RAM unit 207BH (SCF) into "0" or "1" (see instruction list for how to do it), or by resetting the receiver and going through the initialization steps once more.

4.6 Overflow handling

Overflow is a tricky problem for TDEM measurement. Great effort was made to solve it in the NGUTFEM-85 system.

If overflow occurs before scaling is finished, the related amplification will be reduced. During measurement, the CPU checks the A/D-converted data of the 18 channels and the outputs of the peak value detectors which are connected to A5 and A6. Take the TD channels as an example, if one of the TD channels overflows, the measured data for all the 16 channels in the single cycle (40ms) will be discarded, an "overflow in a group" (SOVGxx, xx is the channel number) byte for this channel is set to 1, and a "number of overflowed groups" (SOVTxx) is incremented. If any channel overflows more than once before a group of 14 cycles of measurements are finished, the whole group of data, 14 (or less) times 16, will be discarded. Then the 16 SOVGxx bytes are reset, and a new group of cycles starts. When the value of the maximum SOVTxx reaches 20% of N1 (number of groups), the receiver will display the channel number of the maximum SOVTxx, and beep to inform the operator. The operator can decide whether the measurement should be continued or not. For instance, if the overflow warning occurs only a few times and then disappears as N1 grows larger, the maximum error by the overflows will be less than 20% and the measurement can be continued. But if the receiver beeps often, the best is to use the "!DN" instruction to lower the related amplification(s) and re-start measurement from measuring the background noise (see the next section).

If a SOVTxx byte is larger than 20% of N1, the other SOVTxx bytes will also be checked against a number "LIMOVT" which value is related to N1 (LIMOVT=5 when N1<64, =12 when N1<256, =51 when N1<1280 and =255 when N1 >1280). In case SOVTxx of any channel is larger than LIMOVT, a corresponding bit will be set in one of the three bytes OVCH, OVCL or OVC56 which are marks for high frequency channels (F, S1-S3), low-f channels (S4-S7) and A5A6 respectively. When "!DN" is issued, these three bytes will be examined, and amplifications of those channels indicated by these

three bytes will also be lowered.

SOVGH (SOVGL) keeps the number of overflows of A5 and A6 in a group when A5 and A6 are connected to FHV (FLV) and FHH (FLH) respectively. If overflow happens there, the measured data of the 16 TD channels in that cycle will also be discarded. SOVTH (SOVTL) keeps number of overflowed groups of A5 and A6 during the measuring times of P-S3 (S4-S7).

If overflow happens in V8 (V9), the measured data will be discarded, and the related bytes SOVGV8 (SOVGV9) and SOVTV8 (SOVTV9) will be set and incremented, but the measurement in the TD channels will not be affected. If V8 (V9) overflows more than once in a group, the whole group of V8 (V9) data will be discarded and a new group starts.

Eighty bytes of overflow information are kept in RAM from 2400H to 244FH, and 6 bytes of them are to be stored in the bubble memory for each observation.

4.7 Lowering amplifications

When the number of overflowed group is larger than 20% of N1, the operator can key in an instruction "!DN" to lower the related amplification(s) and re-start the measurement. First, CPU will look at OVC56. If OVC56 is not zero, the amplification of A5A6 for the corresponding channels will be lowered by 1 step. For instance, if A5A6 overflows when they are connected to the high frequency channels, the amplifications of A5A6 will be lowered during P-S3 time, and once this is done, OVCH does not need to be checked any more because the total amplifications of all the high frequency channels have been lowered. If OVC56 is zero, OVCH and OVCL will be examined. If only 1 bit in OVCH or OVCL is "1", the amplification of the last amplifier (A7 and F) for that single channel will be lowered by one step. In case more than one bit in OVCH (or OVCL) are "1", the amplifications of A5A6 for high (or low) frequency channels will be reduced.

When an amplification needs to be lowered but it is already in the lowest step, the amplification of the previous amplifier will be lowered. In case the amplification can not be lowered any more, the display will show "STRONG !" and wait for instruction from the key board.

"Lower" is part of the main program, but it is branched to from inside the subroutine "MON". The return address, stack pointer, etc. have been properly taken care of.

4.8 Statistic calculation (subroutine CAL2)

Statistic calculation is carried out to estimate the quality of the measured data and to eliminate the influence of noises and interferences.

For each channel, every 14 measurements form a small group. A "goodness factor" K_j is defined for the K -th group:

$$K_j = n * n * A / \left[\sum_i^n (x_i * x_i) - n * a_j * a_j \right],$$

where $a_j = (1/n) \sum_i^n x_i$. A_j is the mean value of the j -th group,

x_i stands for a single number in the j -th group, $n=14$, $A=2**18$. x_i is in the range $(-2**11, 2**11)$. The denominator of K_j can be a big number, $14*(2**22)$. A is used to make K_j big enough so as to avoid the trouble of handling floating numbers, which is difficult for the 8-bit microprocessor.

The weighted overall mean value is defined as

$$M = \frac{\sum_j^G (K_j * a_j)}{\sum_j^G K_j} \quad (4-1)$$

where G is the number of groups. M is a better estimate of the expectation of x than the mean value found in the normal ways:

$$M' = (1/G) * \sum_j^G a_j.$$

During a field working day, the noise level may vary quite much. In quiet periods, less stacking time is needed to obtain the data in good quality. The NGUTFEM-85 system constantly checks the qualities of the measured data and once the uncertainties of the mean values are smaller than the demand, stacking will be stopped automatically. The relative uncertainty of M is defined as

$$u = (1/M) * \sqrt{A} / \sqrt{\sum_j^G K_j}.$$

We can demand the uncertainty (in 0.1%) to be less than a small number D , i.e., $u * 1000 < D$. D can be any integer between 0 and 65535.

Subroutine CAL2 performs the statistic calculation. The flow chart of CAL2 is shown in fig.4-3, where MI stands for a_j , $\sum XI$ for $\sum x_i$, KI for k_j , $\sum (XI)**2$ for $\sum (x_i * x_i)$, and U for $u * 1000$.

At first MI , KI and $\sum KI$ are calculated. Then $\sum KI$ is checked and if it is very big already (>FCXXXXXH), the following calculation will be skipped. If not, M will be found according to (4-1). When M is too small, as could be often the case in the later channels, it may take extensively long time to get the uncertainty u small enough. So M is tested and if it is smaller than 64, it will be replaced by 64 in the calculation of the uncertainty U .

The corresponding CC bit is reset to zero if the uncertainty becomes smaller than the criterion D or $\sum KI$ has been very big, which also means high quality of the measurement. There is no CC bit for V8 and V9 because they are most often with good quality.

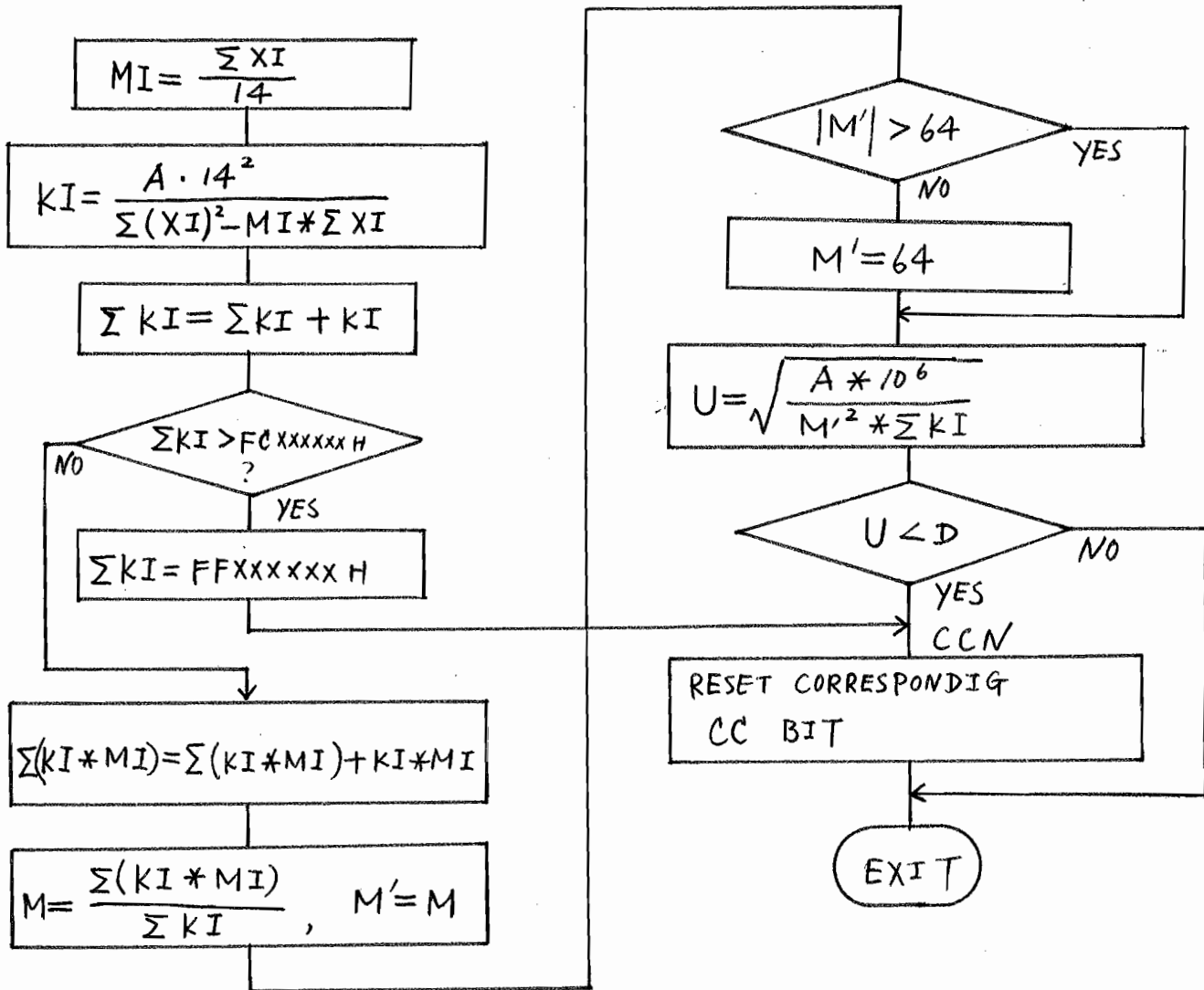


Fig. 4-3 Flow chart of subroutine CAI2.

4.9 Monitor (subroutine MON)

MON is a subroutine developed to execute the instructions given via the keyboard. It has two entrances, MON and MONI (fig.4-4). When MON is called, the CPU will wait for a key strike. If the key strike is "RET", it means an instruction has been keyed in and the CPU starts to interpret and execute the instruction. If it is not "RET", the key strike will be identified, stored and displayed.

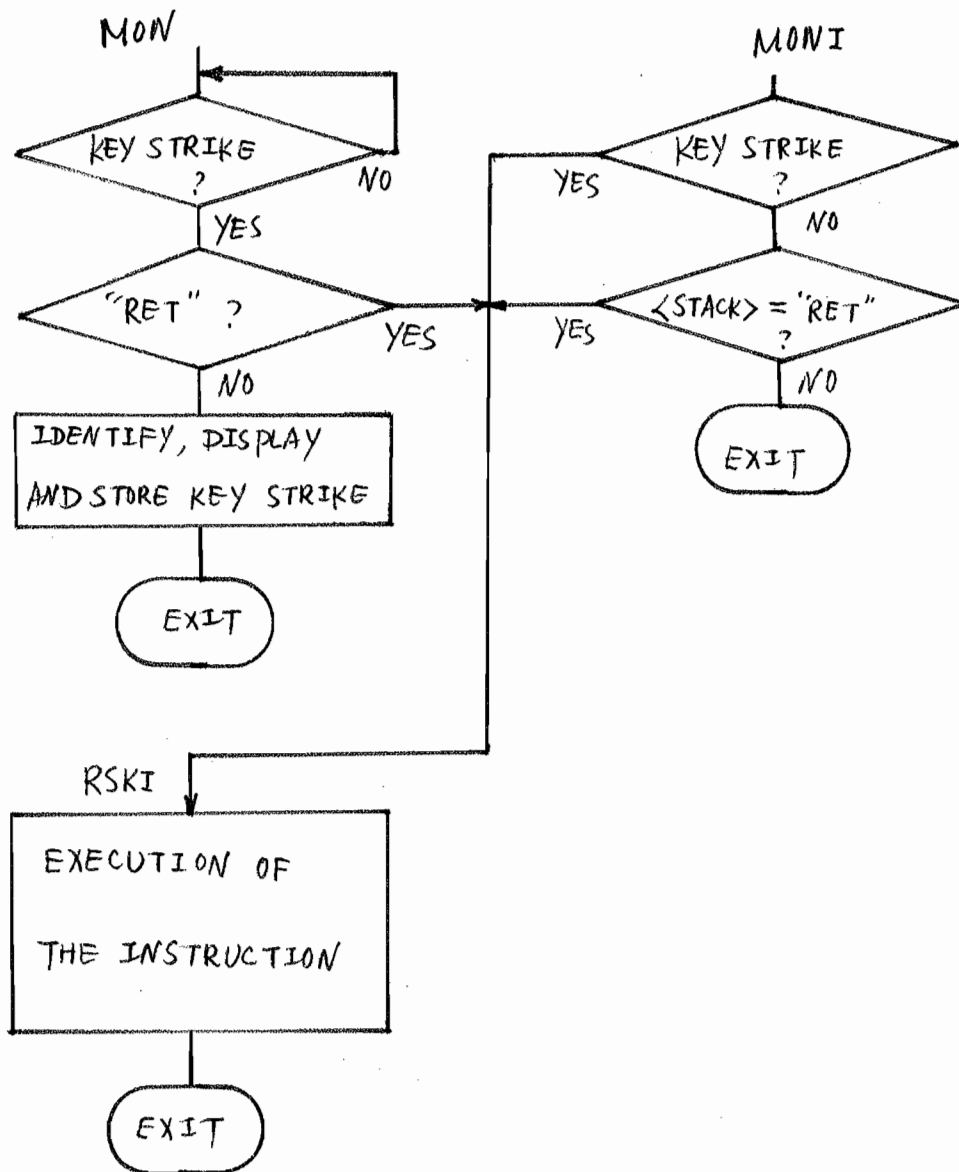


Fig. 4-4 Flow chart of MON (monitor).

MONI is an entrance for MON during stacking time. "STACK" is the top of the key strike stack (KBS). If "RET" is stored in STACK, the instruction stored below STACK will be executed every 40ms during stacking time. This was designed for instantaneous display of many quantities which vary during stacking, such as time, N1, N3, N5, mean values of the 18 channels, uncertainties, CC bytes, overflow state, etc.

The default instruction stored in KBS is "?V0 RET". Once the stacking start, voltage of V0 will be displayed. If "RET" is struck once after the stacking has begun, the instantaneous value of V0 will be displayed.

In case an erroneous instruction is given or a instruction can not be executed correctly, "ERR" (error) will be on the display.

4.10 Explanation of instruction list

This is an explanation to those instructions of which the brief explanation given in the instruction list in Document A might not be sufficient.

?: to read from RAM
!: to write to RAM
fbytes: number of bytes
the number next to "fbytes": address of the lowest byte in RAM
C1,C2 and Cd: coordinates x, y and increment of x
CH,CV: control bytes of uncertainties (CC). Before stacking, they are copied from CHS and CVS.
CHS,CVS: masks of CH and CV. If quality of some of the channels is not care, reset their corresponding CHS or CVS bits via keyboard.
D: demand on uncertainties (0.1%). Default value: 0.
DH0-DH7,DV0-DV9: uncertainties of channels H0-H7 and V0-V9.
HO-H7,V0-V9: overall mean values of channels H0-H7 and V0-V9.
NH: number of groups of cycles of the TD channels to be finished. Default value: 200.
NS: number of pages stored in bubble.
N1,N3,N5: numbers of finished groups of the TD channels,V8 and V9
SH0-SH7,SV0-SV9: amplification codes for H0-H7, V0-V9.
SHH,SNH: amplification codes of A5 and A6 in high (low) frequency channel time.
S13,S24,S25: amplification codes of A1A3, A2A4 and state of K21.
S0-S7: power supply values in volts. The standard values are -8v, -12v, -15v, 5v, 8v, 0v, 12v, 15v.
VC: channel number of the analogue output from connector C2 for modelling or testing purpose.
1(2,3,4)Hxxx: display 1(2,3,4) byte(s) in HEX starting from the address 2xxxH (and down).
1(2)Dxxx: display 1(2) byte(s) in DEC starting from address 2xxxH (and down).
ST1,ST2: starting and ending page numbers when transferring data from the receiver to HP-85.
STH: start data transferring from receiver to HP-85.

4.11 Memory map

There are 4 K RAM on the CPU card in the receiver addressed from 2000H to 2FFFFH (see the memory map). The first 128 bytes are memories for temporary storage of the data to be stored in the bubble memory. MH0-MV9 are two-byte mean values of the 18 channels. SCH0-SCV9 are one-byte amplification codes. UH0-UV9 are two-byte uncertainties in 0.1%. S (D) is the demand on the uncertainties. See the instruction list for CHS--NS. SOVTmax--OVCh are overflow information. MONTH--SEC are real time. Y,X and ϕ X are coordinates. I, W and L are transmitter current in 0.1 A, width and length of the transmitter loop in M. SCF is the answer to the question "SCALE?". 207CH and 207DH are spare bytes and can be defined by the operator. PN1 is the page number which indicates the address to where the 128 bytes are going to be stored. In the bubble one page equals to 64 bytes. Each time two pages is written into the bubble. Pages 0 and 1 in the bubble are reserved to keep the latest PN1 only. Each time before writing to the bubble, Pages 0 and 1 are read back to get PN1.

Memories 2080H-209FH keep the background noise for the TD channels. BG limit is the limit of the background noise. READvo and READrho are answers to questions "VO?" and "HO?".

Memories 20B0H-20D3H keep the measured values of the 18 channels. TEMP3 and X2 are for temporary data storage. N1max keeps NH. See Sect.4.10 for VC, ST1 and ST2. N2, N4, N6 are numbers of cycles of the TD channels, V8 and V9 in a group.

Memories 2100H-21DFH, 21F2H-21FFH and 2200H-22FFH are used to keep the intermediate results of calculation. 21E0H-21F1H are used to indicate the channels for which CAL2 has been executed.

2330H-233FH are keyboard stack. 2350H, 2351H and 2360H-2386H are amplification control bytes. 2352H-2356H are some flags for measurement. 2358H-23BFH keep data from the 4 peak value detectors. 23C0H-23CFH keep power supply values in 0.1 volt.

2400H-244FH are overflow information (see Sect.4.6). 2450H-247FH are used to keep return addresses when calling subroutines. 2480H-24FFH are memories to where the data read back from the bubble, for verification or transferring to HP-85, are first stored.

Memories from 2600H to 2FFFFH (40 pages) are used as an intermediate data stack during data transferring from the bubble to HP-85. Memories from 2500H-25FFH are not used.

V. TRANSMITTER

5.1 Introduction

The first model transmitter was a combination of a power supply and a transmitter. The conducting angle of the rectifier bridge was dynamically adjusted according to the voltage drop across the regulating power transistor so that this drop is between 15v and 30v. Trouble arose from the fact that both the frequency of the AC power supply and the repeated frequency of the transmission are 50 Hz. As they are not synchronized, the gradually changing phase difference causes large fluctuations on the rectified output voltage which consequently resulted in damage of the power transistors.

The second model transmitter does not include a power supply part. A separate power supply was built to convert the AC power into a DC power. The new transmitter was built to perform the following functions:

A). To send current pulses of up to 10 A (peak value) with alternative polarity into a transmitter loop or a grounded transmitter cable. The trailing edge of the current pulses should be cleanly terminated and should have a width in the range (100 μ s, 2.5ms).

B). To keep synchronization between the transmitter and the receiver by oven-stabilized crystal oscillators so that no line connection is needed during measurement. The drift of the synchronization must be less than 10 μ s in 8 hours.

C). To monitor the input and output parameters instantaneously during transmission. If any error occurs, it should be kept in the memory together with the real time. These information will be needed for correction or compensation on the measured values in data processing stage. In case something is seriously wrong, transmission must be stopped at once to avert accident or damage.

An simple over-current protection circuit was built in the transmitter. But the error control part and other protection countermeasures have not been finished or involved yet. Some suggestions have been made in chapter VIII.

5.2 Hardware discription

Figure 5-1 is a block diagram of the transmitter. See Document D for the details.

A). Transmitting network See Document D, page 1. The main network is formed by 4 thyristors SC1-SC4 and a power transistor T3. When SC1 and SC4 are triggered and T3 is switched on, the transmitter current flows through SC1, the loop, SC4, and T3 for 10ms. Then T3 is switched off, the transmitter current continues

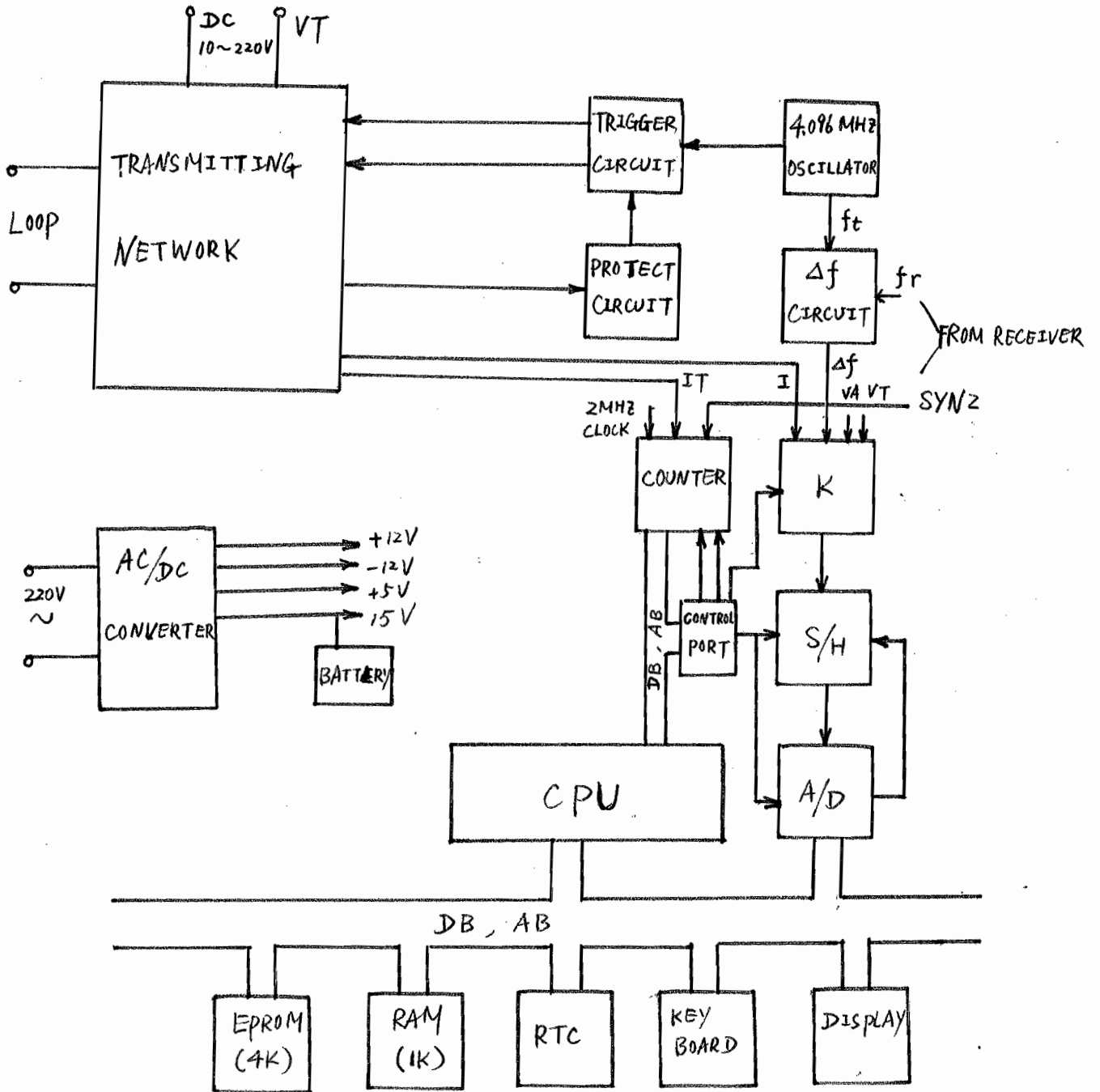


Fig.5-1 Block diagram of the transmitter.

to flow through SC4, D8, D7, T1, D5 and the loop and decreases almost linearly to zero in several tens or hundreds of microseconds. Ten milliseconds later, SC2 and SC3 are triggered and T3 is switched on, and a similar cycle is started except that the direction of the transmitter current in the loop is reversed. OPT01 is used to get information of the width of the trailing edge and to generate synchronization pulses. The transmitter current value is found by measuring the voltage drop over R078.

B). Trigger circuit See Document D, page 3. Counters and combination circuits are used to generate triggering signals for SC1-SC4 in two alternating groups and the control signal for T3 (via T2).

C). Protection circuit When the transmitter current is higher than 12A, C1 is triggered and it will hold T3 (via B2 and T2) off for a few seconds.

* In case the loop is broken during transmission, a very high emf will be induced across the broken points. The transmission must be stopped at once. This protection has not been involved in the transmitter but it is very easy to be realized in software (see Chapter VIII).

D). Δf circuit This circuit mixes f_r and f_t , and outputs their difference to S/H circuit. The output waveform is like full-wave-rectified half sine wave pulses with a peak value of 1v.

E). K 8-to-1 switch AC7501. Only 4 inputs are used. Input I, VA, VT and Δf are measures of the transmitter current, the AC voltage, the DC transmitting voltage and the difference frequency between f_r and f_t .

G). A/D A/D convertor. Only the eight highest output bits are used.

H). Control port An output port which sends control signal to K, S/H, A/D and the counter.

I). Counter It is used to count the 2MHz clock pulses gated either by IT to measure the width of the trailing edge, or jointly by IT and SYN2 to measure the synchronization drift (in us).

J). AC/DC power converters and battery 220v AC input is converted by the converters into +/-12v and +5v as the operating power supplies and +16.5v to charge a 4AH, 14.4v rechargeable battery pack which is used to keep the crystal oscillator running during transportation.

K). CPU, 4.096MHz oscillator, key board, display, RTC, RAM and EPROM Identical to those in the receiver (see Chapter IV).

5.3 Main program

Figure 5-2 is a flow chart of the main program of the transmitter.

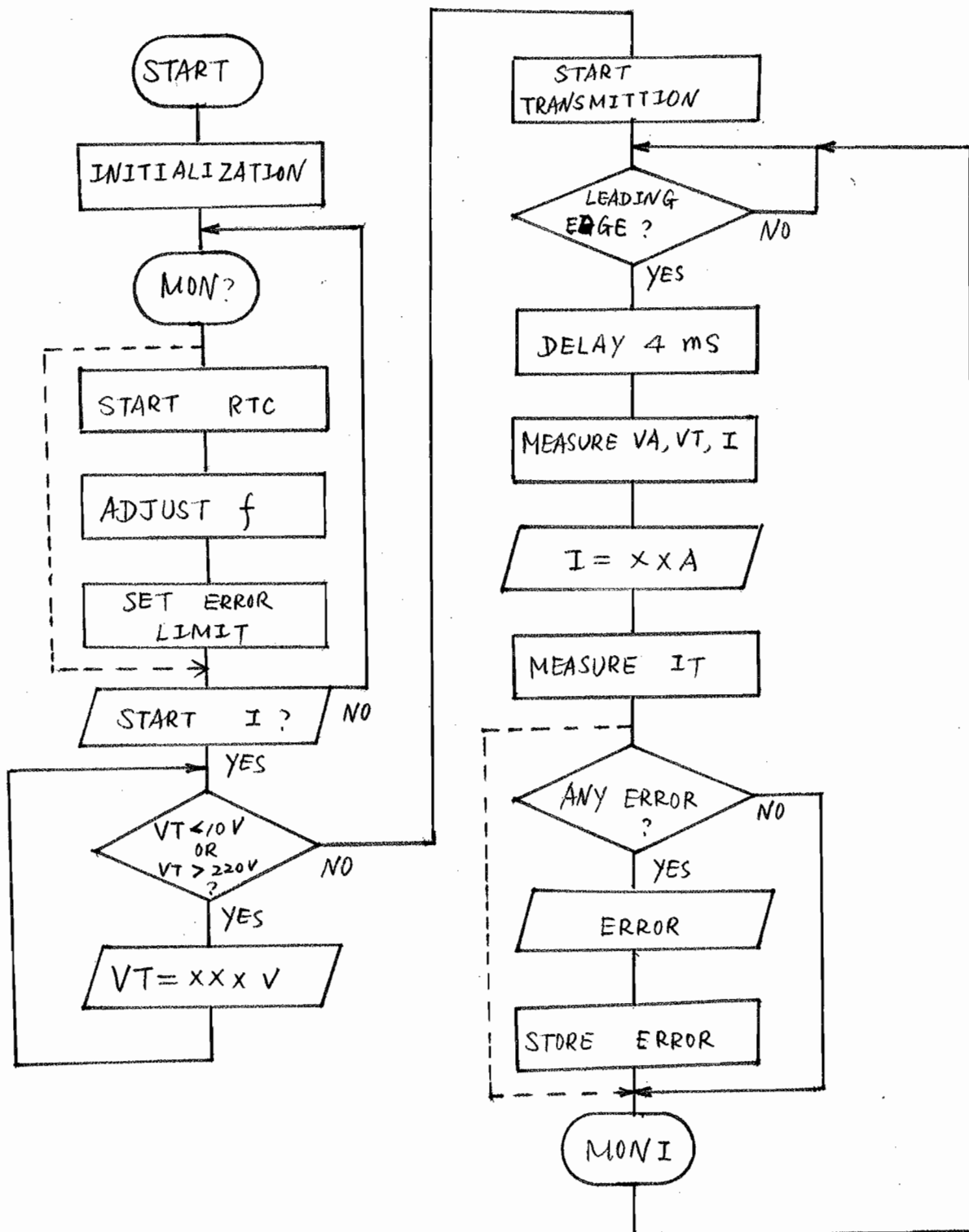


Fig.5-2 Flow chart of the main program.

When the transmitter is turned on, the initialization is done automatically. Then the operator can go into MON(itor) program to check transmitter parameters such as VA and VT, or to measure the frequency difference and to adjust the oscillators (see Document D).

After that, a question "START I?" is displayed (follow the dashed line). If "1" is keyed in, transmission will be started if VT is within the range 10-220v. The CPU measures VA, VT and I during the transmitter on-time and displays the current value in amperes. The width of the trailing edge IT is measured in the turn-off time. These measured values should be checked and if any error occurs, it should be displayed and stored together with the real time. This part of the program has not been properly tested yet, so it has been branched over (the dashed line).

If there is any key strike during transmission, MON will be called at MONI.

Once the transmission is started, it will continue until the reset button is pushed.

Between "MON ?" and "START I?" there exists a part of program located between address 0035H and 020EH, which allows the operator to set the real time, to set the error limits, and to adjust the oscillator's frequency. Since the error control part has not been finished yet, the real time have no use at present. Therefore, this part of program was skipped over.

5.4 Monitor (subroutine MON)

MON is a subroutine similar to that of the receiver except that this MON is much shorter. The following instructions from keyboard can be recognized and executed by the MON.

VA: display AC voltage in volt.

VT: display transmitting voltage in volt.

I: display transmitter current in Ampere.

IT: display width of the trailing edge in microsecond.

R: calculate the loop resistance by $R=(VT-6)/I$, where 6 is the voltage drops across the switching components, then display R. Only after transmission has been started can this calculation be correct.

ET: check synchronization and display the drift in microsecond. The transmitter and the receiver must be connected.

FF: calls subroutine OSAD to measure the time needed for Δf to vary for one degree. The time is displayed in a special form such that when the displayed number is bigger

then 1500, the synchronization drift will be less than 10us during a working day (8 hours).

H: hold the last measured transmitting parameters as the standards which will be compared to in the following transmitting cycles.

T: display the real time (as the time setting program in the main program has been skipped, the displayed time is only random values).

Many more instructions related to the error control program can be recognized by the MON, but their service programs have not been finished. Malfunction may occur if these instructions are keyed in. Such instructions include:

LVA (LVT, LI, LIT)--list VA (VT, I, IT) values stored in the memory during a day.

VAH, VAL (VTH, VTL, IH, IL, ITH, ITL)--the maximum and minimum VA (VT, I, IT) during a day.

ER-- list errors occurred during a day.

In case malfunction occurs, push the reset button and restart transmission.

VII. FIELD TESTS

The NGUTFEM-85 system was tested seven times at Tempervoll, Trondheim and twice at Kangsvoll, Hjerkin. The profile curves drawn by HP-85 are given in Documents F and G. In Document F we can see that the anomalies obtained on Oct. 14, 1985 and Oct. 21, 1985 were strong, obvious and repeatable. In Hjerkin both a big loop and a long grounded cable were used to transmit the primary field. The shapes of the curves of the early secondary field channels as well as H0 are quite different. This may imply that when using the grounded cable, the primary current in the ground was concentrated to the conductors and thus resulted in an anomalous distribution of the primary field. The anomalies recorded when using the loop are relatively easier to interpret. In either case, the anomalies in the early channels were much stronger than the noise and they indicated a conductor some 400M below the surface.

The measurements at Kangsvoll were not repeated because of time shortage.

An inductor of 25mH was used to prolong the width of the trailing edge to 105us when the grounded cable was used.

Four transient curves were drawn in Document G. The curve sections between S3 and S5 look strange especially those of curve 4. The apparent time constant of the section between S3 and S4 of curve 4 became longer than that of the section between S4 and S5. This could hardly be correct. If the delay time correction (see Sect. 2.6) is applied to the curves, that is, to move the first three channels forward for 80us and the last four channels forward for 330us, at least curves 1, 2 and 3 will look normal, and curve 4 will not be so odd any more.

VIII. PROBLEMS AND SUGGESTIONS

8.1 Receiver

A). When measuring in a noisy environment and overflow happens frequently, sometimes all the channels show small values. This is believed to be caused by a software mistake in the overflow handling program or in the CAL2 subroutine. The best way to solve this problem is of course to go into the program and find out the mistake. At present, one way to avoid the possible error is to check the V0 value before storing the measured data at each station. This is easy to do because the receiver automatically display the V0 value when the stacking starts, and the instantaneous value of V0 will be displayed if the "RET" key is striked once. V0 should gradually decrease as the receiver moves away from the cable. If at some place it suddenly drops to zero or a very small value, simply discard this observation and re-start again. In case overflow happens too often, use "!DN" to lower the related amplification(s).

B). Electric field measurement can be easily involved by using one or two pairs of electrodes together with preamplifiers.

C). The cable connecting the receiver coils to the receiver should be prolonged to at least 5M to avoid false anomaly caused by the metallic box of the receiver and to reduce the interference caused by movements of the operator.

D). The receiver can not be used under 0 deg.c. because many key components, such as the LCD, A/D convertor, bubble, etc., can not stand low temperature. Better components have to be used if the system is to be employed in low temperature.

8.2 Transmitter

A). If the loop is broken during transmission, a very high electromotive force may be induced at the broken point. Transmission should be stopped at once to avoid any hazard. This protection can be realized in software. During transmission, the current I is measured in every cycle. A short program shown below can be inserted at address 0288H which will check I value and stop transmission if I becomes smaller than 0.1A.

See Document I. Add the following (under lined part) to 0288H and two labels IR and DI (also under lined).

```
SHR;STR B          ..I/2 TO GET ...
  BNZ             IR
  REQ             ..STOP TRANSMISSION
  BR             DI
IR              RLDI    C,HDC+7
                  LDN      C
                  LBNZ    MAIN2      ..NOT TO...
DI              ..DISPLAY I="XX.XA"
```

B). The 4.096 MHz crystal oscillator in the transmitter needs better isolation to keep stable.

C). The synchronization circuit need to be improved. (see Document D, page 3, diagram of card 1 of the transmitter). OPT02 and the two 1k ohm resistors connected to the anode of the diode of OPT02 should be moved into the receiver. To do this, one more line is needed for the transmitter ground GNDt which has no direct connection to the receiver ground GNDr even during synchronization. As far as I remember, EF3 pin on C2 on the receiver panel is only for testing purpose. This pin may be used for GNDt.

D). To carry the transmitter back every afternoon to keep the crystal oscillator running over night is very inconvenient. It may be avoided by using a bigger pack of rechargeable battery in the transmitter, or by adding a connector to the transmitter panel and using an extra pack of battery outside.

8.3 Data processing

The profile curves given in Documents F and G were drawn by a preliminary data processing program on the station computer HP-85. To make full use of the vast information carried by the data collected in the field, much more advanced data processing programs have to be developed.

Some suggestions have been made in Document B.

APPENDIX. A LIST OF OTHER NGUTFEM-85 DOCUMENTS

- A. NGUTFEM-85 User's Manual: Receiver
- B. NGUTFEM-85 User's Manual: Transmitter & Power Supply Unit
- C. NGUTFEM-85 Hardware: Receiver
- D. NGUTFEM-85 Hardware: Transmitter
- E. NGUTFEM-85 Hardware: Power Supply Unit
- F. Field Test Results: Tempervoll
- G. Field Test Results: Kangsvoll
- H. Receiver Programs
- I. Transmitter Programs
- J. Photographs Of The Instruments And The Coil System
- K. Receiver Memory map