A LOW COST TELLUROMETER

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Submitted to the University
of Cape Town in fulfilment
of the degree of Master of
Science in Engineering.

I declare that this thesis is my own unaided work.
It is submitted in fulfilment of the requirements for the degree of Master of Science in Applied Science to the University of Cape Town.
It has not been submitted before for any degree or examination at this or any other University.

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signature removed

Signature of Candidate

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ABSTRACT

This thesis describes the development of a low-cost microwave electronic distance measurement instrument using the Tellurometer phase-measurement principle. In a simplified form the instrument can be configured as a full-duplex 9 600 Baud datalink.

The Tellurometer was invented in 1957 by the late Dr.Trevor Wadley of the National Institute of Telecommunications Research. Since then there has been a continuous development of Tellurometers that are used world-wide in the surveying profession. Sophisticated instruments are now available, but this development has been accompanied by increased costs and complexity.
There is a growing need in underdeveloped countries for a simple low-cost microwave Tellurometer with good performance and maintainability. These countries survey with low budgets, cannot afford expensive equipment and do not necessarily require all the features and performance of today's instruments.

To meet this need it has been the objective of this work to develop a Tellurometer with a range of 10 m to 15 km, with an accuracy in the order of 3 cm, and to keep the materials cost to within R700 per instrument. This has been reached by reducing circuit complexity, current consumption, and cost to a minimum, without compromising the required performance. Only essential features have been included, except where their inclusion has not compromised the cost.
The use of a single-chip microprocessor, a simple narrow-band pattern-synthesiser, a low-cost microwave source, low-power technology and a very simple mechanical arrangement has resulted in a cheap simple instrument. Built-in test features of the software allow sophisticated maintenance with a minimum of test equipment.

To My Father
Dr. John Paul Marsden
(for my education)

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List of Abbreviations and Symbols

A_e	Horn aperture in the E-field
A_h	Horn aperture in the H-field
$A_{e\lambda}$	Horn aperture in the E-field in free-space wavelengths
$A_{h\lambda}$	Horn aperture in the H-field in free-space wavelengths
AGC	Automatic Gain Control
AFC	Automatic Frequency Control
AM	Amplitude Modulation
AT	Autotune
B	IF Bandwidth
C	Speed of light in a vacuum
CMOS	Complementary Metal Oxide Semiconductor
δ	Excess path length in a horn antenna
δt	Time between measurement of straddle and centre patterns
d	Excess path length of an indirect beam causing ground-swing
dB	Decibel, a logarithmic power ratio
dBc	dB ratio of a sideband level with respect to a carrier
dBm	dB ratio of a power level with respect to 1 mW
dec	Decimal, number system to the base 10
D	Distance between two instruments
e	Error in apparent measured distance due to ground-swing
E	Partial pressure in millibars
EPROM	Erasable Programmable Read-Only Memory
F	Noise factor (a ratio)
F'	Noise figure (in decibels)
FET	Field Effect Transistor
FM	Frequency Modulation
FSK	Frequency-Shift Keying
G_r	Gain of receiving antenna
G_t	Gain of transmitting antenna
h	Instrument Height (in particular the height of the direct beam over the point of reflection of the indirect beam)
hex, $_h$	Hexadecimal, number system to the base 16

List of Abbreviations and Symbols, continued

HPF	High Pass Filter
IF	Intermediate Frequency (amplifier stage)
K	Boltzmann's Constant
λ_c	Wavelength of microwave carrier signal
λ_m	Wavelength of modulating pattern signal
LCD	Liquid Crystal Display
LED	Light Emitting Diode
Lo	Locally generated pattern signal
LPF	Low Pass Filter
M	Integer multiplying factor
N	Integer multiplying factor
NAND	Not-AND, a logic gate with an inverting AND function
Φ_{cm}	Phase error term in Master centre pattern
Φ_{cr}	Phase error term in Remote centre pattern
Φ_{sm}	Phase error term in Master straddle pattern
Φ_{sr}	Phase error term in Remote straddle pattern
P	Atmospheric Pressure in millibars
PCB	Printed Circuit Board
RAM	Random Access Memory
RI	Atmospheric Refractive Index
Rx	Received pattern signal from far instrument
S	Relative Speed between two instruments
T_d	Temperature (°C) measured by the dry-bulb of a psychrometer
T_K	Dry-bulb temperature in Kelvin
T_w	Temperature (°C) measured by the wet-bulb of a psychrometer
TCXO	Temperature-Compensated Crystal Oscillator
Vg	Group Velocity
Vp	Phase Velocity
VCO	Voltage Controlled Oscillator
VSWR	Voltage Standing Wave Ratio
ω_m	Reference frequency for pattern generation in Master
ω_r	Reference frequency for pattern generation in Remote

CHAPTER 1

Subdivision of the Thesis

This thesis is divided into six Chapters, a Conclusion, a Bibliography and four Appendices.

Chapter 1 introduces the history of this project, what the objectives of the development have been and outlines the provisional specification of the instrument.

Chapter 2 gives an overview of the modules and their different configurations. The instrument's operation and built in test features of the software are described. The Tellurometer Principle and Digital Phase-Return technique of distance measurement are described.

Chapter 3 describes the Datalink configuration of the instrument including the development of the microwave source, the IF stage, the Autotune, and the Speech and Modem circuits.

Chapter 4 describes the modulator and synthesiser (the Modusynth), and the pattern set used for the evaluation of distance.

Chapter 5 describes the Microprocessor and Phase Counter section, and gives an overview of the software.

Chapter 6 is a discussion of subjects relevant to Tellurometers and surveying in general, and in particular to what extent these factors affect the Micromin.

The Conclusion describes what the author believes has been accomplished by this work.

The Bibliography lists related works and databooks that have been referred to for this work.

Appendix A is a mathematical treatment of the Tellurometer principle as used in this instrument.

Appendix B is a summary of relevant meteorological formulae and unit conversion constants for use at microwave frequencies and are appropriate to this instrument.

Appendix C is a summary of the results of field-trials performed to evaluate the cyclic contamination, accuracy and range performance of the prototype instruments.

Appendix D is an assembled software listing of the latest version of the Micromin program.

INTRODUCTION

History of the Project

The concept of a very low cost Tellurometer has long been discussed in the development laboratory of Plessey. It was the opinion of the late Dr.Trevor Wadley (the inventor of the Tellurometer) that Tellurometers were being made too complex and expensive for their full market potential to be realised. During one discussion with Mr.Bob Evans, Dr.Wadley asked quite seriously why Tellurometers were not being sold in supermarkets.

It was this background that inspired Mr.Evans to lay the foundation of an instrument with this concept, and in April 1984 invited the author to join him in a private development of a **MIN**imum **MICRO**wave measuring system that became known as the **MICROMIN**.
The mechanical arrangement of the horn, the front panel and the battery compartment were designed by Mr.Evans, and the author designed the electronic circuitry, wrote the software and developed the microwave source.
What followed was a year of homework in which a prototype measurement system was constructed, and in May 1985 it was presented to the management of the Plessey company as a potential new product.

In April 1985 the author registered this work for fulfilment of the requirements of an M.Sc. degree at the University of Cape Town. Work then continued on the instruments and major modifications and improvements to the original design were made.
This design concept gained joint second prize in the Overseas Category of the International Plessey Design Competition in November 1985, and in that same year Mr.Bob Evans and the author were awarded the "Managing Director's Award for Innovation and Achievement", a prize awarded annually within the Plessey Company.

The main features that have contributed to the design aim being met are;

- Dedicated Master and Remote instruments. This removes the extra circuitry required to make both instruments perform the Master or Remote function.

- The microprocessor is a single-chip processor with all the memory and port requirements on one chip.

- The Modusynth has a fine pattern of 20 MHz thus allowing the design to be realised entirely in CMOS, cutting down on complexity, cost and current consumption.

- The datalink has been changed from simplex to full-duplex and the speed increased from 2 400 to 9 600 Baud.

- The microwave source, originally configured as a self-oscillating mixer, is now a separate mixer configuration. This reduced the noise figure of the receiver and has increased the range of the instrument.

- Integral batteries, either rechargable or Alkaline cells, can be fitted into the instrument. Survey instruments often do not contain the batteries they use, thus requiring another item to be carried into the field.

At the time of writing there are only two Micromin instruments in existence, the two prototypes. There are no plans (yet) to produce any more. The status of these instruments is that they are ready for introduction into a pre-production manufacturing environment.
Tooling-up costs are minimal, the design is mature, tested and the performance is expected to be reproducible.

Instrument Cost

The costs of all the materials contained in the instruments have been calculated from the latest industry price lists available at the time of writing (August 1987). Assuming that components for 100 instruments are procured their cost per instrument will be:

Micromin in the Tellurometer Configuration:
Master R678, Remote R651,

and in the Datalink Configuration:
Master R337, Remote R352.

Instrument Specification

The instrument specification is as follows:

Configuration	Dedicated Master and Remote instruments
Range	10 m to 15 Km
Accuracy	approximately ±3 cm under favourable conditions of ground-swing
Carrier Frequency	10 300 MHz ± 10 MHz
Dynamic Operation	"Track Mode", range update once per second
Data Link	FSK 9 600 Baud Duplex
Speech Link	Push-to-talk
Power Requirements	12 Volts DC, 340 mA
Temperature	Operating ambient range 0 to 55 'C
Radiated Power	8 mW, vertically polarised
Antenna Beamwidth	14,05 deg vertical, 15,6 deg horizontal
Size	300 mm (L), 116 mm (H), 125 mm (W)
Weight	2,4 kg including batteries
Carrying case	Provided

CHAPTER 2

General Description

The Tellurometer Principle

The Micromin uses the Tellurometer Principle of distance measurement invented by the late Dr.Trevor Wadley at the National Institute of Telecommunications Research of South Africa in 1957.
In particular this instrument uses a technique called "digital phase-return" involving the measurement and storage of simultaneous measurements in both the Master and Remote instruments, and the subsequent comparison of these results.

Microwave carriers radiated from both the Master and the Remote instruments are mixed in both instruments to produce 10,76 MHz IF signals. The frequency discriminator in the Remote's IF produces a voltage output which is dependent on the frequency of the incoming signal. This is used to keep the instruments in tune.
The carrier waves are modulated with measurement frequencies (patterns) in the range of 10 to 21,25 MHz. These patterns are frequency-locked to a reference standard (5 MHz TCXO) in each instrument.

The modulation at the Master is mixed with the received modulation from the Remote and this difference is compared in phase with the reference. Likewise the modulation at the Remote is mixed with the received modulation from the Master and this difference is compared in phase with the reference in the Remote.

Consider the transmission of these signals as shown in Fig.2-1.

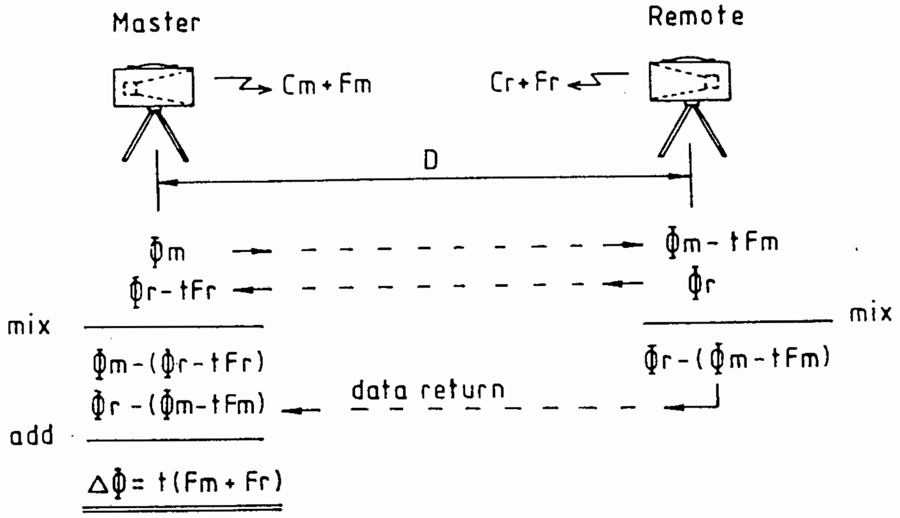


Fig.2-1, Transit Path Time and Phase Measurement

The signal transmitted from the Master is a carrier wave of frequency Cm, frequency modulated by pattern frequency Fm. Similarly the signal transmitted from the Remote instrument is a carrier wave of frequency Cr, frequency modulated by pattern frequency Fr.
If the pattern frequency Fm has at some instant a phase value of Φm, then this signal received at the Remote, at that same moment, will have a phase value of (Φm - tFm), where t is the time that the wave took to travel the distance D from the Master to the Remote. Similarly if the pattern frequency Fr has (at the same time) a phase value of Φr, then this signal received at the Master will have a phase value of (Φr - tFr), owing to the transit path delay t over the path D.

The carriers mix to produce the 10,76 MHz IFs, and the pattern modulations mix to produce beat frequencies that are used in the phase measurements process. The phases of the carriers play no part in the phase measurement of the pattern beat frequencies.
The FM pattern modulations mix to produce 39,062 kHz AM beat frequency components, the phases of which are measured with respect to the frequency references in each instrument.

The phases measured are:

in the Master $\Phi m - (\Phi r - tFr)$
in the Remote $\Phi r - (\Phi m - tFm)$

These phases are recorded in digital form by microprocessors in each instrument. The Remote then transmits the result to the Master via the datalink and the the results are added. This gives:

$\Delta\Phi = \Phi m - (\Phi r - tFr) + \Phi r - (\Phi m - tFm)$
i.e. $\Delta\Phi = t(Fm + Fr)$ cycles or $2\pi t(Fm + Fr)$ radians
also $\Delta\Phi = N + \Delta\Phi'$ cycles or $2\pi(m + \Delta\Phi')$ radians

In the phase discrimination only the part of the cycle $\Delta\Phi'$ is measured as the value of the integer N is unknown.

The Tellurometer is essentially a time measuring instrument, for if $\Delta\Phi$ is observed and Fr and Fm are known then the value of t can be calculated. From this the value of D can be calculated if the value of the velocity of propagation C, is known.

The value of the integer N is determined by using progressively increased values of pattern wavelength in binary steps. This could be done by simply reducing Fm and Fr. In practice however, with the long distances involved the frequencies of Fm and Fr would become inconveniently low. It is therefore arranged to measure a convenient pattern frequency and to then change the values of Fm and Fr by the frequency of the pattern that is required to be measured, the value of this difference is then found by subtracting the resultant phase measurements of these two patterns. For example to measure the phase of a pattern frequency Fd, due to the transit path delay, this can be achieved by measurement of two patterns F1 and F2 where $F1 - F2 = Fd$. For example, as before:

$\Delta\Phi 1 = t(F1m + F1r)$
and $\Delta\Phi 2 = t(F2m + F2r)$

subtracting the two results gives,

$$\Delta\Phi d = \Delta\Phi 1-\Delta\Phi 2 = t[(F1m + F1r) - (F2m + F2r)]$$

Thus the measurement of the phase of a low frequency pattern is achieved by the measurement of the phases of two high frequency patterns differing in frequency by the low frequency "Difference Pattern".

In the Micromin the lowest frequency pattern, 2,441 KHz, is measured by the differential phase measurement of 20,000 000 and 20,002 441 MHz patterns. The unambiguous range of this pattern is 61 397,503 metres, since N is zero for distances shorter than this.

The accuracy of the determination of the distance increases by a the ratio of the pattern frequencies (x2, x4 or x8) with each of the eight patterns up to the finest pattern which has an ambiguous wavelength of 3,747 m. Averaging 16 frames of phase measurement of this pattern results in a final instrumental accuracy of approximately 3 cm.

Furthermore this measurement technique is improved by the repetition of the first pattern after the second. The two measurements of the first pattern are averaged and appear as if their average was calculated at the same time as the second pattern, thereby cancelling any errors due to movement of one or both of the instruments. This gives a accurate dynamic measurement capability which is available in the TRACK mode of operation of the Micromin where the distance readout is updated once per second.

This process of repeating the first pattern after the second pattern has resulted in the terminology of a "Straddle Pattern" and a "Centre Pattern". The measurement of the eight patterns in the Micromin are all achieved by a differential straddling process contained within a "frame" 300 ms long involving data transmission between the two instruments, and three phase measurement periods, the first Straddle, the Centre and the second Straddle patterns.

The measurement frame is described in more detail in Chapter 5, and the pattern set is described in Chapter 4.

Mechanical Arrangement of the Micromin

The general assembly of the Micromin with the outer case removed is shown below in Fig.2-2.

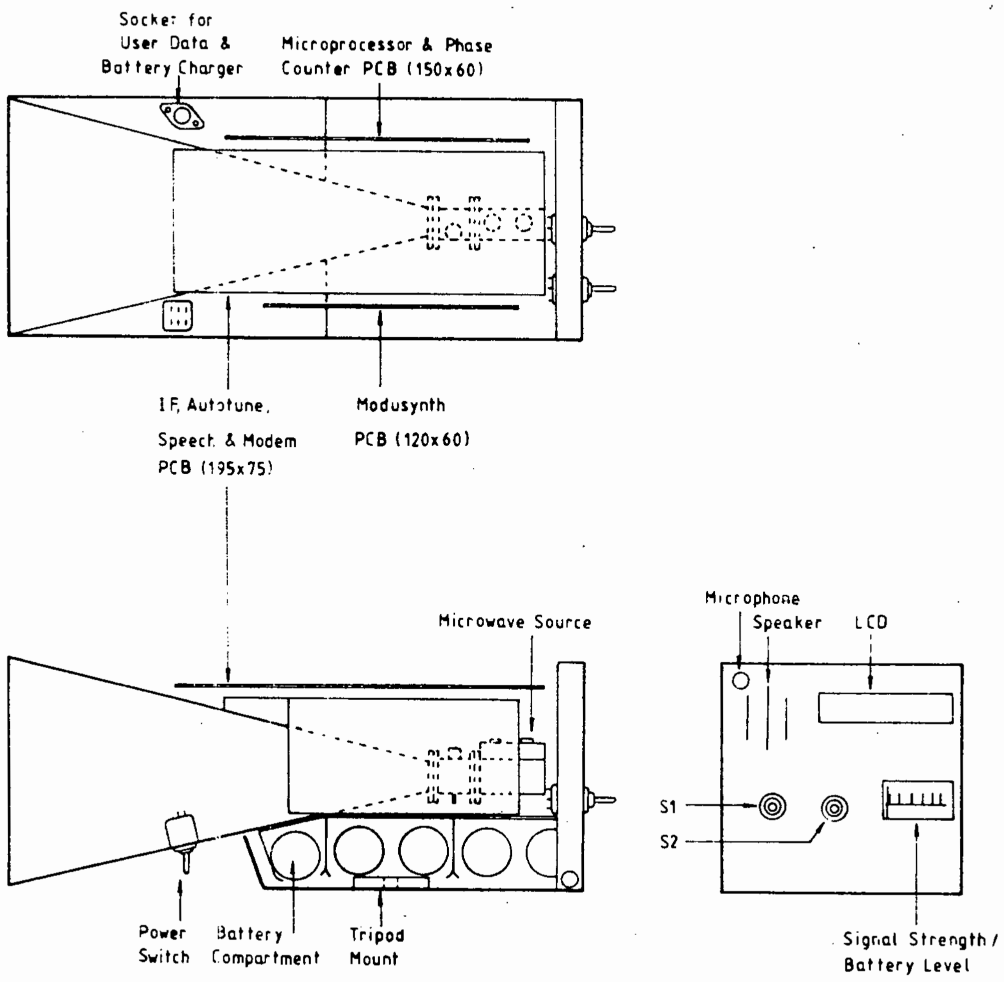


Fig.2-2, Mechanical Arrangement of the Micromin

The combination of,

small size, light weight, internal batteries,

low power consumption, carrying case and rugged construction

make the Micromin a convenient and very portable survey instrument.

The Micromin in the Tellurometer Configuration

The block diagram of the Micromin in the full Tellurometer configuration is shown in Fig.2-3.
The major components are;

- the Microwave Source and Horn Antenna (S and H),
- the Intermediate Frequency stage (IF),
- the Autotune (AT),
- the Modem (FSK TX, RX, HPF and LPF),
- the Speech Facility,
- the Modusynth (MS),
- the Squarer (SQ),
- the Microprocessor (µP),
- the Phase Counter (Φ), and
- the Liquid Crystal Display (LCD).

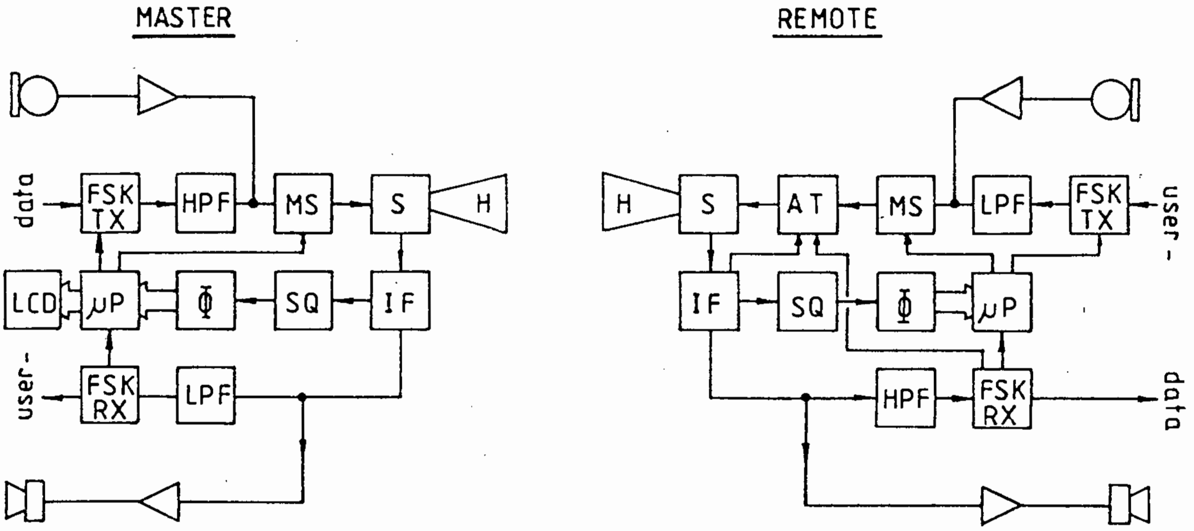


Fig.2-3; Block Diagram of the Tellurometer Configuration

A description of the function of each of these sections follows.

The microwave source (S) consists of a varactor-tuned Gunn oscillator, Plessey type GVD03/001, and a mixer assembly. The source device mounting posts are replaced with larger ones to increase the tuning range. The choice of 10 GHz (X-band) for this instrument was influenced by the availability of low-cost sources and measurement equipment. In the past other survey instruments have achieved acceptable results at 10 GHz, with the main limitation to accuracy being ground swing (described in Chapter 6). Whilst ground swing is less at higher frequencies the accuracy improvement is gained at the expense of higher device costs and greater atmospheric path losses.

The IF is a wideband FM and AM receiver with a bandwidth of 250 KHz and designed to receive signals as low as 1 µV. In order to recover an AM product from the FM/FM system of this instrument, an AGC loop is employed. The IF detects the FSK datalink signals in the ranges of 25-35 KHz and 75-85 KHz, and the phase comparison signal (AM) at 39,062 KHz. The FM discriminator outputs are fed to the Autotune which locks the frequency of the Remote to that of the Master.

The modems are phase-continuous FSK transmitters, and phase-locked-loop receivers. Full duplex operation is possible at any rate up to and including 9 600 Bauds. Transmission from the Master to the Remote is in the range of 75-85 kHz and from the Remote to the Master in the range of 25-35 KHz. The datalink is used during the measurement of distance, but at all other times it is automatically switched over to allow the user to use it with any other serial data transmission equipment.

The speech facility is a simple baseband modulation system; transmission is enabled by a press-to-talk switch on both instruments, and modulation level is controlled by an automatic level control. The audio amplifier in each instrument provides approximately 400 mW to an 8 Ω loudspeaker mounted on the front panel.

The measurement patterns are generated by the modusynth (MS), a frequency-locked loop generating pattern frequencies for the eight sets of binary-related phase measurements. The pattern set gives unambiguous distance measurements up to a maximum range of 61,397 km. All these pattern frequencies fall between 19,6 MHz and 21,25 MHz with the exception of one pattern using 10 MHz, which is generated by division of the 20 MHz signals by 2. The modusynth is realised entirely in CMOS technology and has a very low current consumption of only 60 mA.

The squarer is a selective amplifier tuned to 39,062 kHz to recover the AM comparison-frequency used for the phase measurement process. To ensure accurate phase measurement of the zero-crossings of this signal a comparator is used to "square" the signal waveform. The output of this circuit is fed to the phase counter on the microprocessor board.

The microprocessor and phase counter (µP and Φ) are also realised entirely in CMOS technology (with the exception of the reference 5 MHz TCXO); current consumption of this circuit is a low 40 mA. Only the Master instrument has an LCD, in order to reduce the system cost.

Instrument Operation

The operation of the Micromin has been kept as simple as possible. The two toggle switches on the front panel S1 and S2 are used in the following way:

For Master and Remote instruments, in both the Datalink and Tellurometer configurations,

Press-to-Talk,	S1 up, hold up while talking,
Battery Voltage,	S2 down, hold down to read battery condition.

For the Master instrument in the Tellurometer configuration only:

Static Measurement	S1 in centre, briefly push S2 up and release,
Dynamic Measurement	S1 down, briefly push S2 up and release,
Stop Measuring,	push S2 up and hold up until speech is unmuted, then release S2.

Built-in Test Features

- Instrument Alignment

The TEST switch on the microprocessor board is used in the adjustment of the synthesiser tuning range and the modulation index for each of the patterns. Pressing the TEST switch sets up the synthesiser and modulates the carrier with the centre pattern frequency of the first pattern (0). Further pressing the TEST switch cycles the synthesiser through the rest of the patterns allowing the modusynths to be adjusted.

The instruments can be tuned in to each other and then by applying the patterns one at a time, the 39,062 kHz difference frequency can be recovered at the output of the squarer of each IF.

The tuned circuit and gain of both the squarers can be set up this way. This procedure gives a good indication of phase noise on each of the patterns (see Fig.6-9).

- Phase Measurement of One Pattern at a Time

A feature of the Micromin that can be used for both factory testing and operator training is the facility to measure the angle of one pattern at a time and manually repeat, or increment the pattern being measured. Instead of the pattern phase being interpreted as a possibly ambiguous distance, the pattern number and the possibly ambiguous phase angle, in degrees, is displayed on the LCD.

Measuring the angle of one pattern at a time is achieved by having the two instruments tuned in to each other, and physically aligned. Then at the Master instrument, press up S2, then press the TEST switch, then release S2, and then release the TEST switch. The Micromin will then start by measuring the phase of pattern 0, display the pattern number and the phase in degrees, and then wait.

The measurement of the current pattern can be repeated by holding up and then releasing S2.

The measurement of the next pattern can be made by pressing the TEST switch. The pattern count cannot be incremented further than the finest pattern (7).

In order to return to normal measurement the Master instrument can be reset, either with the RESET switch or by switching off and on again.

This feature can be used to demonstrate that the angle of a pattern two, four or eight times that of the previous pattern, or to determine the scatter in the phase readings of various patterns. An example of this has been recorded in Appendix C under the heading of "Pattern Analysis" to show the phase scatter and pattern-ratio fit of the prototype instruments.

CHAPTER 3

The Micromin in the Datalink Configuration

The block diagram of the Micromin in the datalink configuration is shown in Fig.3-1.
The major components are:

- the Microwave Source and Horn Antenna (S and H),
- the Intermediate Frequency stage (IF),
- the Autotune (AT),
- the Modem (FSK TX, RX, HPF and LPF),
- the Speech Facility,
- the interface to the optional Modusynth (m).

Because the data input and output lines go to both the Microprocessor option and the USER RS232 connection, they are shown as broad arrows. Note that only the Remote instrument has an Autotune. The Master instrument is kept at a constant frequency and the Remote sweeps and locks onto the Master with an AFC (automatic frequency control) circuit.

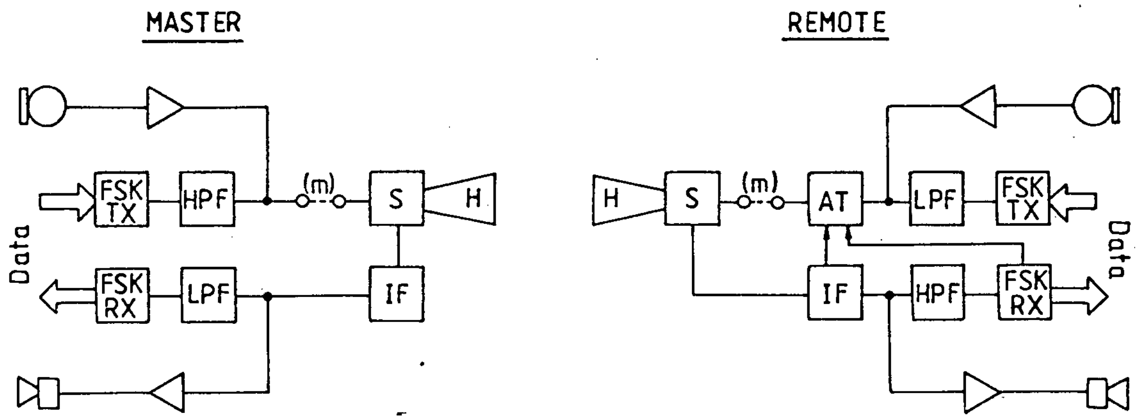


Fig.3-1, Block Diagram of the Datalink Configuration

Each of these sections and their development will be described in this chapter.

Development of the Microwave Source

A Plessey Optoelectronics and Microwave GDV03/001 varactor-tuned Gunn oscillator is used as the microwave source.
It was chosen because of the following features:

+8 Volt Gunn voltage,
low current consumption (nominally 115 mA),
low cost,
availability,
small size and light weight.

The source has a nominal tuning range of only 50 MHz.
To simplify the requirements of the modulator it is necessary to increase the tuning range of the source to approximately 120 MHz.
To achieve this the diameter of the varactor post is increased; this increases the coupling of the varactor to the Gunn diode. More power is absorbed in the varactor reducing the output power, and in order to maintain power output from the source it is necessary to increase the size of the Gunn post. Increasing the size of the Gunn post in the cavity increases the coupling between the Gunn device and the external load, and increases the output power to the load.
This has the result of reducing the cavity Q-factor and degrading the temperature stability and noise performance. The resulting noise and temperature stability are however still acceptable for this application.
Two GDV03/001 sources #1378 and #1379 were tested and the tuning ranges were found to be 49,1 and 45,4 MHz respectively.
Here the tuning range is defined as the change in frequency when the varactor voltage is varied from 5 to 15 Volts.
In order to increase the tuning range of source #1378 the posts were increased from the original, Gunn= 3,5 mm, varactor= 3,0 mm;
to Gunn= 9,0 mm, varactor= 9,0 mm.
The tuning range was then found to be 88 MHz. This tuning range was not wide enough, so the posts were increased again to Gunn= 11 mm, varactor= 11 mm.

This resulted in a satisfactory 5-15 V tuning range of 129 MHz. The results of this exercise are shown below in Fig.3-2.

(Each time the posts were changed the cavity tuning screws were readjusted to deliver an output power of 15 mW, and a carrier frequency of 10,3 GHz at a varactor voltage of 8 V.)

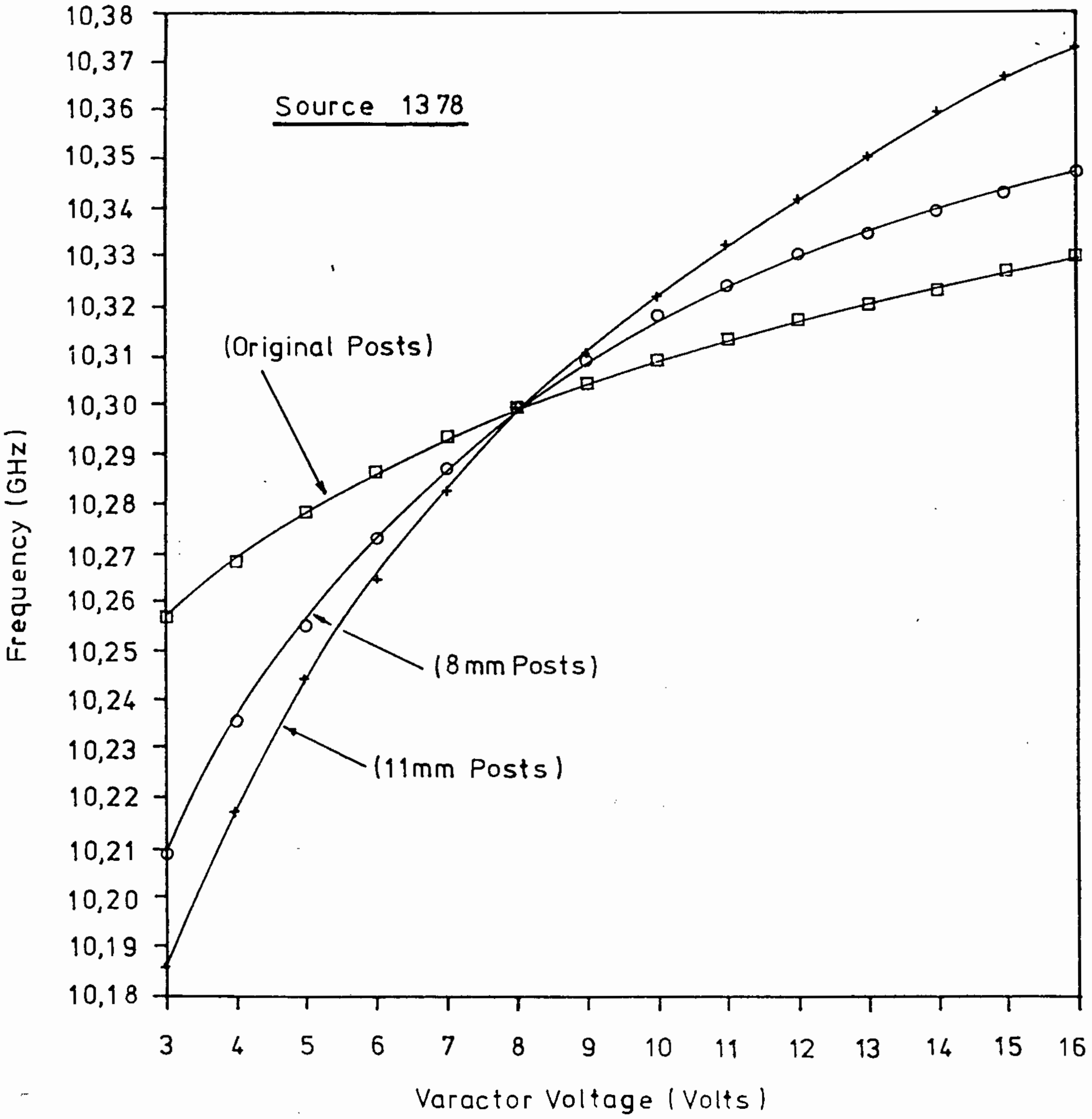


Fig.3-2, Tuning Curve of Source #1378

In order to increase the tuning range of source #1379 the posts were increased from the original Gunn= 3,6 mm, varactor= 2,09 mm; to Gunn= 10,0 mm, Varactor 10,0 mm.

This increased the the tuning range to 116 MHz, as shown below in Fig.3-3.

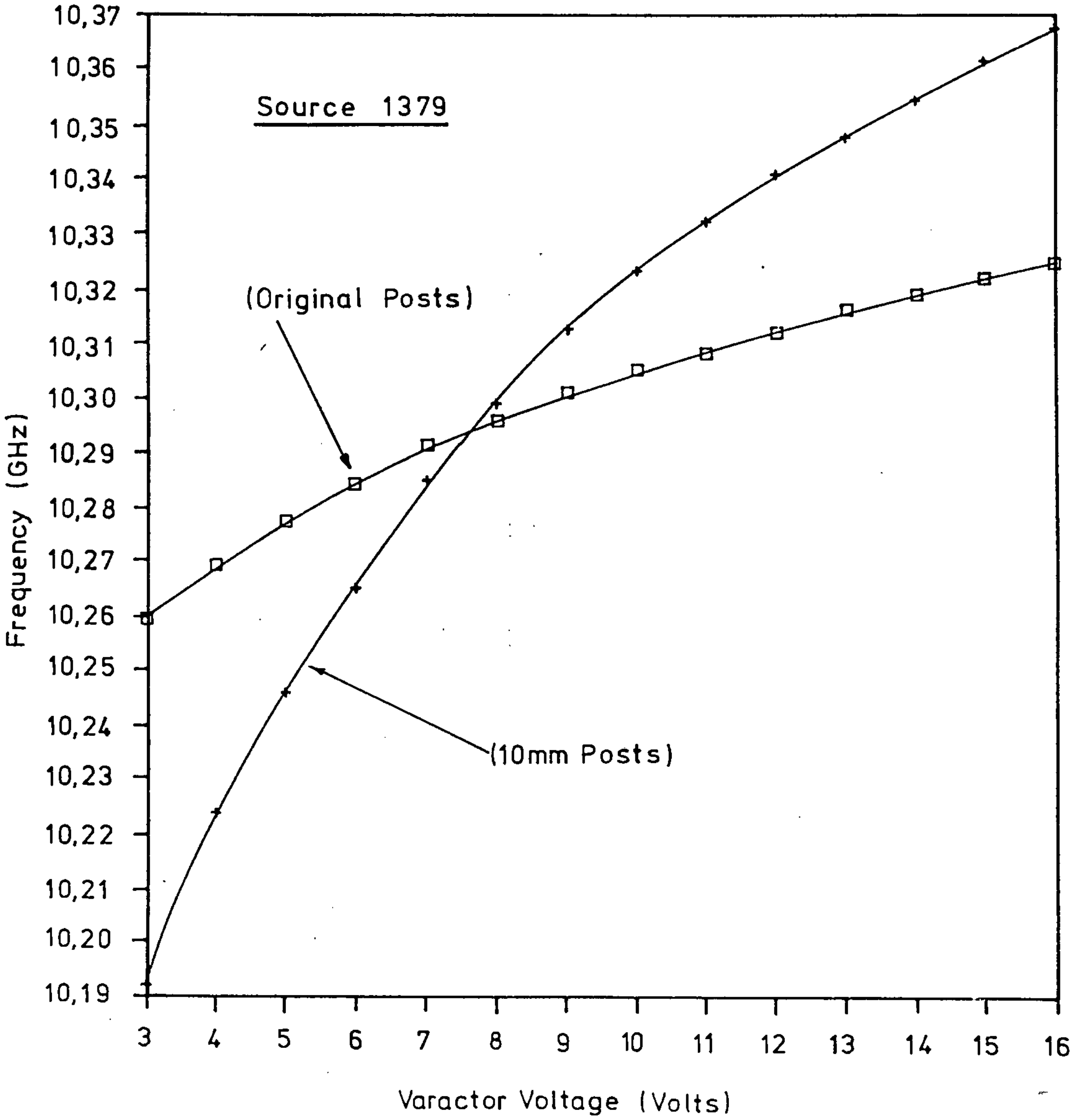


Fig.3-3, Tuning Curve of Source #1379

The Mixer Mount

The mixer diode is a standard 1N23C silicon Schottky-barrier mixer diode, designed for X-Band waveguide mounting.
Vertical polarization for both transmit and receive paths is used.
Local oscillator bias is achieved by mounting the mixer diode in front of the Gunn diode and off-centre in the waveguide to control the amount of transmit power that is absorbed. This configuration also loses receive power, so there is a compromise between getting sufficient local oscillator bias (and not absorbing too much of the transmit power), and not losing too much of the received signal by positioning the mixer too far to the side of the waveguide.
If 3 dB of the transmit power is absorbed as mixer bias, then 3 dB of receive signal is sacrificed. With the Gunn oscillators providing 15 mW this means that approximately 7 mW would be absorbed and 8 mW transmitted. The mixer mount is shown in Fig.3-4.

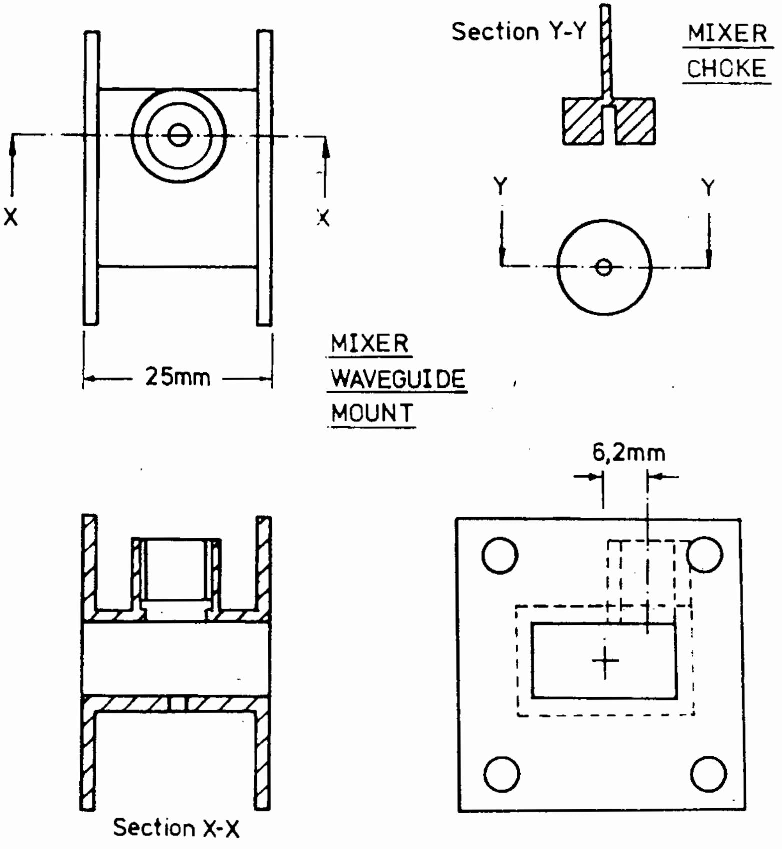


Fig.3-4, The Mixer Waveguide Mount

The arrangement of the source assembly, consisting of the modified GDV03/001 source and the mixer mount, is shown in Fig.3-5.
The chokes for the varactor, Gunn and mixer are insulated from the source body by heat-shrink sleeving.
For simplicity Fig.3-5 does not show the source-frequency-adjustment or power-matching screws.

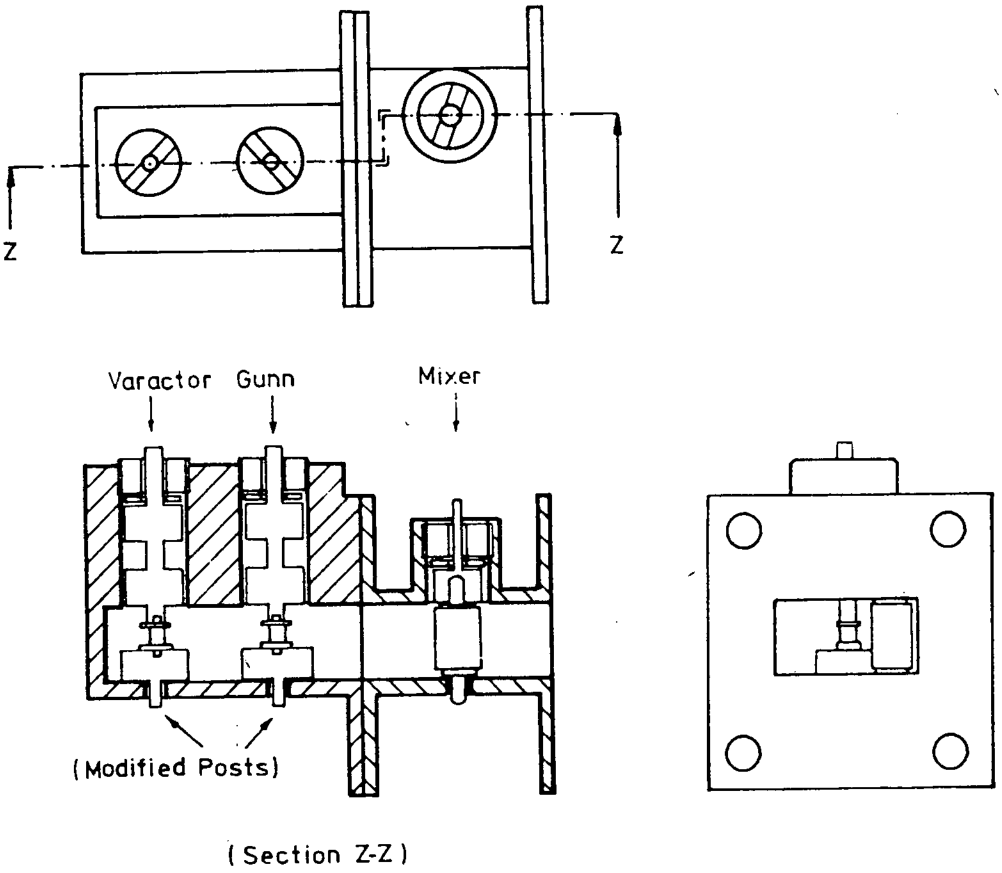


Fig.3-5, The Microwave Source and Mixer Assembly

The resultant power output and tuning bandwidth of the two sources are shown is shown in Fig.3-6. Note that the power output of #1379 has been reduced, by adjusting the power matching screw, in order to ensure reliable starting of the Gunn oscillator.

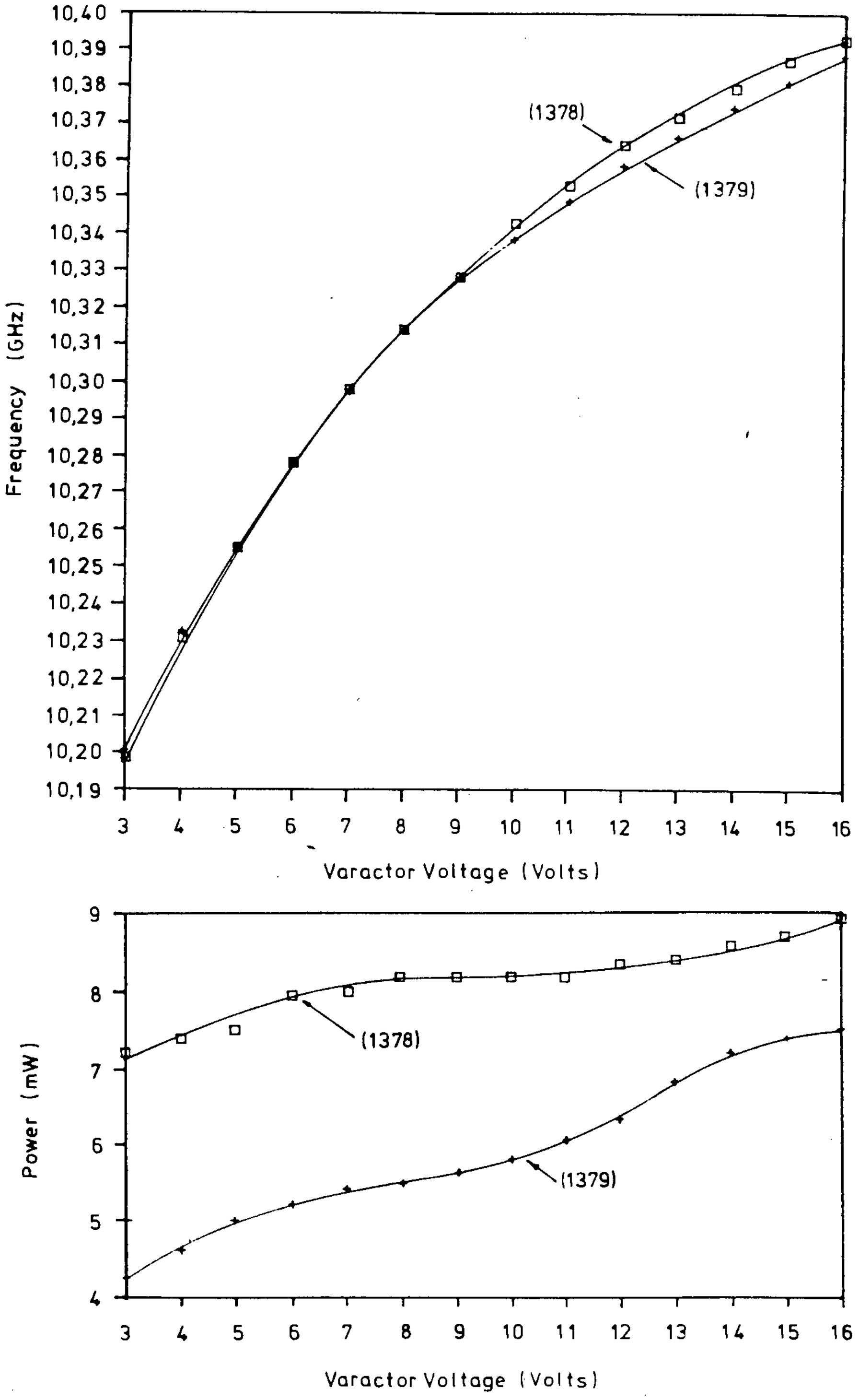


Fig.3-6, Tuning and Power Curves of the Microwave Assemblies

Gain of the Horn Antenna

The horn antenna was designed as a straight-flare pyramidal horn which provides a simple mechanical arrangement and a convenient base on which to mount the printed circuit boards.

Assuming a TE01 mode of excitation, the gain of this antenna over a half wave dipole is defined as

$$G = 4{,}5 A_{e\lambda} A_{h\lambda} \qquad \mathbf{3.1}$$

where;

$A_{e\lambda}$ = horn aperture in the E plane in free space wavelengths
$A_{h\lambda}$ = horn aperture in the H plane in free space wavelengths

The free space wavelength at 10,3 GHz is, $(\lambda = C/f)$

$$(300 \times 10^{6})/(10{,}3 \times 10^{9}) = 2{,}91 \times 10^{-2} \text{ m}$$

and with $A_e = 116$ mm and $A_h = 123$ mm
giving

$A_{e\lambda} = 3{,}99$ and $A_{h\lambda} = 4{,}23$

therefore $G = 4{,}5 \times 4{,}23 \times 3{,}99 = 75{,}95$ times,

which expressed in dB is $10\log_{10}(75{,}95) =$ **18,81 dB**

(There is a discussion of Antenna Swing, and the VSWR of the horn antenna, in Chapter 6.)

Noise Figure Of The Receiver

The noise power of a receiver is given by the formula

$$S = KTB \qquad 3.2$$

and if the receiver is preceded by a mixer of noise factor F' (or noise figure F, in dB) this becomes

$$S = F'KTB$$

where

F' = noise factor of the mixer (5, equivalent to 7 dB)

K = Boltzmann's constant ($1,38 \times 10^{-23}$ Joules/Kelvin)

T = absolute temperature (290 K)

B = IF bandwidth (250×10^{3} Hz)

giving

$$\begin{aligned} S &= 5 \times 1,38 \times 10^{-23} \times 290 \times 250 \times 10^{3} \\ &= 5,01 \times 10^{-15} \text{ Watts} \\ &= 5,01 \times 10^{-12} \text{ mW} \\ &= \mathbf{-113\ dBm} \end{aligned}$$

The mixer is mounted off-centre in the waveguide attenuating the received signal by 3 dB. The mixer has an image input increasing the noise level by 3 dB, while the IF has a noise figure of 2 dB.

This 3 dB loss and the extra 5 dB of noise component mean that to equal the level of the internal receiver noise, an incoming signal from the far instrument will need to be at a level of **-105 dBm**.

Impedance Matching of the Microwave Source Assembly

Another loss in the receive path that must be considered is the impedance matching of the mixer and the source.
The impedance of the mixer assembly was measured using a Hewlett Packard 8510A Network Analyser. The mixer assembly was fitted in front of a tapered dummy load and the VSWR of the combination was measured as shown below in Fig.3-7.

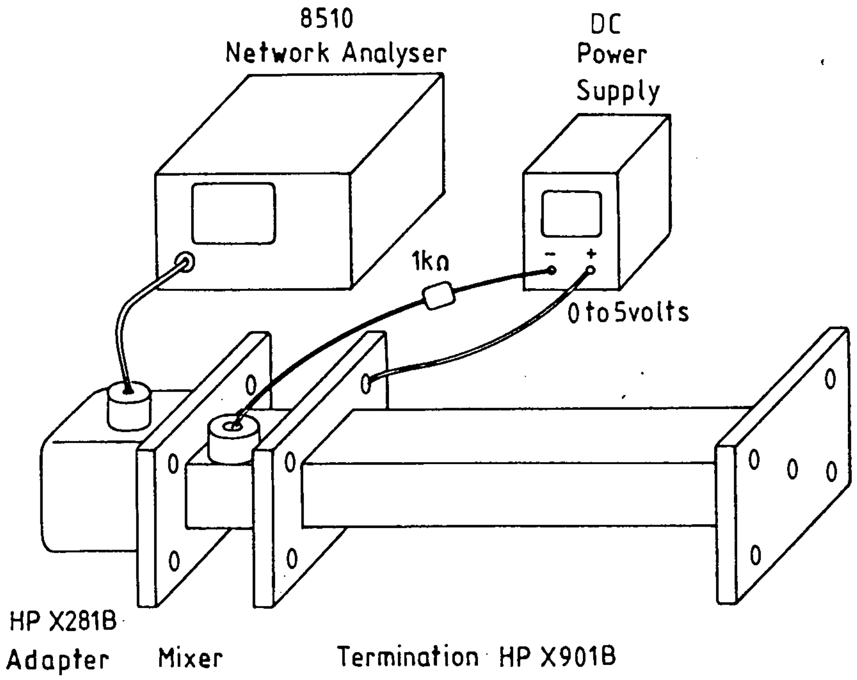


Fig 3.7, Measurement of the Mixer Mount Impedance Matching

With no mixer current the VSWR was 1:1, showing that the mixer was not loading the waveguide at all, (not being in conduction), and that the dummy load was a good match.
A mixer current of 5 mA is generated when mounted in front of the source. To emulate this a bias current of 5 mA was injected into the mixer diode from an external DC power supply, changing the VSWR to approximately 2:1.

As the impedance of the dummy load is 400 Ω and the parallel combination of the dummy load and the biased mixer is 200 Ω it follows that if no power is being reflected from the mixer it has an impedance equal to the dummy load i.e. 400 Ω.
With a waveguide and mixer impedances of 400 Ω the match between the mixer diode and the source is important since it affects the coupling of the receive energy into the mixer.
It was found impossible to measure the VSWR of the source looking into the cavity as this would necessitate powering up the source and disturbing the network analyser. The power match between the source and the load is adjusted by the power-matching screw, but this only matches the impedance to a VSWR of about 3:1. Any improvement in this can only be made by increasing the length of the waveguide and using more power-matching screws. This is not done in practice as it would be uneconomical, resulting in only a 25% increase in output power.

If the VSWR match of the source to the waveguide is in fact 3:1, the impedance of the source as seen by the mixer assembly can be from 133 Ω to as much as 1200 Ω, depending on the phase of the reflection. The received signal will be present across both the 400 Ω load of the mixer and the unknown load of the source and a loss of as much as 6 dB of the receive energy can be expected due to absorption by the source.

Taking the worst case then of the phase of a reflection from a 3:1 VSWR mismatch between the mixer assembly and the source, for an incoming signal to equal the level of the internal receiver noise, it must be 6 dB greater in strength than previously calculated, i.e. **-99 dBm**.

Maximum Range of the Micromin

The maximum range that the Micromins can work over is determined by the formula;

$$Pr = Pt \times Gt \times Gr \times (\lambda/4\pi D)^2 \qquad 3.3$$

where

Pr = power of the received signal (mW)
Pt = power of the transmitted signal (8 mW)
Gt = gain of the transmitting antenna (75,95 times)
Gr = gain of the receiving antenna (75,95 times)
D = distance between the antennas (m)
λ = wavelength of the carrier (m)

From this, given that the transmitted power of the weaker of the two sources is 5 mW (in future instruments this should be increased), the antenna gain at each end is 75,95 times, and the wavelength is 29,1 mm, the power of the received signal at a distance of **30 Km** is;

$$Pr = 5 \times 75{,}95 \times 75{,}95 \times (0{,}0291/(4\pi \times 15\ 000))^2$$

$$= 6{,}88 \times 10^{-10} \text{ mW}$$

$$\equiv \mathbf{-91{,}6\ dBm}$$

With this received signal strength there will be a signal to noise ratio of **+7,4 dB** if the losses and receiver noise levels as previously discussed are correct. With this margin, it indicates that the maximum range of the Micromin is in the order of 15 Km. This has proven to be the case as shown by the results of the field-trials reported in Appendix C.

Dynamic Range of the Receiver

The dynamic range requirements of the IF can be determined by calculating the received power at the minimum range, say 50 metres. Again using equation 3.3 ;

$$Pr = Pt \times Gt \times Gr \times (\lambda/4\pi D)^2$$

$$Pr = 8 \times 75,95 \times 75,95 \times (0,0291/4\pi)^2 \times (1/50)^2$$

$$= \mathbf{9,9 \times 10^{-5}\ mW}$$

There will be a loss of 3 dB due to the offset position of the mixer diode, and a further possible loss of 6 dB due to the VSWR of the source, this implies that at 50 m the IF will receive a power level;

$$= \mathbf{12,46 \times 10^{-6}\ mW}$$

Since the input impedance of the IF is 150 Ω this level of signal strength will develop a voltage of **1,36 mV**.
This amplitude defines the gain parameters for the design of the IF amplifier stage.

The receiver noise-floor is at a level of -99 dBm, which is equivalent to a power level of $1,26 \times 10^{-10}$ mW.
Since the input impedance of the IF is 150 Ω this level of signal strength will develop a voltage of **4,3 µV**.

It follows then, that the IF will have to handle input voltages ranging approximately from **4 µV to 1,5 mV**.

The Intermediate Frequency (IF) Stage

The first two stages of the IF have a maximum gain of 30 dB, which is distributed as shown in Fig.3-8.

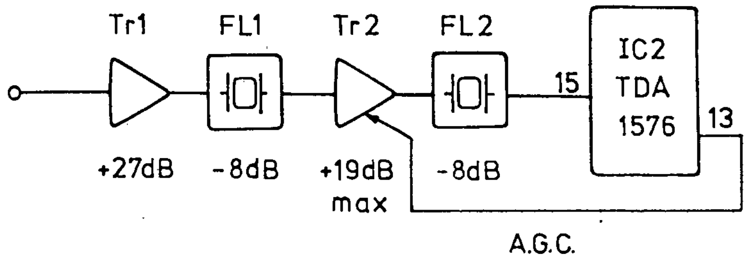


Fig.3-8, Gain Distribution in the IF Front-End

FL1 and 2 are ceramic filters with a passband insertion loss of 8 dB. With an overall gain of 30 dB it follows that the input of IC2 (pin 15), will receive an input voltage ranging from 126 µV to 47 mV. This is a reasonable operating range for the TDA 1576. However the Micromin relies on the recovery of a 39,062 kHz AM component from the TDA1576 and this is a limiting factor in the design of the IF's dynamic range. The TDA1576 is an FM receiver and limits the incoming signal by a series of saturating amplifiers. With large signal strengths all of the stages of the TDA1576 saturate causing loss of detected AM.

This saturation is minimised by the AGC circuit which reduces the gain of Tr2 for IF input voltages greater than 10 µV. Referring to the circuit diagram of the IF, shown in Fig 3-9; IC3b is controlled by the output voltage level of the TDA1576 (pin 13) and controls the gain of Tr2 by varying the current flowing through the PIN diode D1. This varies the decoupling effect of C11.

The AFC output and its inverted form, FMI, are fed to the Autotune. The AFC signal contains the demodulated FM buffered by the unity gain amplifier of IC3a and is fed to the audio amplifier and the receive modem.

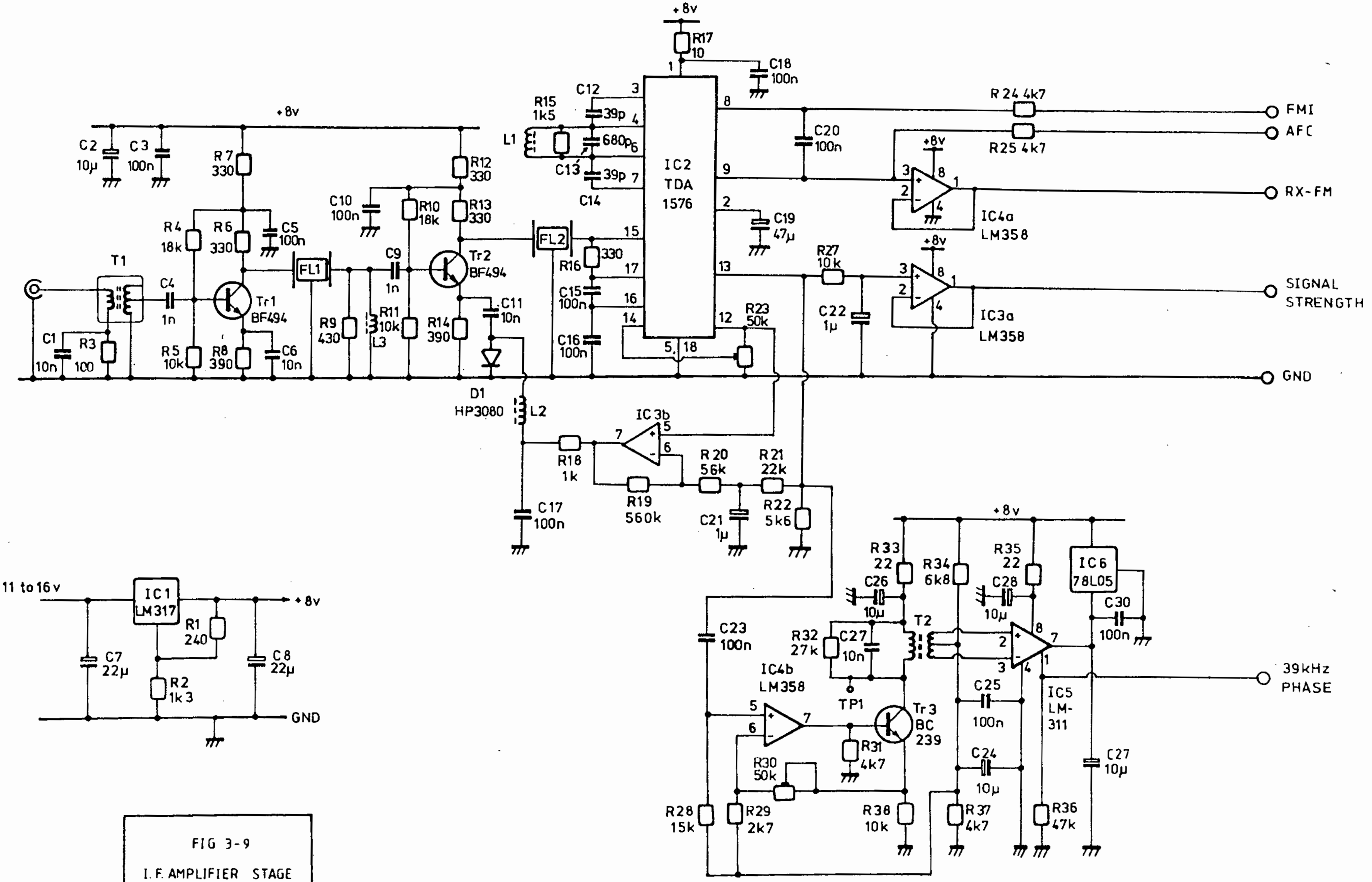


FIG 3-9

I. F. AMPLIFIER STAGE

The "signal strength" output is fed to the switching circuit that applies this level or the battery voltage to the meter.

When used in the Tellurometer configuration the IF recovers an AM component from the "signal strength" output of the TDA1576 (pin 13) which is fed to the filter and squarer circuit of IC4b, Tr3 & IC5. The gain of the squarer is set by R30. Tr3 increases the current gain of the amplifier. The parallel arrangement of C27 and the primary of T2 is resonant at 39,062 kHz. The Q of this tuned circuit is set to 66 by R32. The value of R36 is kept high (47 kΩ) to keep the output current as low as possible, so as to prevent contamination, (refer to the section on contamination in Chapter 6). The output signal is fed to the phase counter of the microprocessor. It is necessary to feed the phase counter with a clean, fast rising edge to ensure accurate phase measurement. This is achieved by arranging the output circuit of IC5 to pull up pin 1 quickly to get a fast rising edge, and having R36 slowly let it decay again. The output configuration and waveform are shown in Fig.3-10.

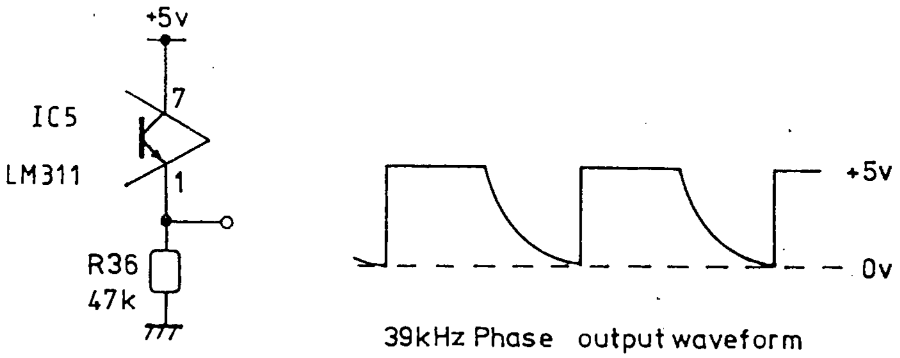


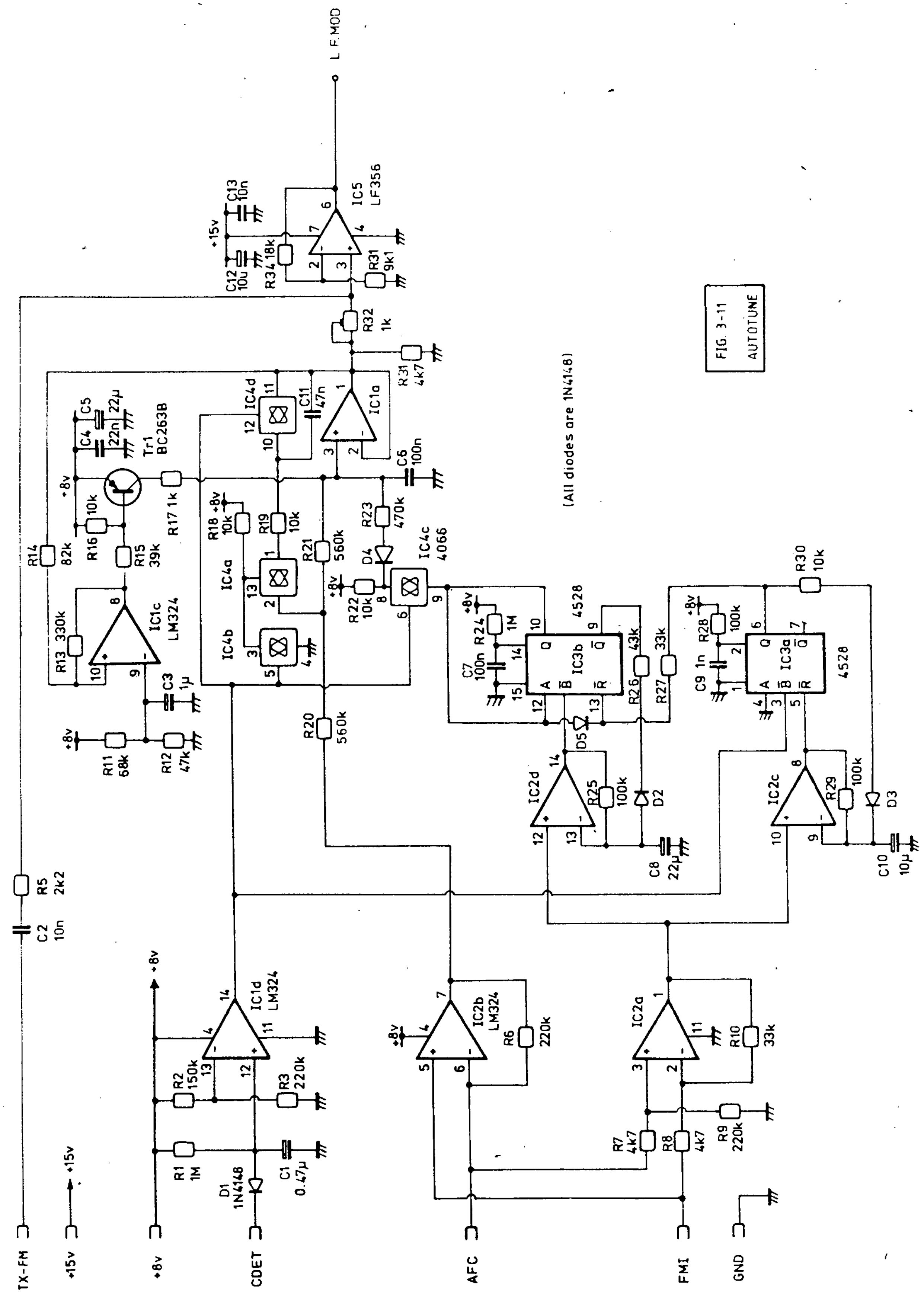
Fig 3-10, Output Configuration and Waveform of the Squarer

The Autotune

The circuit diagram of the autotune is shown in Fig.3-11. The function of this circuit is to sweep the frequency of the Remote instrument, stop the sweep when an IF signal is detected and then lock the Remote instrument's frequency onto the Master with an AFC loop.

The circuit of IC1a, IC1c & Tr1 generates a ramp waveform on C6. IC1c is a comparator which switches state when the ramp waveform pulls the non-inverting input above or below the preset bias point of the inverting input (set at 3,27 V by R11 and R12). The amplitude of the ramp waveform is set by the hysteresis action of R13 and R14. Switching the comparator output low switches Tr1 on and this charges C6 rapidly through R17. The voltage on C6 decays slowly through R23 with a time constant of 300 ms, as long as the gate IC4c is turned on and the Q output of IC3b is low.

The sweep action is stopped by reverse-biasing D4 which prevents C6 from being further discharged. This is achieved by the S-curve detection circuit of IC2a,c & d and IC3. The two inputs FMI and AFC are derived from the IF. AFC is the frequency discriminator output, and FMI is the inverse of AFC. When the sweep circuit sweeps the Remote signal past the Master signal an S-curve is generated by the FM discriminator of the IF. This S-curve is amplified by IC2a and fed to two peak detectors IC2c and IC2d. In the absence of any signal the discriminator outputs a noise signal. The voltage on C8 is held to the lower limit of the amplitude of this noise signal by the comparator action of IC2d and the monostable IC3b. Likewise the voltage on C10 is held to the upper limit of the noise signal by the comparator action of IC2c and the monostable IC3a. (R25 and R29 prevent latch-up of the comparators). It is so arranged by the polarity of the discriminator and the direction of the sweep, that when an S-curve is detected it first (if it is strong enough) goes higher than the upper limit of the noise.



(All diodes are 1N4148)

FIG. 3-11
AUTOTUNE

This is detected by IC2c, and triggers the monostable IC3a for 100 µs (set by C9 and R28). This trigger then enables IC3b to be triggered by taking the reset of IC3b (pin 13) high and reverse-biasing D5. The continuing sweep pushes the S-curve down below the lower limit of the noise which is then detected by the comparator IC2d which can then trigger IC3b. The time constant of this monostable is set by R24 and C7 to 100 ms and is the time for which the Q output (pin 10) goes high. This stops the sweep by reverse biasing D4.

Note that to stop the sweep there must be a signal that exceeds the upper limit of the noise and then within 100 µs goes below the lower limit of the noise. Noise is unlikely to have this characteristic so an S-curve from the IF will very likely be the only thing to stop the sweep.

The Master's signal in the IF will be confirmed by the presence of the datalink subcarrier which will, when detected by the modem, force the carrier detect line, CDET, low. CDET is fed from the modem to the autotune and used to prevent the sweep circuit from sweeping on after the S-curve detector's 100 ms time-out has elapsed.

The CDET line going low discharges C1 via D1, and switches the output of IC1d low. This will then do three things:

- Firstly the monostable IC3a is inhibited from triggering by setting its B input high (this prevents it causing any noise that may interfere with the AFC loop).
- Secondly the gate IC4c is switched off, so keeping D4 reverse-biased and ensuring that the sweep circuit does not oscillate.
- Thirdly it closes the gate IC4a and opens the gate IC4d thus turning IC1a from a buffer into a Sallen Key filter for the AFC loop. (IC4b is used as an inverter).

If the modem's CDET line goes high due to loss of datalink tone detection, the voltage on C1 is slowly charged by R1 (with a time constant of 470 ms). This allows a period of approximately half a second before the sweep is restarted.

This prevents the autotune resweeping in the measurement frames when the datalink tones are switched off. (The datalink tones are switched off during phase measurement to prevent phase corruption of the recovered AM).
The IF discriminator outputs, FMI and AFC, are differentially amplified by IC2 to provide the control loop for the autotune. Any increase in the IF frequency will result in an increase of the AFC voltage and a decrease of FMI voltage resulting in a fall in the output voltage of IC2b.
This is filtered by IC1a and will lower the output of IC5, lowering the frequency of the Remote instrument. The AFC loop will therefore lock the two frequencies together only when the Remote's frequency is 10,76 MHz higher than that of the Master.

The loop filter is a low pass filter with its bandwidth limited to 200 Hz so as not to prevent modulation of baseband speech. The lowest components of the speech signals are around 300 Hz.

The image frequency, where the Remote is 10,76 MHz lower than the Master, will not give the S-curve peaks in the correct order during the sweep and so will not halt the sweep circuit. Moreover the polarity of the AFC loop is reversed on reception of an image and will not sustain a stable lock condition.

Speech from the microphone amplifier and datalink tones are summed together with the AFC control voltage at the input of IC5. The output of IC1a is a low-impedance point so the modulation index of the AF+DATA signal is set by the voltage dividing action of R5 and R32.

The Modem and Speech Circuits

The requirement for a datalink originated with the need for the two instruments in the Micromin link to transmit data to each other. In the measurement frame the Master instrument informs the Remote what pattern to measure on, and the Remote replies with the resulting phase measurement of that pattern.

The datalink for the Micromin only needs to be simplex for this purpose, but during its development it was realised that it would be very simple to allow the user access to the datalink during the time when the instruments are not using it for measurement. It was also decided to supply a fully duplex link, as this could be achieved with the addition of only a small number of components (a low and a high pass filter in the data path of each instrument) which only marginally increases the cost.

The maximum usable Baud rate is limited by the bandwidth available over the microwave link. The ceramic filters used in the IF stage are the Murata SFJ10.7MA2. These have a -3 dB bandwidth of 300 KHz and an -80 dB stop bandwidth of 800 KHz. Assuming a low modulation index (β=0,7) this bandwidth alone would imply that a maximum modulating frequency of as much as 150 KHz would be possible. However there are two of these filters in each instrument and the tolerance of the two filters has to be considered.

The setting of the discriminator coil in the Remote's IF determines the point on the S-curve to which the AFC circuit locks, and this should be exactly in the centre of the passband of the filters. If it is not so, the filter roll-off will attenuate one sideband of the datalink more than the other.

Considering the temperature stability and the manufacturing tolerances, the usable IF bandwidth is taken to be 250 KHz (as used in the calculation of receiver noise figure in equation 3-3), and the modem frequencies were chosen to lie below 100 KHz to guarantee the performance of the datalink.

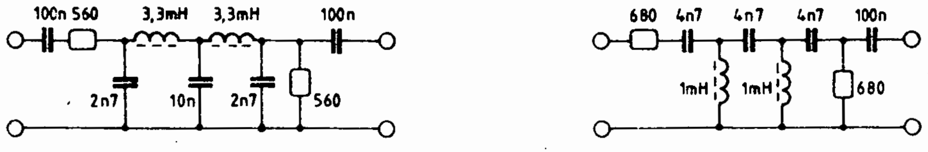
The modems used are the Exar XR2206 FSK transmitter and the XR2211 FSK receiver.

The link from the Remote to the Master is in a band from 25 kHz to 35 kHz and the link from the Master to the Remote is in a band from 75 kHz to 85 kHz.

These mark and space frequencies are far enough apart to allow a maximum data rate of 9 600 Baud. This data rate is considered high enough to satisfy a very wide number of possible applications.

The wide separation (of 40 kHz) between these two frequency bands allows the use of simple filters to achieve a high degree of isolation between the two channels. The best filters for the Exar modems are Butterworth filters, due to their linear phase response within the passband.

The filter characteristics and circuit diagrams of the Master and Remote transmit and receive filters are shown below in Fig.3-12.



LOW PASS FILTER

HIGH PASS FILTER

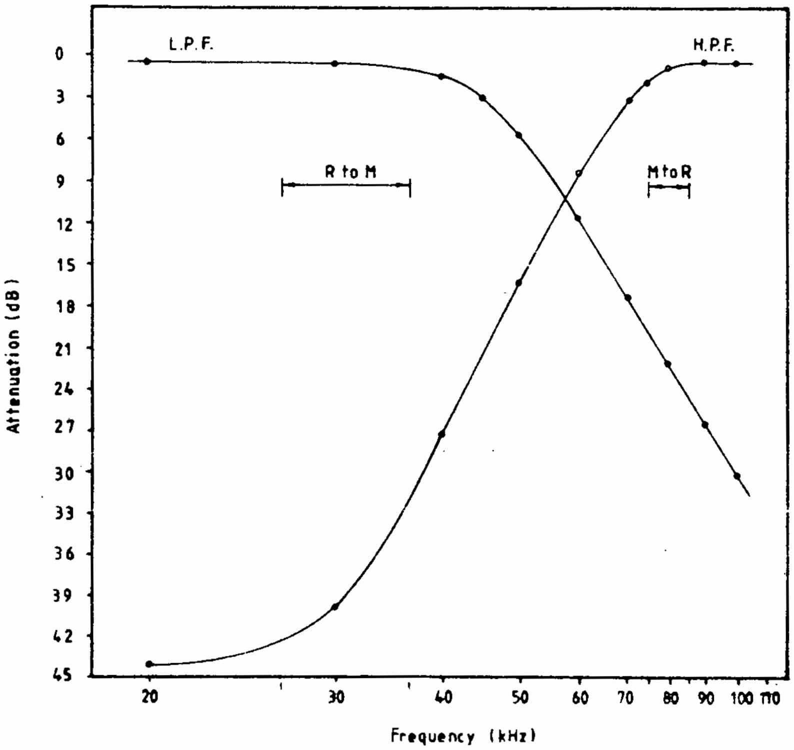


Fig.3-12, Circuits and Frequency Responses of Modem Filters

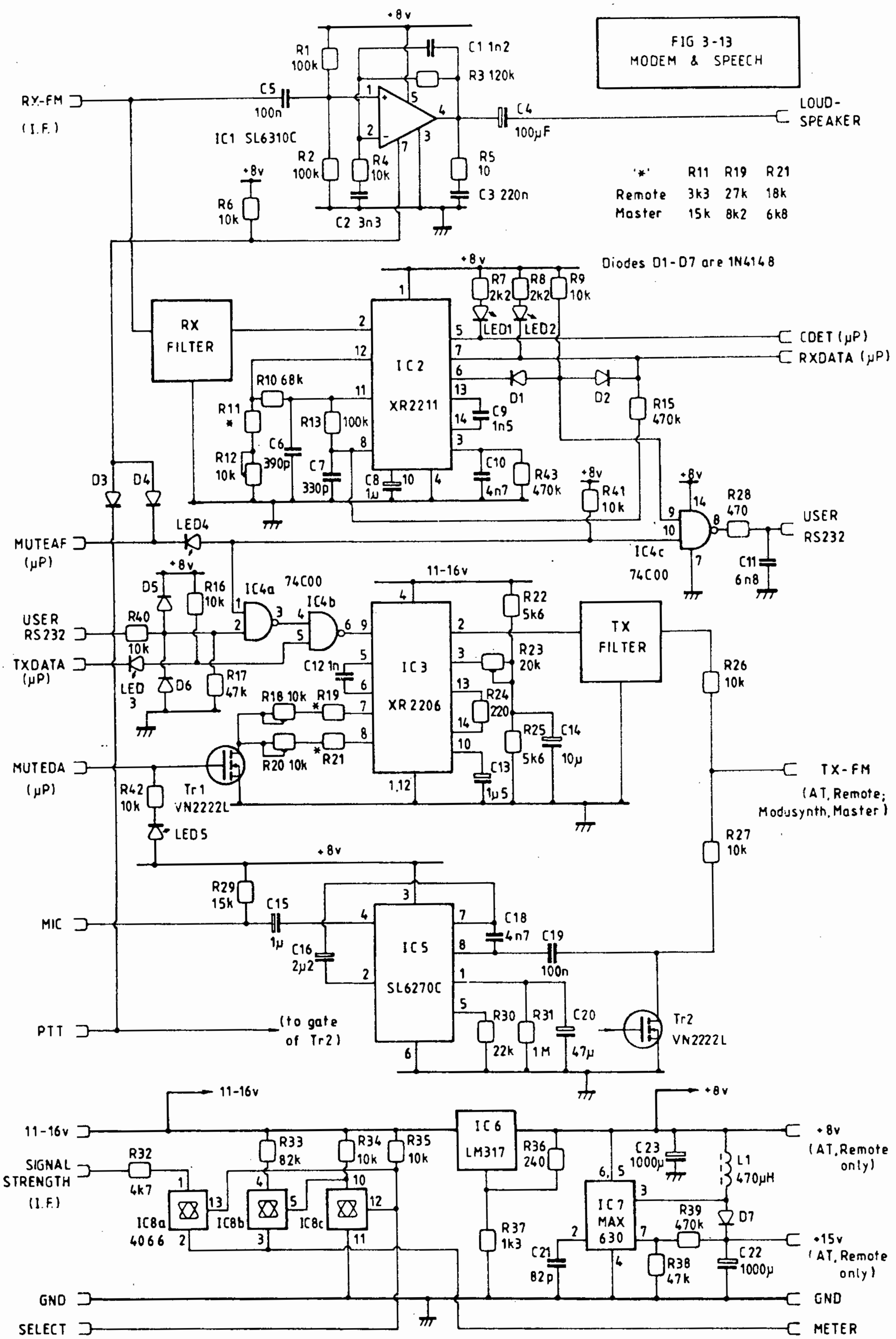


FIG 3-13
MODEM & SPEECH

'*'	R11	R19	R21
Remote	3k3	27k	18k
Master	15k	8k2	6k8

Diodes D1-D7 are 1N4148

The ancillary circuits for the Micromin shown in Fig.3-13 include;

the modem, IC2 and IC3,
the speech circuitry, IC1 and IC5,
the meter select circuit IC8, and
the +15 V switching supply, IC7 for the Autotune.

IC8 is a 4066 quad transmission gate which is used to switch the meter from displaying the incoming signal strength to displaying the battery voltage.

The DATA & AUDIO signal from the IF feeds the baseband speech signal to the loudspeaker amplifier IC1. This has a gain of 12, set by R3 and R4, and provides approximately 400 mW of power to an 8 Ω speaker. During measurement and when speaking, IC1 is muted by taking the voltage level at pin 7 below 1 V. This is done by the diode OR-gate of D3 and D4. No volume control is provided as this was not found to be necessary (the hiss from the speaker is a most obvious indication to the operator that the instrument is switched on, and the quieting when in lock is a clear indication that the instruments are tuned into each other).

The microphone preamplifier is a two stage amplifier with a voice-operated gain-adjustment device (VOGAD) which provides an almost constant output amplitude of 90 mV rms for any signal input greater than 2 mV rms. The attack and decay times are controlled by R31 and C20. The attack time is defined as the time for the output to return to within 10% of the original level following a 20 dB increase in input level. With C20=47 µF this time is 19 ms. The decay time is determined by the discharge rate of this capacitor via R31, which at 1 MΩ is 20 dB in 0,5 seconds. The microphone used is a small electret device mounted on the front panel of each instrument. These microphones need a DC supply and this is provided by R29.

Press-to-talk is provided by muting the output using Tr2. Various methods of muting IC5 have been tried, muting the input at pin 4, muting the signal from the output of the first amplifier stage at pin 2, switching off the supply, and muting by shorting the output. The first two methods resulted in a small but unacceptable residual noise output due to the high gain of the following unmuted stage(s).

Switching on and off the power supply to IC5 resulted in clicks that could throw the instruments out of tune under weak signal conditions. The last method, of muting by shorting the output, works the best and gives a clean muting action with no residual noise output. When the PTT line is low Tr2 is off and the output signal is unmuted.

The DATA & AUDIO line from the IF also feeds the data signal to the receive modem IC2. The RX FILTER is configured to be a low-pass filter in the Master and a high-pass filter in the Remote. The selection of R11 determines that the receive modem can be tuned, in the case of a Remote (with R11=3,3 kΩ) to 75-85 kHz, and in the case of the Master (with R11=15 kΩ) to 25-35 kHz. The outputs of IC2 are the carrier detect line CDET from pin 5 and the received data RXDATA from pin 7 which are fed to the microprocessor board option. These are open-collector outputs and interface from the 8 V rail of IC2 to the 5V rail of the microprocessor by the pull-up which is voltage-limited by light-emitting diodes LED1 and LED2.
Diodes D1 and D2 form a diode OR-gate which mutes any data output from IC2 in the absence of any carrier detect, such as when the instruments are not in tune. This is controlled by the open-collector output of pin 6, which is the inverse of the CDET signal on pin 5. In the absence of a carrier detect pin 6 is held low thereby muting any random data output by disabling IC4c.
When there is a carrier detect pin 6 of IC2 goes open-circuit and the open-collector data output of pin 7 can pull down pin 9 of IC4c (via D2) which drives the USER RS232 output. The MUTEAF line, normally held high by R6, is pulled low by the microprocessor during measurement. This disables IC4c to ensure that the data passed between the two Micromins during measurement is not transmitted to the USER RS232 output.
Note that the USER RS232 output is not a true RS232C signal which is defined as a bipolar signal where a "space" is between +3 V and +25 V, and a "mark" is between -3 V and -25 V. The USER RS232 output only supplies a 0 to 8 Volt signal. This simplifies the design of the power supply, by not having to generate a negative supply rail in the instrument.

The signal risetime of the USER RS232 output is limited by R28 and C11 to less than 30 V/µs, in compliance with the EIA RS232C specification.

The FSK transmitter IC3 is an Exar XR2206 and its frequency of operation is configured by selection of R19 and R21. As a Remote IC3 works in the band 25-35 KHz with R19=27 KΩ, and R21=18 KΩ. As a Master it works in the band 75-85 KHz (R19=8,2 KΩ, and R21=6,8 KΩ). The XR2206 is a function generator capable of producing sine, square, triangle, ramp, or pulse waveforms of high stability. In this application it is configured to provide a sine wave; R24 optimises the waveform. The output amplitude of IC3 is set by R23. The minimum supply voltage of the XR2206 is 10 V and so IC3 is connected to the unregulated 11 to 16 V supply. A change in supply voltage from 11 V to 16 V results in an insignificant change in output frequency of only 42 Hz at 85 KHz (0,01 %/V).

The data inputs to IC3 come from either the microprocessor option or the USER RS232 input.

During measurement MUTEAF from the microprocessor goes low to disable IC4a, and prevent any USER RS232 data affecting the datalink. LED4 and R41 interface between the microprocessor CMOS running at 5 V and IC4 74C00 running at 8 V. TXDATA from the microprocessor is normally held high by the software (or R16 if the microprocessor option is not installed). LED3 and R16 provide additional 5 V to 8 V interfacing. A low state on TXDATA pulls pin 5 of IC4b down to about 2,4 V, which is a guaranteed low state for IC4. A high state on TXDATA allows the voltage on pin 5 of IC4a rises to about 7,5 V which is a guaranteed high state.

The mute data line MUTEDA from the microprocessor switching Tr1, is used to switch off IC3 by stopping its oscillator. This method of muting is very effective, and is used during the measurement frame to switch off the modems at both instruments during phase measurement.

In the datalink configuration (where the microprocessor is not fitted) R42 and LED5 ensure that the transmit modems are permanently enabled.

The frequency of the oscillator of IC3 is controlled by C12 and by either R18 & 19 or R20 & 21, depending on the logical input state of pin 9. If pin 9 is high (>2 V) then R18 and R19 are activated, if pin 9 is low (<1 V) then R20 and R21 are activated. In this way the output frequency is keyed between two frequencies.

The TX FILTER is a high-pass filter in the Remote, and a low-pass filter in the Master.

The RX and TX filters are Butterworth filters giving minimum passband ripple and phase change. They are designed to give a 20 dB/octave roll-off and the cut-off frequencies are 45 KHz for the low-pass filter and 70 KHz for the high-pass filter. In both receive and transmit cases the filters are driven from low-impedance sources and drive high-impedance loads, so the 560 Ω and 680 Ω resistors define the characteristic impedance of the filters. The 100 nF capacitors are only to provide DC blocking and play no part in the filtering action.

Note that the printed circuit board track design for both the high- and low-pass filters is the same, capacitors simply being changed for inductors and vice versa. The same printed circuit board layout can be used in both the Master and the Remote instruments.

The step-up switching-regulator, IC7 etc. uses a Maxim MAX630 which provides +15 V needed for the Autotune in the Remote instrument. The output voltage is set by the ratio of R38 to R39, pin 7 of IC7 being compared to an internal 1,31 V bandgap reference. The frequency of the oscillator of IC7 is set by C21 to 25 KHz, and the output ripple is adequately filtered by C22.

(Note that IC7, R38, R39, D7, L1, C21 and C22 are not fitted in the Master instrument as it does not have an Autotune.)

Microwave Source Power Supply Circuit

A regulated 8 Volt supply derived from the unregulated battery supply (11 to 16 V) is provided for the Gunn sources.

The varactor bias for the Master instrument is also taken from this 8 V supply to maintain the source at a frequency of 10,30 GHz.

The varactor bias for the source in the Remote instrument is provided by the AFC circuit of the Autotune.

The Gunn supply circuit is shown in Fig.3-14.

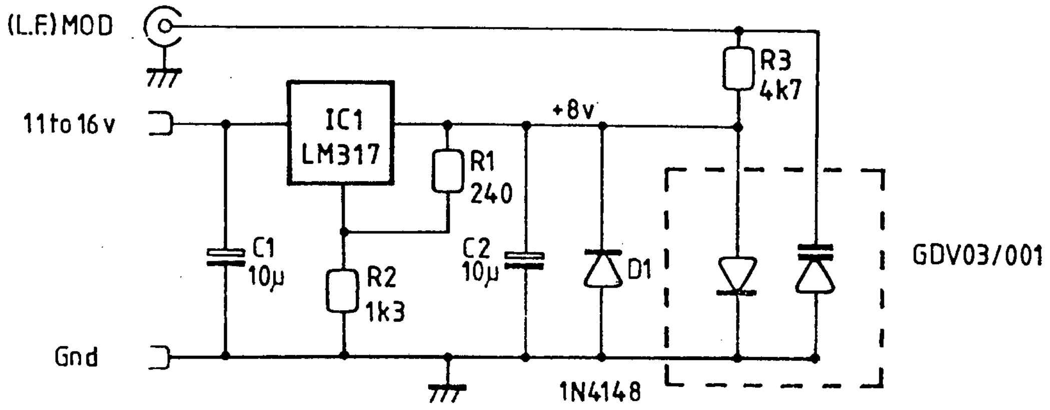


Fig.3-14, Microwave Source Power Supply Circuit

References for the formulae

3.1 Kraus J.D. (1950)
"Electrical and Electronic Series, Antennas", McGraw Hill,
page 380, equation 13-49.

3.2 "ITT Reference Data for Radio Engineers, 6th Edition",
1982, page 29-1.

3.3 Glazier E.V.D. and Lamont H.R.L. (1958),
"The Service's Textbook for Radio, Volume 5, Transmission and Propagation", H.M.S.O., London,
page 272, equation 9.25.

CHAPTER 4

The Modusynth

Modusynth is derived from the term "**modulator** and **synthesiser**".
The circuit diagram of the modusynth, shown in Fig.4-1, consists of two sections,

a synthesiser, or frequency-locked loop, used to generate pattern frequencies with very low phase noise and,

a modulator, used to buffer, divide and filter the loop signal, and to modulate the microwave source.

The frequency-locked loop is shown in the top half of Fig.4-1, and the modulator is shown in the bottom half.
The loop generates a signal in the range of 19,6 MHz to 21,25 MHz in steps of 2,441 KHz, with special attention being made to reduce phase noise to improve measurement accuracy.

The loop has a 2,5 MHz reference derived from the TCXO on the microprocessor board. This is fed to IC3 the synthesiser chip, where it is divided by a further 2^{10} to form the 2,441 KHz reference for the phase comparator.

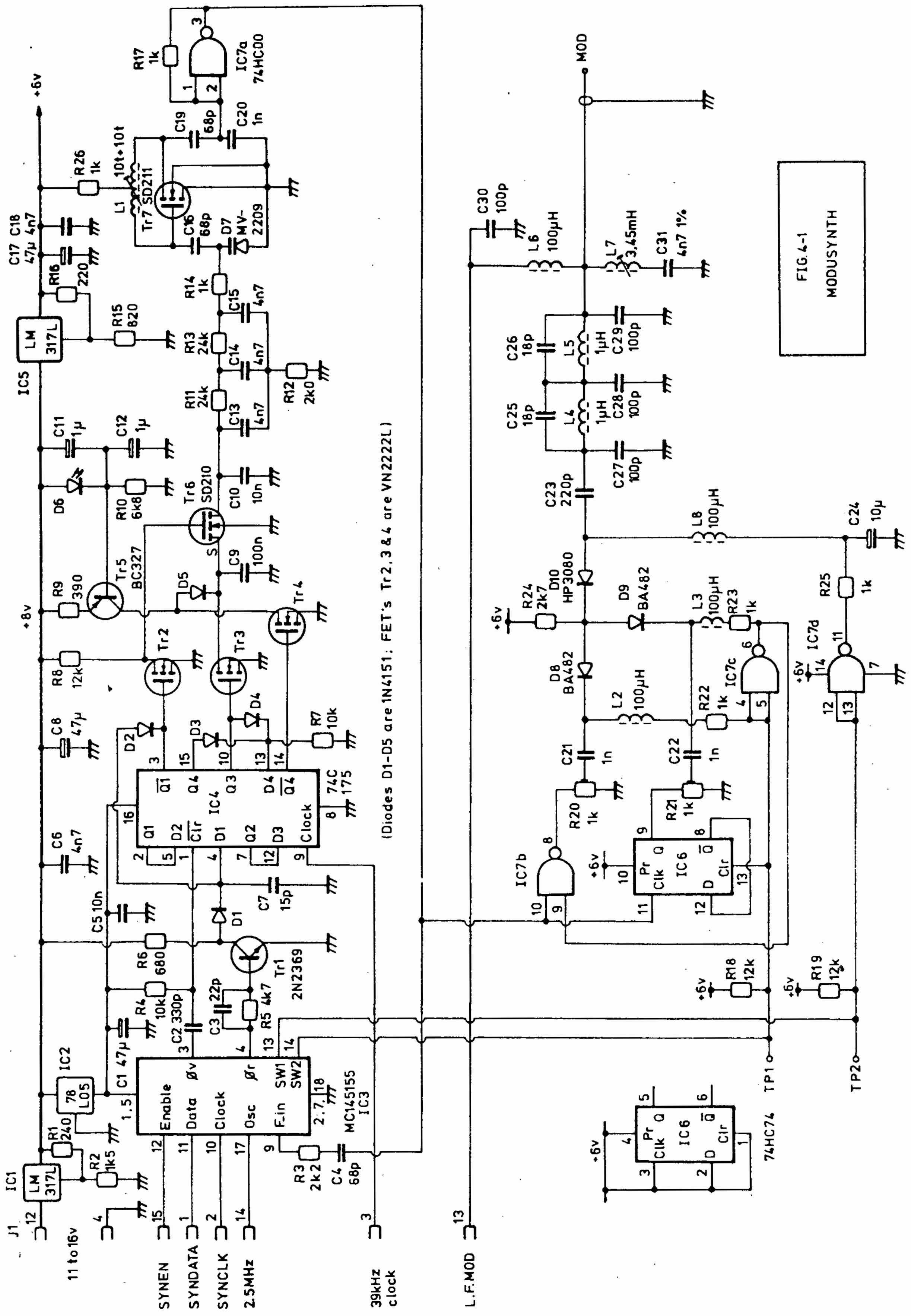
The component values of the VCO, which consists of Tr7, D7, L1, C16, C19 and C20, have been chosen to achieve a tuning range from 19,5 MHz to 22,5 MHz with a change in control voltage from 1 V to 8 V.

The VCO output is amplified by IC7a (biased into a linear mode by R17) and fed back to the loop (via C4 and R3), and into the modulator, (IC7b pin 10 and IC6 pin 11).

The VCO signal is divided by a programmable divider in IC3 which is set via the serial data bus SYNDATA, SYNCLK and SYNEN.
The minimum division ratio is 8 184 and the maximum is 8 712 (dec), setting the VCO frequency to 19 980,468 kHz and 21 269,531 kHz respectively.

A digital phase detector in IC3 compares the phase of the 2,441 kHz reference with the divided VCO signal and produces the control signals Φr and Φv.

The sample-and-hold circuit produces an output voltage proportional to the pulse width of Φv which is used to control the frequency of the VCO.



(Diodes D1-D5 are 1N4151; FET's Tr2,3 & 4 are VN2222L)

FIG.4-1
MODUSYNTH

The Loading Sequence of the Synthesiser.

The data bus lines SYNCLK (synth clock), SYNDATA (synth data) and SYNEN (synth enable) are driven by the microprocessor.

The sequence of loading the division register of IC3 with a value of 2018 (hex) is shown in Fig.4-2.

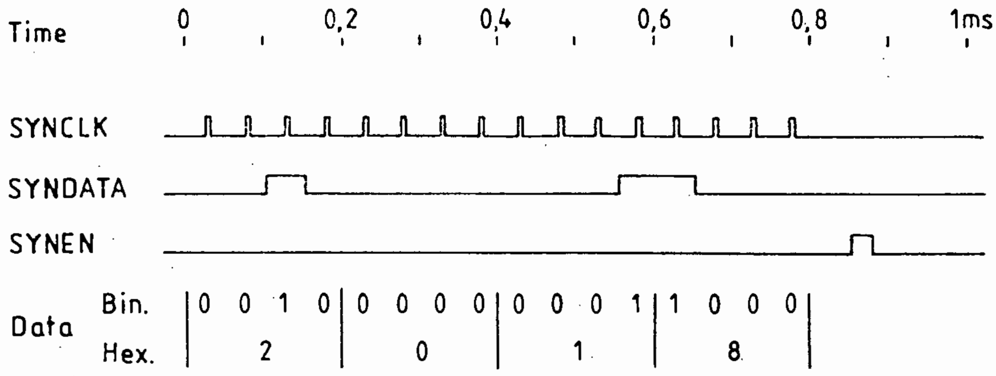


Fig.4-2, The Loading Sequence of the Synthesiser

The synthesiser loading is controlled by subroutine SYNTH which can be found on line 1606 of the software listing.

The rising edges of SYNCLK clock 16 bits of data into a shift register in IC3; SYNEN then moves the data from the shift register into a latch.
Serial loading of the synthesiser is achieved in 0,9 ms.
The loop operation is undisturbed during the serial data transmission, because the new data bits affect the loop only after the SYNEN strobe.

The first two bits in the serial data stream (the 00 in the 2 (hex) in Fig.4-2) are fed to open-drain outputs, SW1 and SW2, which are used to switch the modulator division ratio and to turn the modulator on and off.

The Sample-and-Hold Phase Detector

The outputs of the phase comparator, Φ_r and Φ_v, control the sample-and-hold circuit in which IC4 (74C175) switches the transistors TR2,3,4,& 6 to control the amplitude of a ramp waveform on C9.

Fig.4-3 shows the operation of the sample-and-hold phase detector.

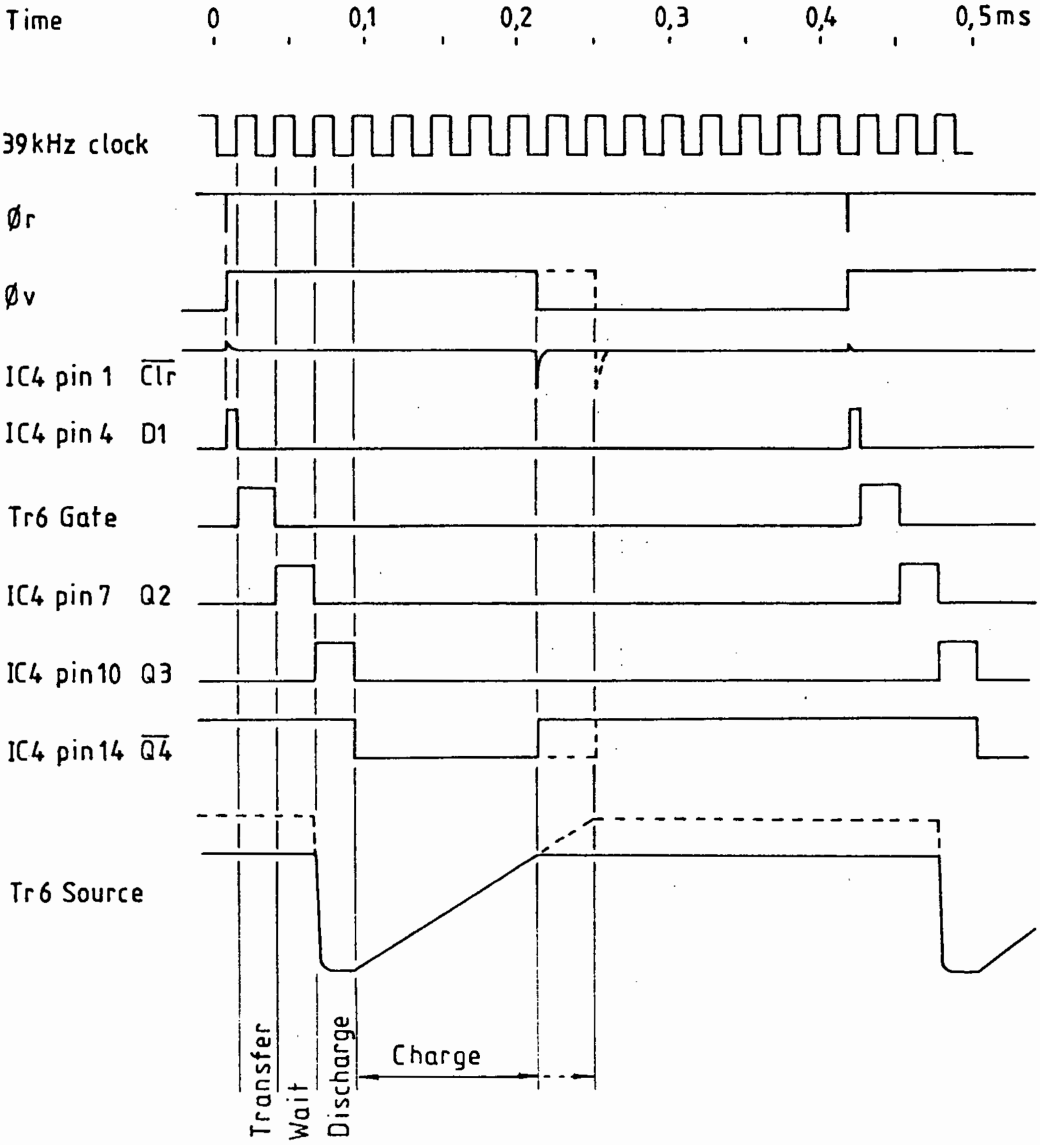


Fig.4-3, The Sample-and-Hold Timing Diagram

The function of the sample-and-hold circuit is to set the DC voltage on C10 proportional to the pulse width of Φ_V.

An operational cycle of the sample-and-hold is a sequence of six actions controlled a shift register consisting of four serially connected D-type flip flops (IC4), clocked by 39kHz-Clock derived from the microprocessor.

The six parts of the cycle are described as follows.

1) The cycle is initiated by the Φ_r pulse which is inverted by Tr1 allowing R6 to charge up C7 via D1.

2) The charge on C7 is held on the data input D1 (pin 4 of IC4) until the next rising edge of the 39 kHz clock which clocks this high state through to Q1. Q1(bar) discharges C7 via D2, and switches on Tr6 (via Tr2) to charge of C10 from C9.
This is the TRANSFER part of the cycle.

3) The logic 1 state of Q1 is clocked through to Q2 on the following rising edge of the 39 kHz clock. This constitutes a WAIT separating the TRANSFER and DISCHARGE parts of the cycle.

4) The logic 1 state of Q2 is clocked through to Q3 on the next rising edge of the 39kHz clock, switching on Tr3 to discharge C9. This is the DISCHARGE part of the cycle.

5) The logic 1 state of Q3 is clocked through to Q4 on the next rising edge of the 39 kHz clock, Q4(bar) goes low switching off Tr4 thus allowing the 3,2 mA constant current source of Tr5 to charge C9 through D5. This is the CHARGE part of the cycle.

6) The charging of C9 is interrupted by the falling edge of Φ_V, which is differentiated by C2 and R4 to create a pulse which clears all the Q outputs of IC4.

The charge on C10 remains steady until the next transfer from C9 due to the very low leakage current through the varicap diode D7.

The dotted lines in Fig.4-3 show how the loop responds to a change in frequency.

The Notch Filter

The notch filter of R11,12,13, C13,14 & 15 attenuates ripple in the control voltage at the sampling frequency of 2,441 KHz. The frequency response and circuit of this filter is shown in Fig.4-4.

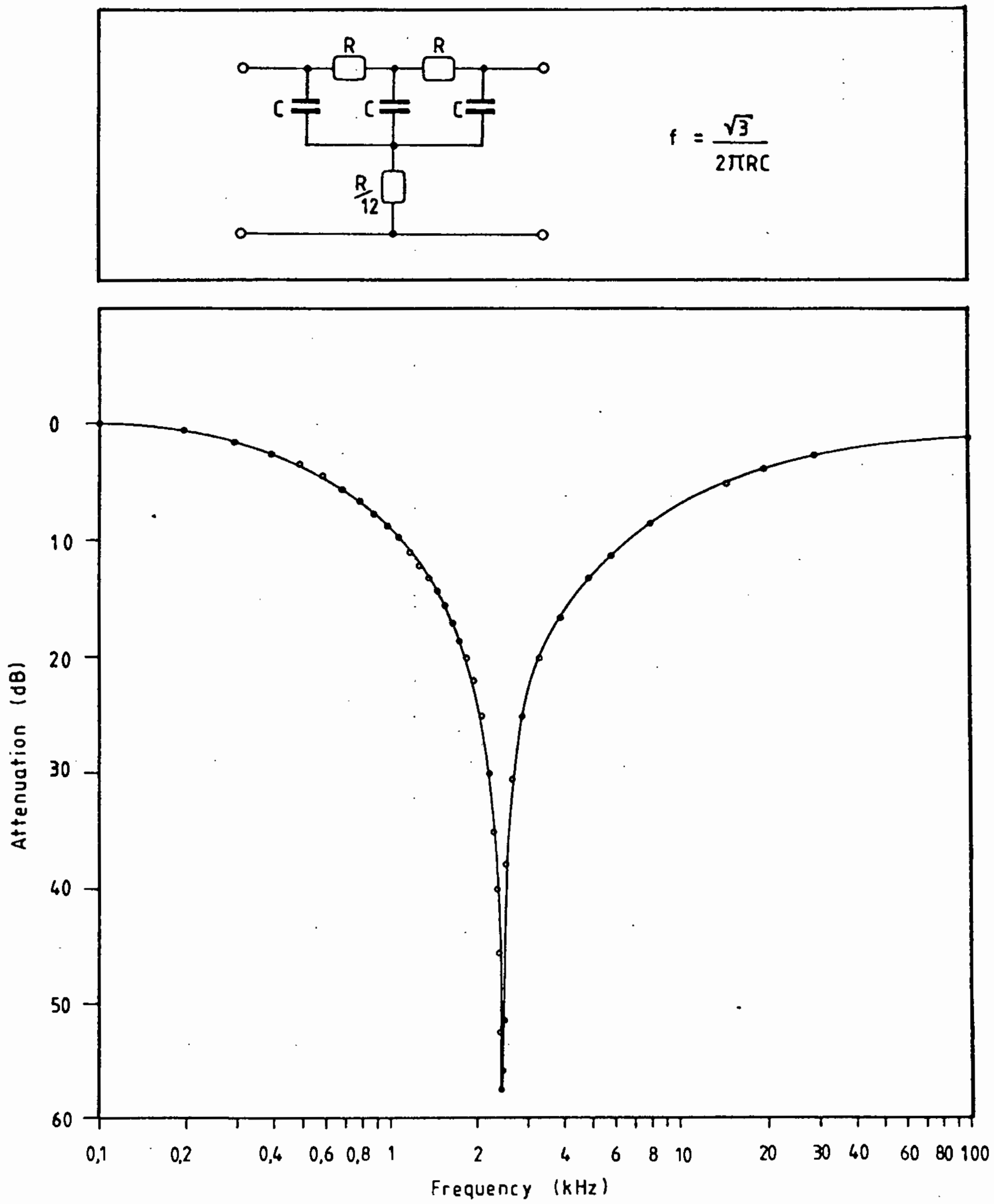


Fig.4-4, Notch Filter Circuit and Frequency Response

Synthesiser Locking Time

Synthesiser locking time is kept to a minimum because the loop frequency is changed three times in each frame. Too slow a response time will have an accumulative effect on the length of the frame, thereby lengthening the total time for the measurement. The change in measured position of a moving platform between frames is also affected by the frame length, so keeping the frame length short helps the position-updating capability of the dynamic mode of operation.
The loop response to a change in frequency from 20 136 kHz to 20 605 kHz is shown in Fig.4-5, which plots the change in voltage across the varicap diode D7.

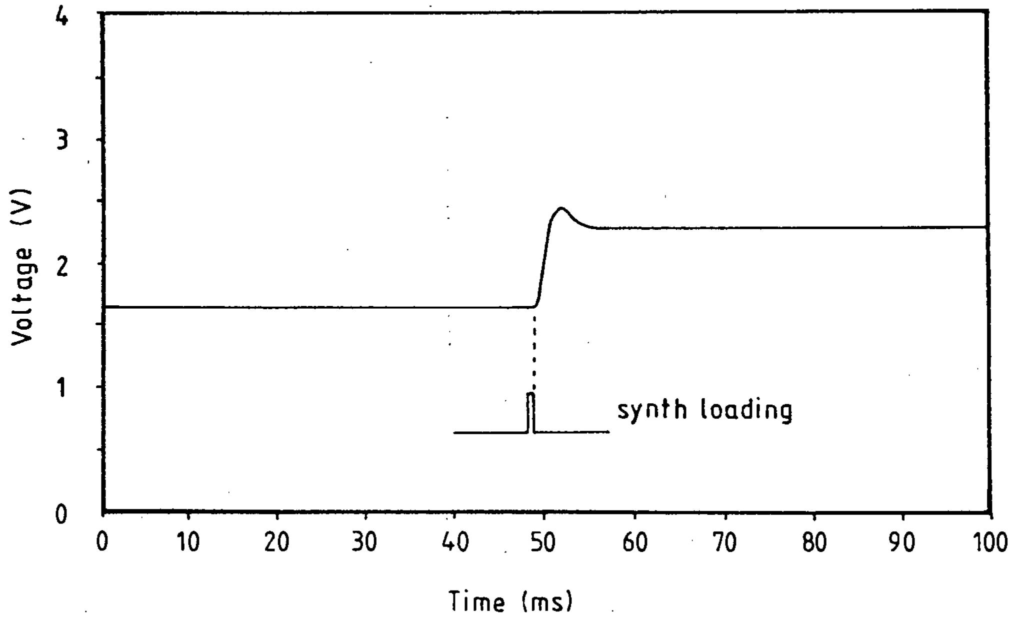


Fig.4-5, Synthesiser Locking Time

As shown above a typical settling time for the synthesiser is <10 ms. In the measurement frame a settling time of 35 ms has been allowed before phase measurement of the 39kHz-Phase signals. This is more than adequate time to allow the phase of the 39kHz-Phase signals to stabilise to within 1 part in 64 (the measurement accuracy of each sample).

The Output Spectrum

A typical output spectrum of the modusynth is shown in Fig.4-6, showing noise components at approximately -70 dBc.

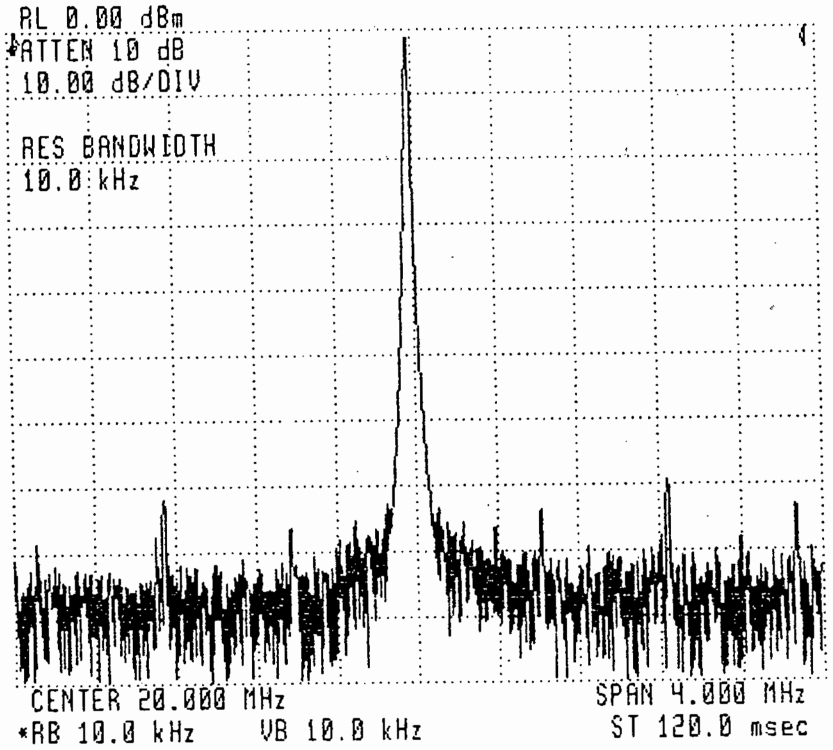


Fig.4-6, Modusynth Output Spectrum

The low synthesiser noise level results in low phase-noise on the final Comparison-Frequency phase measurements.

The Modulator

The modulator halves the synthesiser output frequency (when required), filters it, adds low frequency modulation to it and feeds this composite signal to the varactor diode in the microwave source.

For 20 MHz patterns SW2 of IC3 is low, switching D8 on and D9 off, and disabling the divider IC6. IC7b buffers the output of the synthesiser and R20 sets the signal amplitude

For the 10 MHz signals required for pattern 6, SW2 of IC3 is high allowing the divider to operate, switching off D8 and switching IC7c which switches on D9 and mutes the 20 MHz buffering action of IC7b. IC6 divides the VCO output by two and R21 sets the signal amplitude.

The modulation output can be switched off by D10. The switching speed is set by R25 and C24 to limit the rate of change of modulation amplitude. Due to the non-linear tuning curves of the microwave sources (see Figs.3-2 and 3-3) modulation has an asymmetrical effect on the frequency of the source, the average effect of which pulls the centre frequency. Fast changes in modulation index can pull the carrier frequency out of the IF passband faster than the AFC loop can compensate for, and the AFC loop will lose lock. It is for this reason that R25 and C24 have been chosen to set the time constant for the change in modulation level to 10 ms.
The software allows 35 ms for the modulator to switch on during the measurement frame prior to phase measurements being made.

The output of the modulator is filtered by a low-pass filter consisting of C25, C26, C27, C28, C29, L4 and L5.
The frequency response of this filter is shown in Fig.4-7.

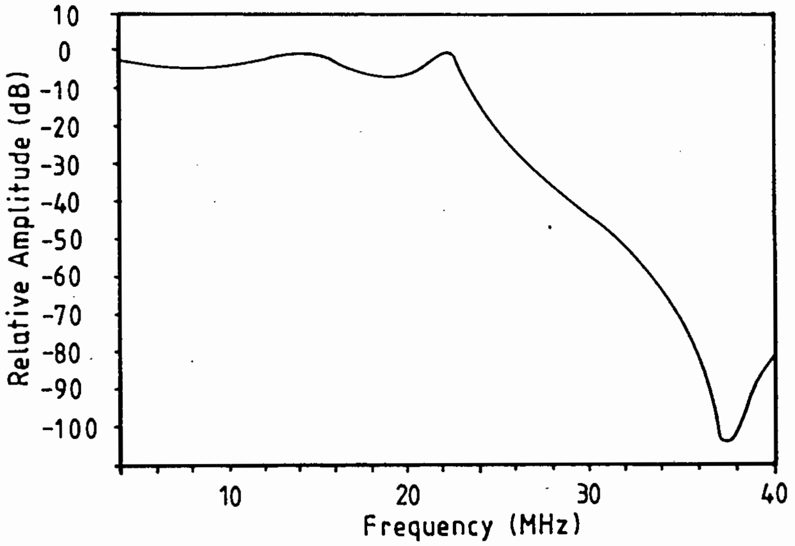


Fig.4-7, Modulator Filter Frequency Response

The output of the modulator is filtered to prevent any unwanted signals mixing to produce components that fall within the IF passband that might contaminate the phase of the desired mixing product at 39,062 kHz.

The output of IC6 has a 1:1 mark-space ratio and hence contains very little 2nd harmonic so it is not necessary to have a separate filter for the 10 MHz output. A common filter is used that attenuates the 3rd harmonic of 10 MHz by 45 dB, and the 2nd harmonic of 20 MHz by approximately 80 dB. This is more than satisfactory for the requirements of the Micromin.

The filter has a slight decrease in attenuation from 20 MHz to 22 MHz which equalises the modulation index of patterns from 20 to 21,25 MHz, particularly pattern 5 which has a 21,25 MHz centre pattern straddled by 20 MHz patterns.

For a given modulation index the required amplitude of the modulating signal is proportional to frequency.

Experience has shown that a modulation index of 0,7 at both the Master and Remote results in the best recovery of AM from the IFs.

Modulation index is related to frequency deviation and frequency of modulating signal by the following;

$$\beta = \Delta f / f_m$$

where,

β = modulation index (a ratio),
Δf = frequency deviation (MHz), and
f_m = modulating frequency (MHz).

It follows that for a modulation index of 0,7 and given a varactor sensitivity of 10 MHz/Volt, the following peak-to-peak levels of modulating signals are necessary,

f_m	**Signal Level**
10,0 MHz	2,0 V p-p
20,0 MHz	4,0 V p-p

The maximum output signal of the modulator is 5 V p-p, sufficient signal level to achieve the required modulation index.

Low-frequency modulation from the Modem and Speech circuit is fed into the modulator on the L.F.MOD line. The high-frequency pattern outputs of the synthesiser are prevented from being shunted by the low-frequency drive circuitry. L6 and C30 form a low-pass filter allowing the speech and data low-frequency modulations through to the varactor, and blocking the pattern frequencies.

A series resonant trap formed by L7 and C31 shunts any modulation at 39,062 kHz. Baseband frequency modulation at 39 kHz is the cause of cyclic contamination, described in Chapter 6. This series resonant trap effectively removes this source of error.

The Pattern Set

The pattern set produced by the modusynth is shown below:

Patt	Straddle	Centre	Ambiguity (m)	Ratio
0	$20M^-$	$20M^-$+2K441	61 397,503	
1	$20M^-$	$20M^-$+9K765	15 349,376	4:1
2	$20M^-$	$20M^-$+39K062	3 837,344	4:1
3	$20M^-$	$20M^-$+156K25	959,336	4:1
4	$20M^-$	$20M^-$+625K	239,834	4:1
5	$20M^-$	$20M^-$+1M25	119,917	2:1
6	$10M^-$	$10M^-$+10M	14,990	8:1
7	$20M^+$	$20M^-$	3,747	4:1

The $^+$ and $^-$ signs indicate the "plus" and "minus" patterns.
For example a $20M^-$ pattern means that the Master and Remote are simultaneously modulated with sidebands of $(20-8\omega_m)$ MHz and $(20+8\omega_r)$ MHz respectively,
where $16\omega_m = 16\omega_r = 39{,}062$ kHz, the Comparison-Frequency.

Similarly a $20M^+$ pattern is one where the Master and Remote are simultaneously modulated with sidebands of $(20+8\omega_m)$ MHz and $(20-8\omega_r)$ MHz respectively.

As mentioned in Chapter 1, the simultaneous modulations of the Master and Remote always differ by the Comparison-Frequency of 39,062 kHz. It is by mixing these two sidebands in the microwave mixers of both instruments that this signal is recoverable as an AM component of the 10,76 MHz IF signal.

The "Ambiguity" column shows the distance at which the resultant phase of the pattern will be 360°, and beyond which the measurement will be ambiguous.
The "Ratio" column shows the amount the phase readings are multiplied by (shifted in the binary arithmetic) for comparison with adjacent patterns in the measurement "breakout".

Patterns 0 to 6 are Difference Patterns, and pattern 7 is an Absolute Pattern.
The Straddle Patterns for patterns 0 to 5 are 20M⁻ and the Centre Patterns differ from the Straddle Patterns by amounts increasing by a factor of x2, x4 or x8 between each pattern. The differential phase measurement of the Straddle and the Centre Patterns results in a measurement of the phase of the Difference Frequency, (the difference in frequency between the Straddle and Centre Patterns).

The Straddle Pattern of pattern 6 is a Minus Pattern at 10 MHz and the Centre Pattern is 10 MHz higher. This results in a phase measurement of the Difference Frequency of 10 MHz.

Straddle Patterns can be at any frequency as long as the Centre Pattern falls at the correct Difference Frequency above (or below) them. This can be used to avoid frequencies that fall too close to the IF passband.
(Note that if the Centre Pattern is chosen to fall below the Straddle pattern then the sign of the resultant phase measurement will be reversed, for example 20° will become 340°. This would have to be accounted for in the breakout software.)

Pattern 7 is an Absolute Pattern centred on 20 MHz, resulting in a phase measurement of 20 MHz. The Straddle is a ⁺ pattern and the Centre is a ⁻ pattern, the Comparison Frequency is applied to both in opposing sense, resulting in a 4:1 phase relationship between the 10 MHz Difference and the 20 MHz Absolute Patterns (see Appendix A equation A.13).

The following table shows the pattern set in more detail.

Patt	N_s	Straddle (KHz)	N_c	Centre Freq (KHz)
0M	8 184	19 980,468	8 185	19 982,910
0R	8 200	20 019,531	8 201	20 021,972
1M	8 184	19 980,468	8 188	19 990,234
1R	8 200	20 019,531	8 204	20 029,296
2M	8 184	19 980,468	8 200	20 019,531
2R	8 200	20 019,531	8 216	20 058,593
3M	8 184	19 980,468	8 248	20 136,718
3R	8 200	20 019,531	8 264	20 175,781
4M	8 184	19 980,468	8 440	20 605,468
4R	8 200	20 019,531	8 456	20 644,531
5M	8 184	19 980,468	8 696	21 230,468
5R	8 200	20 019,531	8 712	21 269,531
6M	8 176/2	9 980,468	8 184	19 980,468
6R	8 208/2	10 019,531	8 200	20 019,531
7M	8 200	20 019,531	8 184	19 980,468
7R	8 184	19 980,468	8 200	20 019,531

The first column indicates the pattern number, the M and R refer to Master and Remote, and N_s and N_c refer to the synthesiser division ratio (in decimal) for the straddle and centre frequencies respectively.

For example, 0M is pattern 0 for the Master instrument, and for the Straddle the synthesiser generates

(0M) = 8 184 x 2,441 = 19 980,468 KHz.

The "/2" following the divisor for Pattern 6 shows that the modulator divides the synthesiser output by 2, for example the Master Straddle on pattern 6 is generated by

(6M) = 8 176 x 2,441 / 2 = 9 980,468 KHz.

CHAPTER 5

The Microprocessor and Phase Counter

The Microprocessor

The microprocessor and phase counter board controls the timing of the measurement frame and all the tasks involved in the measurement, e.g. the control of the modusynth, data communications with the distant instrument, and phase measurement.

The circuit diagram of this board is shown in Fig.5-1. The microprocessor IC3 is a Hitachi 63701VOC single chip microcomputer which contains all the RAM, EPROM, timers and ports required for the Micromin. It can be configured to run in several different modes. In this application Mode 5 is selected by appropriate logic levels applied to pins 8,9 & 10, that are read at power-up and upon reset. In this mode the data bus (D0 to D7) is not multiplexed, and a simplified version of the address bus is generated, A0, A6, & A7 being the only lines needed for the address mapping. The unused address lines are configured as input ports, and appear as P41 to P45.

The address lines A6, A7 and the IOS line are decoded by the 1-out-of-8 decoder IC8 which generates four active-low chip select lines, which are;

Chip Select	**Address Range(hex)**	**Device Selected**
IC8 pin 15	0100 to 0130	Phase counter latch
IC8 pin 14	012F to 017F	Liquid Crystal Display
IC8 pin 13	0180 to 01BF	Synthesiser Enable (SYNEN)
IC8 pin 12	01C0 to 01FF	TCXO Control

IC4a & b invert the chip select lines to the LCD and IC9 as these devices require active-high chip select lines.

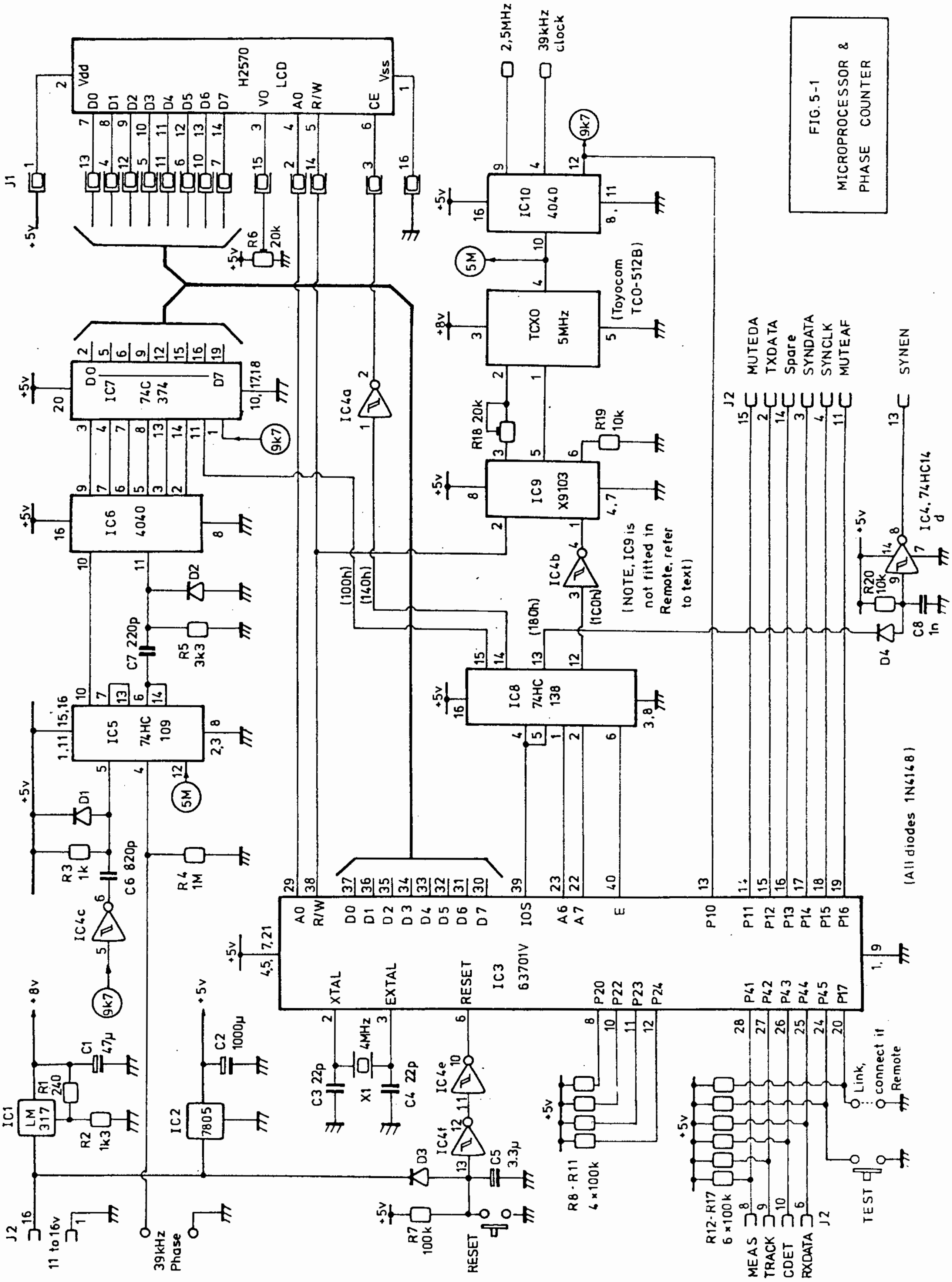


FIG. 5-1
MICROPROCESSOR &
PHASE COUNTER

Crystal X1 determines the clock frequency of 4 MHz, resulting in a bus cycle time of 1 µs. This rate is sufficient for uncritical timing of the real-time data processing in the software.

At power-up the processor is briefly held in a reset state by the delay time constant of R7 and C3. IC4 is a Schmitt trigger inverter to ensure a single clean rising edge on the reset line that ensures reliable starting of the processor.

The liquid crystal display is a Hitachi H2570 single line 16 digit dot-matrix alphanumeric display. The optimum viewing angle is set by R6.
The input and output lines of the microprocessor board are;

11 to 16 V	power supply,
39KHz-Phase	phase comparison signal from the squarer of the IF,
MEAS	front panel switch S1, low to initiate measurement,
TRACK	front panel switch S2, low for static, high for dynamic,
CDET	modem carrier detect,
RXDATA	modem receive data,
2,5 MHz	frequency reference for the Modusynth,
39KHz-Clock	sample-and-hold clock for Modusynth,
MUTEDA	mute data, switches off modem transmission,
TXDATA	modem transmit data,
Spare	spare port,
SYNDATA	serial data to Modusynth,
SYNCLK	data clock to Modusynth,
MUTEAF	mutes audio during measurement,
SYNEN	Synthesiser Enable, data strobe for Modusynth.

The SYNEN strobe for the Modusynth is derived from the chip-select decoder IC8. To create a pulse long enough to guarantee the minimum pulse width required by IC3 of the Modusynth, a pulse is generated four times by the software (see line 1647 of the software listing) and the time constant of R20 and C8 together with the Schmitt trigger of IC4d generate a pulse 20 µs wide.

TCXO Locking

Difference in the frequency of the Master and Remote TCXOs appears as a "slipping" of the two comparison frequencies, which introduces error terms in the measurement (see Appendix A). The TCXOs are locked together during the measurement to cancel these error terms.

The X9103 (IC9) is a 100 step digital potentiometer, controlled in the measurement routine to lock the frequency of the Master TCXO to that of the Remote. At power up IC9 is initialised to the centre of its range by incrementing 100 times and decrementing 50 times (see line 202 of the software listing).

Two groups, each of 128 phase counter readings, make up the phase measurement of each pattern. The averages of these two groups are compared to determine the direction of drift between the Master and Remote references.
The frequency of the Master TCXO is pulled to counteract any detected drift, and in this way the TCXOs are frequency-locked together.

The extent of frequency adjustment is limited to ±15 Hz by R18 and R19.

Subroutine TCXO performs the locking function and can be found on line 1561 of the software listing.

In both the Master and the Remote instruments R18 is used to set the frequency of the TCXOs to 5,000 000 MHz ±5 Hz.
The Master TCXO frequency is adjusted to equal that of the Remote and the Remote does not need IC9. Fig.5-2 shows how the TCXO is configured in each instrument.

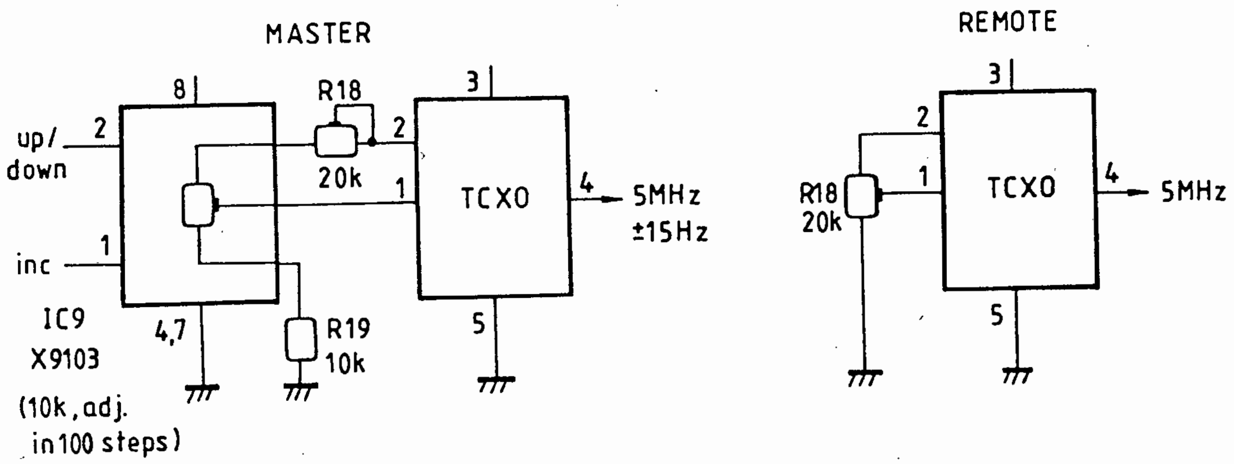


Fig.5-2, TCXO Configuration in Master and Remote

The Phase Counter

The phase counter is shown at the top of Fig.5-1, and appears in more detail in the timing diagram of Fig.5-3.

The function of the phase counter is to measure the phase of the "39KHz-Phase" signal relative to the phase of the 9,7 KHz reference signal derived from the reference TCXO via the divider IC10.

It consists of a dual edge-triggered flip-flop (IC5) that gates a 5 MHz clock (5M) to a counter (IC6), and a latch to transfer the counter value to the microprocessor data-bus via a three-state output.
The use of edge-triggered JK flip-flops to gate the clock was chosen because it produces an integer number of clock cycles of the correct pulse-width, i.e. there is no truncation of the pulses fed to IC6.
A simpler (level sensitive) gating arrangement using a NAND gate was tried but found to create pulses that were less than the minimum pulse width specification of IC6. This had the effect of disrupting the counter state in an unpredictable manner.

The 9,7 KHz reference signal is inverted by IC4c. The falling edge of the output of IC4c is differentiated by C6 and R3 to create a negative-going pulse that is fed to S1(bar) of IC5. This pulse causes Q1 to go high which does two things.

- Firstly, the rising edge of Q1 is differentiated by C7 and R5 to create a positive-going pulse the falling edge of which clears the counter register of IC6.
- Secondly Q1 is fed to J2 of IC5b, Q1(bar) is fed to K2(bar), and this allows the 5 MHz signal feeding CLK2 to toggle IC5b.

IC5b halves the clock frequency and produces a 2,5 MHz clock train to the counter IC6.

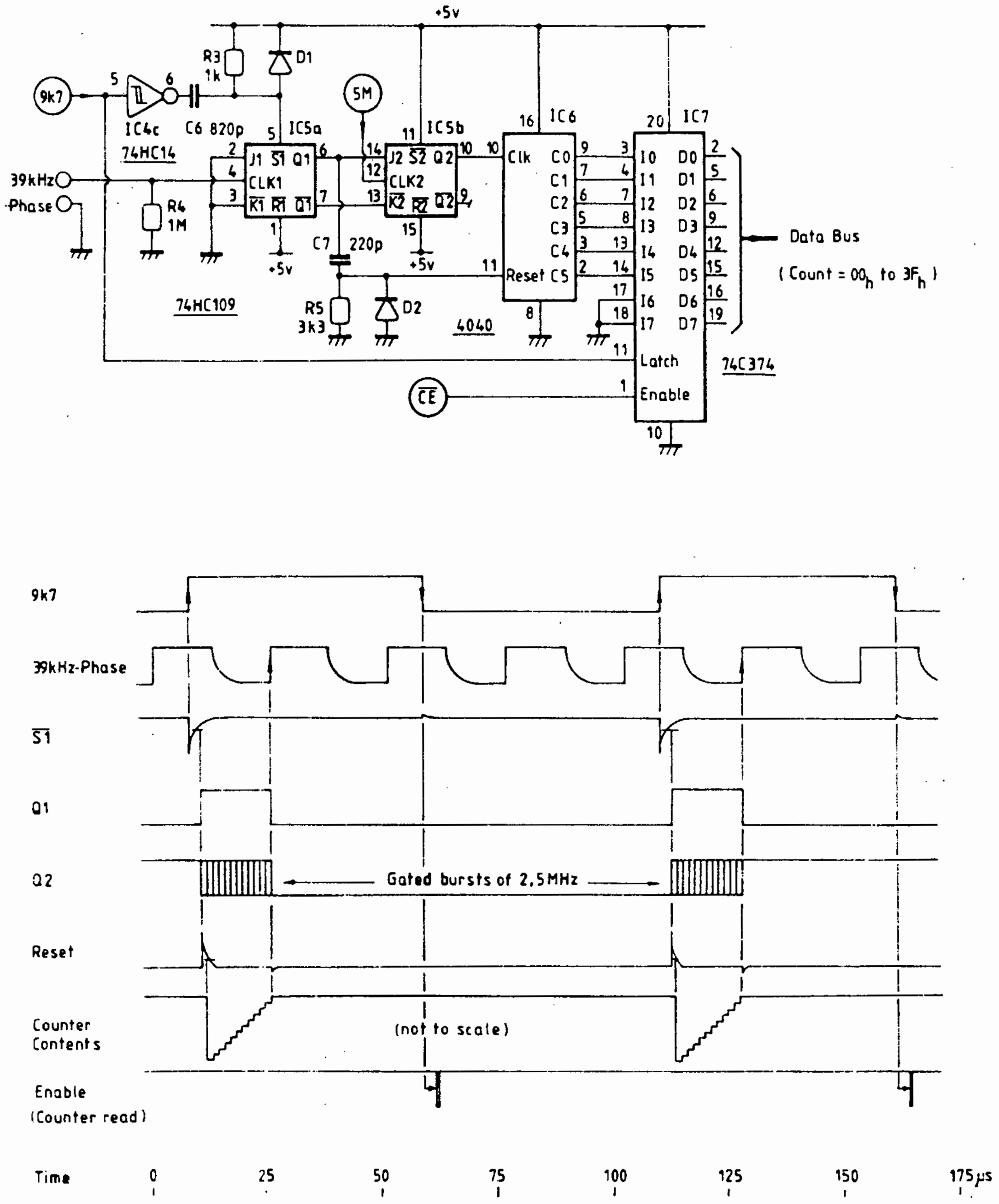


Fig.5-3, Phase Counter Circuit and Timing Diagram

The counter register of IC6 increments with each rising edge of Q2. This continues until there is a rising edge of 39kHz-Phase on the CLK1 input of IC5a, which sets Q1 and clears Q1(bar) and so disables IC5b.

The falling edge of the 9,7 kHz reference transfers the output (C0 to C5) of the counter into a latch in IC7. This falling edge is also detected by the microprocessor (P10 of IC3) which then reads the contents of the latch.

The value of the counter is proportional to the phase difference between the 9,7 kHz reference and 39kHz-Phase.

The maximum value of the reading is the number of cycles of 2,5 MHz that can occur in one cycle of 39,062 kHz, which is 63(dec) or 3F(hex).

It can be seen from the timing diagram that the phase is read only on every fourth cycle of 39kHz-Phase. This is because the rate of data collection by the software is limited by the speed of operation of the software. This is not a critical limit, at the 4 MHz clock rate the microprocessor can comfortably read every fourth cycle of the phase-counter. To read every third (or less) cycle would require a higher speed microprocessor clock, and need a more costly microprocessor chip. This would not result in any justifiable improvement in the performance of the instrument.

The phase-reading routine averages 256 readings of the phase counter in two sets of 128 readings taking into account any roll-under or roll-over in the reading (e.g. if the reading changes from 01 to 00,3F,3E etc.).

The phase-reading software is Subroutine PHSMES and can be seen on line 1483 of the software listing.

The Software

The software listing in Appendix D is written in assembly language on a Hewlett Packard HP64000 microprocessor development system. The comments within the listing adequately describe the code and it forms a readable document in its own right.

The program is contained in a single module allowing the assembler to address all RAM in the Direct Addressing mode, which uses one byte per address, instead of the two-byte addresses needed by Extended-Addressing mode. This conserves valuable EPROM space. (The 63701VOC processor contains 4 096(dec) bytes of internal EPROM and 192 bytes of RAM).

The Micromin program consists of approximately 3 000 bytes of measurement routines and approximately 300 bytes of special test routines to facilitate testing and alignment.
The program uses up 3 334(dec) of the 4 096(dec) available bytes of the EPROM (i.e. 81%). So future enhancements can be added without a major redesign.

RAM variables are declared from 0040(hex) through to 00C8(hex) leaving the area from 00C9(hex) through to 00FF(hex) for the stack. The stack is used by the CPU to store return addresses and register contents for subroutine jumps and interrupt-service routines. The stack-pointer position was traced through all conditions of the program's execution, to confirm the required stack depth. The results of this trace are shown in Fig.5-4.

Fig.5-4 shows the movement of the stack-pointer for both instruments for all conditions of the program's operation, from initialisation through to testing, distance measurement, and display. The stack pointer is initialised to 00FF(hex) and is decremented by one for each byte stored on the stack. The names of the subroutines are shown positioned to the left by the amount of the stack they use, and progress down in the order of program execution.

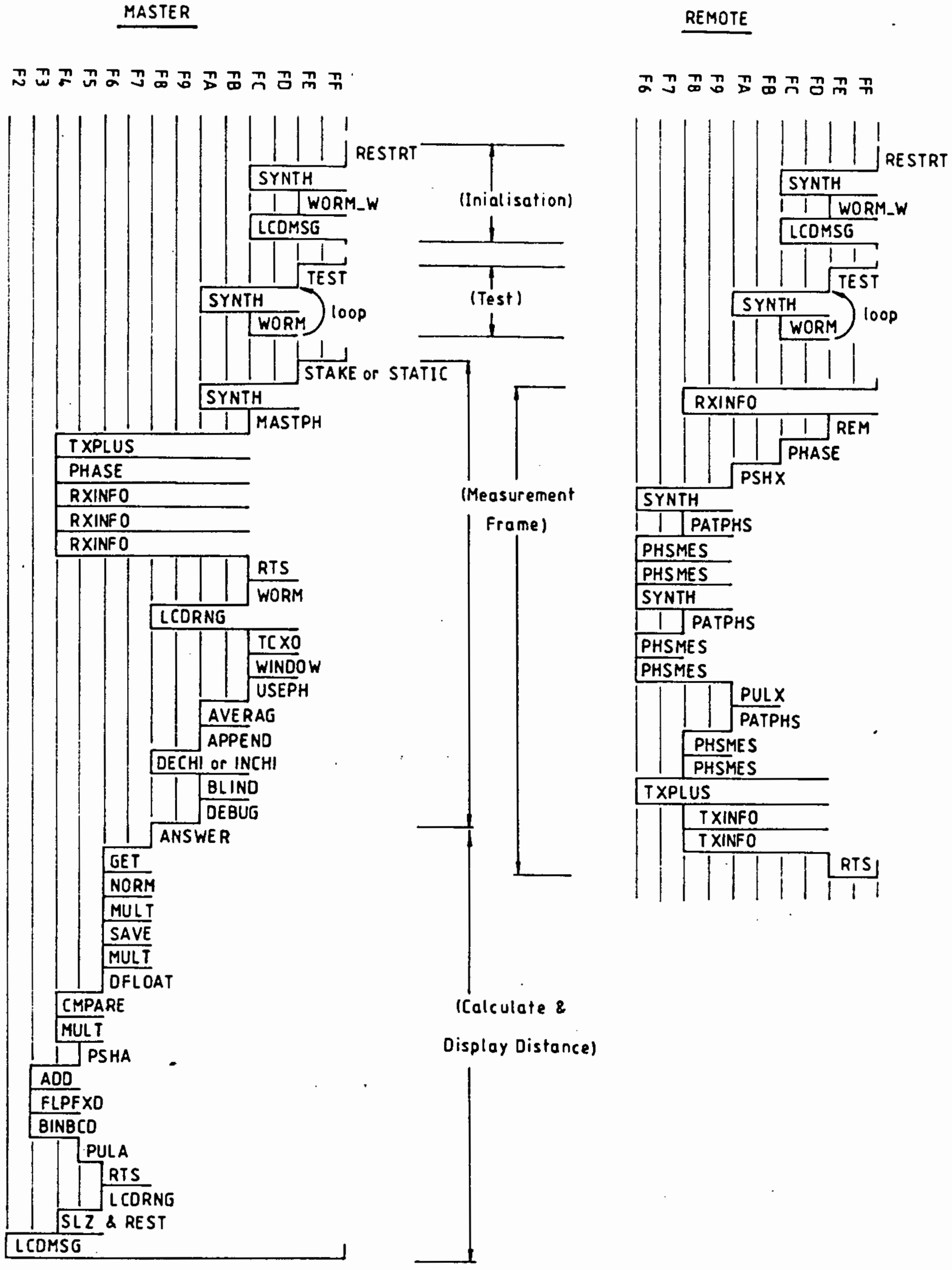


Fig.5-4, Software Operation and Stack Depth

It can be seen from Fig.5-4 that the stack drops down to 00F2(hex) in the Master, and down to 00F6(hex) in the Remote.
An interrupt will store 8 bytes on the stack. Only one interrupt can occur at a time, so the lowest used stack position is 00F2-8 = 00EA(hex) in the Master, and 00F6-8 = 00EE(hex) in the Remote.

If the stack were to drop as low as 00C9(hex) it would overlap RAM variables and writing there would corrupt the stack and result in a program "crash". This will not happen in the Micromin as there are 33(dec) unused bytes between the top-most RAM variable and the lowest possible position of the stack.
Maximum RAM usage is 159 out of the 192 bytes i.e. 83%.

The operation of the software can be described in four main parts,

1) Initialisation
2) Test
3) Phase Measurement Frame
4) Breakout Calculation and Display.

1) Initialisation consists of setting up the Input/Output ports, data-direction registers and the LCD. The Master then waits for a command to measure from the operator panel, and the Remote waits for a command to measure from the Master via the datalink.

2) Test programs allow the pattern modulation-indices to be adjusted, and each pattern's phase to be measured, one at a time. These features are useful training and debugging aids.

3) The Measurement Frame consists of data transmission between the instruments, the phase measurement of a set of patterns (a leading-straddle, a centre and a trailing-straddle) and TCXO adjustment.

4) The Breakout Calculation brings together the results of all the phase measurements replacing the least significant bits of coarser patterns with the most significant bits of the finer patterns to build up the distance register (DIST).
In dynamic or "TRACK" mode the distance is displayed on the LCD every 600 ms. In static mode fifteen measurements of pattern 7 (20 MHz) are averaged before the distance is displayed.

Program Timing

The 16-bit timer-counter, CNTR, in the 63701VOC, incremented by the clock every 1 µs, controls the timing of the program to an accuracy of 1 µs by setting and waiting for timer breakpoints.
The counter-timer overflows every 2^{16} µs (65,536 ms), causing a Timer Overflow interrupt. The Timer Overflow interrupt service routine (LNGTIM) increments a register (LONGTM) which forms an extension to the 16-bit timer. LONGTM-CNTR thus form a 24-bit counter with an overflow every 2^{24} µs (16,777 seconds).
Timer breakpoints are set by reading the counter, adding a value (equal to the number of 1µs clock cycles till the next required breakpoint), storing this sum in the Output Compare Register (OCR), clearing a synchronisation flag (SYNC) and then waiting for the flag to be set. The output compare register is continually being compared with the counter (by the hardware of the microprocessor) and generates an output compare interrupt (OCI) when the values are equal. This interrupt service routine sets the synchronisation flag SYNC.

This technique is used to control the timing of the measurement frame (the names of the timer breakpoints are shown on the top line of Fig.5-5), and in time-sensitive routines such as serial data transmission and reception (Subroutines TXINFO and RXINFO).

Data Transmission and Reception

Data transmission between the Master and Remote instruments during the measurement frame uses the datalink as a simplex link at a rate of 1 200 Baud.

The format of the data is,

1 start bit, 8 data bits, 2 checksum bits, 1 stop bit.

The data transmission is generated by subroutine TXINFO which can be seen on line 1836 of the software listing. TXINFO sets and clears TXDATA (pin 15 of IC3) to produce serial data. The rate is controlled by the 16 bit counter-timer.

The MUTEDA line is used to enable the modems, allowing a 20 ms lead-in to guarantee carrier detection at the receive modem before data are sent. The carrier detect line, CDET (pin 26 of IC3), must be high for data reception to be valid.

Both modems are switched off during phase measurement to prevent intermodulation and phase contamination of the 39kHz-Phase signal.

Data reception is performed by subroutine RXINFO which can be seen on line 1903 of the software listing. RXINFO reads data by sampling the logic state of RXDATA (pin 25 of IC3), the rate being controlled by the 16 bit counter-timer.

The Measurement Frame

Fig.5-5 shows the timing and port activity of a measurement frame.

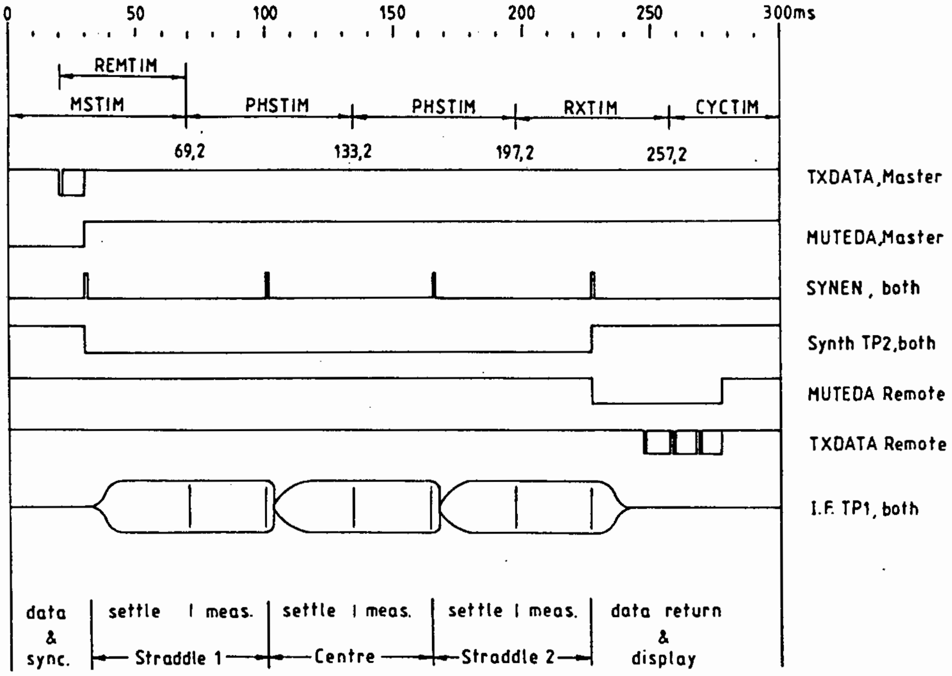


Fig.5-5, The Measurement Frame Cycle

The measurement software starts on line 583 of the software listing. Each frame consists of the following sequence of events.

1) The Master transmits a byte of data (with a 20 ms high lead-in) to the Remote. The Remote synchronises the timing of its frame from the falling edge of the start bit. The data informs the Remote of the pattern number. The Master switches off its transmit modem.

2) Both instruments apply pattern modulation of the first Straddle Pattern for the current frame.
After a delay to allow for phase settling, the phase of the recovered mixed product of these modulations, (39KHz-Phase), is measured and recorded in both instruments. Both instruments wait for 1 ms for the other to stop measuring.

3) Both instruments apply pattern modulation of the Centre Pattern for the current frame.
After a delay to allow for phase settling, the phase of the recovered mixed product of these modulations, (39KHz-Phase), is measured and recorded in both instruments.
Both instruments wait for 1ms for the other to stop measuring.

4) Both instruments apply pattern modulation of the second Straddle Pattern for the current frame.
After a delay to allow for phase settling, the phase of the recovered mixed product of these modulations, (39KHz-Phase), is measured and recorded in both instruments. Both instruments wait for 1 ms for the other to stop measuring.
Both instruments switch off pattern modulation.

5) The Remote transmits a 20 ms high lead-in followed by three bytes of data to the Master. The data contains the results of the Remote's three phase measurements and, as a check of the integrity of the link, the pattern number of the current frame.

6) The Master calculates the phase of the current pattern and updates the distance register.
The Master then increments, decrements or repeats the pattern number (depending on the fit of the breakout phases) and continues onto the next frame; or stops measuring if the measurement is complete. The Master adjusts its TCXO frequency to equal that of the Remote, and updates the LCD.

CHAPTER 6

Parameters Affecting Performance

In this chapter some of the limitations of Tellurometers will be discussed, and their effect on the Micromin in particular.

Antenna Swing

Change in apparent measured distance with variation of microwave carrier frequency is termed "antenna swing". The cause is a frequency-dependent change in the phase-centre of the instrument. The phase-centre of the instrument is the point where incoming received energy mixes with the local oscillator, and is the point from which the distance to the other instrument is measured. This point is ideally at the mixer diode, but departs from this ideal due to the following effects,

1) The Gunn and Mixer not being coincident,
2) The antenna being mismatched to free-space,
3) The group delay through the mixer circuit and antenna.

1) The microwave source and the mixer not being coincident results in antenna swing due to the frequency-dependence of the speed of propagation of information in the waveguide.
The phase velocity, V_p, of a wavefront propagating in a waveguide is defined by the formula

$$V_p = C/\sqrt{(1-(\lambda/2W)^2)} \tag{6.1}$$

where

C = propagation speed in air
W = width of the waveguide (0,023 m)
λ = free-space wavelength
(29,25 mm @ 10,25 GHz; 29,87 mm @ 10,35 GHz)

The velocity at which information can be propagated along this wave is called the group velocity, V_g, and is related to the phase velocity by the formula

$$C^2 = V_g \times V_p$$

Thus V_p is frequency-dependent and the time taken for the local oscillator wave to reach the mixer diode varies with frequency.
This is a mechanism by which the position of the phase centres of the instruments vary with frequency.
In the Micromin, taking the source of the modulated wavefront to be between the varactor and the Gunn diodes (a reasonable assumption), and the mixer diode as 25 mm away from this source, then a frequency change of 100 MHz at 10,3 GHz will produce a change in measured distance of (only) 0,21 mm at each end.
The effect occurs at both ends of the path resulting in a variation of 0,42 mm over the whole path.

Note that if the waveguide is operated at near the cutoff-frequency (where λ approaches 2W) then this effect becomes more significant.

2,3) Any local oscillator energy reflected from the antenna will add to the primary source of mixer local-oscillator bias (i.e. a point between the varactor diode and the Gunn diode). This will shift the effective point of mixer bias.

Graphically this can be shown as in Fig.6-1.

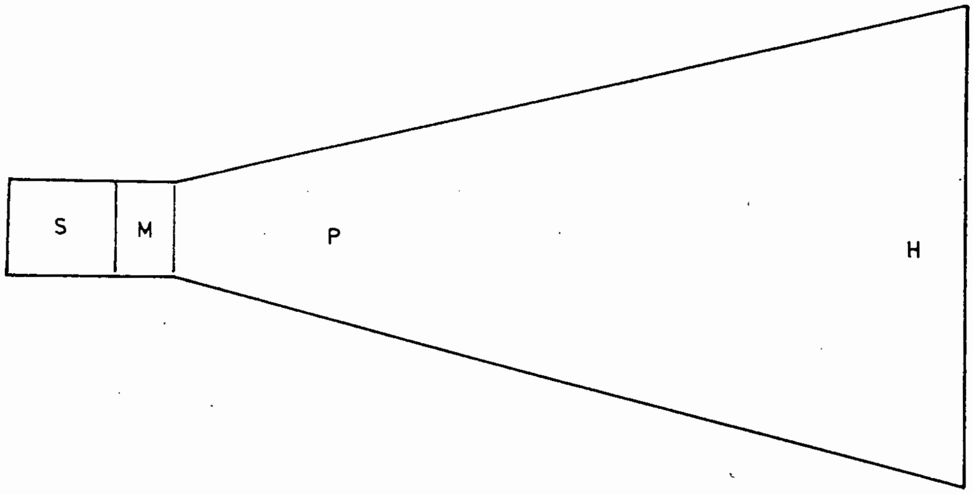


Fig.6-1, Phase Centre of the Horn Antenna

If the antenna is a perfect match there will be no reflection and the phase-centre will be at the mixer diode, at point M.

However, with a reflection of energy from the antenna the mixer bias consists of a proportion of bias from the source at point S, and the reflection from the antenna at point H. The resultant phase-centre is somewhere between these two points at point P. The position of P will be frequency dependent because the antenna match will be frequency dependent.

At microwave frequencies the atmosphere is non-dispersive, i.e. the difference between the velocities of the modulation envelope and the carrier frequency is so small as to be ignored, and the wavefront propagates at a speed of C/RI (RI = refractive index). So the group velocity of the wavefront accelerates from V_g in the waveguide, to C/RI in free space (at the mouth of the horn), and if it is reflected back into the horn it will return to the mixer, decelerating from C/RI to V_g as it returns.

Again, because the group velocity in the horn is frequency dependent this is a further source for "antenna swing".

Because the amount of VSWR phase-centre pulling is governed by the ratio of the amplitudes of the "direct" signal to the reflected signal it is an advantage for the Micromin to have a high level of mixer bias (approximately 8 mW).

The horn antenna has a low VSWR (approximately 1,05:1) and an inherently broad bandwidth. These features make the horn a very attractive antenna for Tellurometer work (compared to stripline antennas, for example).

Maximum directivity of the horn is achieved by ensuring a uniform power distribution across the aperture.
Consider the cross-section through a horn antenna of Fig.6-2.

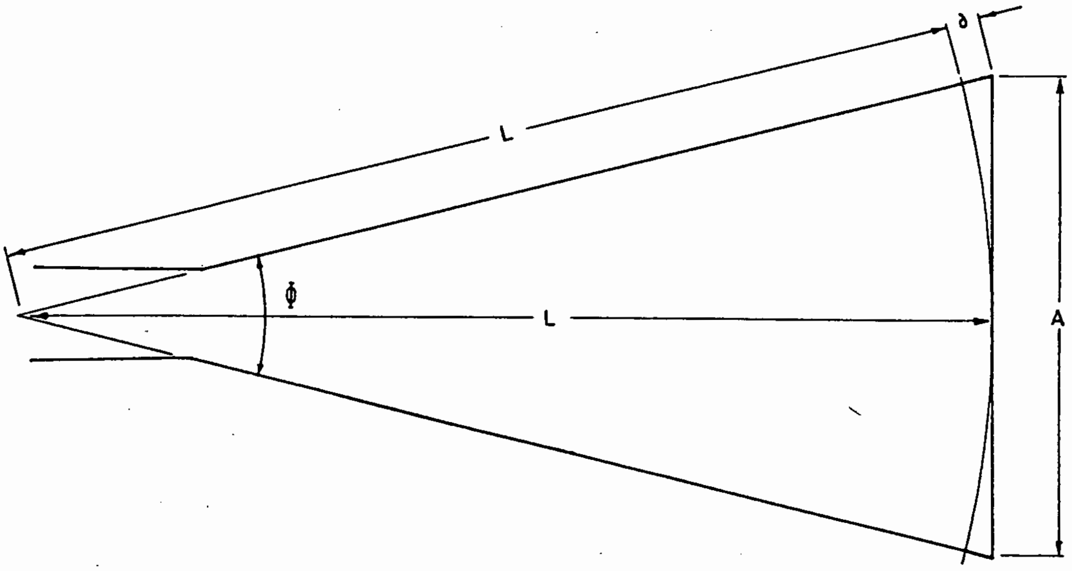


Fig.6-2, Excess Path Length of the Horn Antenna

The axial length of the horn is L, the aperture is A and the total flare angle is Φ. The length δ is the difference in path length for a wave reaching the aperture at the axis and one reaching the aperture at the side of the horn.

If δ is a sufficiently small fraction of a wavelength the field is nearly uniform over the entire aperture. However, when δ = 0,5λ, the phase change at the edges is 180° and the resultant interference increases the side-lobes.

In the Micromin this is minimised as it would decrease both accuracy and maximum range performance.

For an optimum horn δ must usually be in the range of 0,1 to 0,4 free-space wavelengths.

In the Micromin, at 10,30 GHz,

in the E-plane L = 250 mm, A_e = 116 mm, & δ_e is 0,23λ

and

in the H-plane L = 250 mm, A_h = 125 mm, & δ_h is 0,26λ.

The excess path length, or δ-effect described here is an inherent limitation to the length of a horn for a given flare angle.
This excess path length, being a small fraction of λ, ensures low side-lobes and minimum beamwidth for the horn.

The minimisation of sidelobes from the horn antenna reduces another source of error in surveying called "ground-swing".

Ground Swing

Errors in phase measurement are introduced by the influence of ground reflections of the microwave beam.

Considering the simple case of a single reflection off the ground between the two instruments as shown in Fig.6-3, it can be seen that the signal received by each instrument is the vector sum of the two signals. The resultant of these two will normally have a different phase angle from that of the direct beam alone, affecting the measurement.

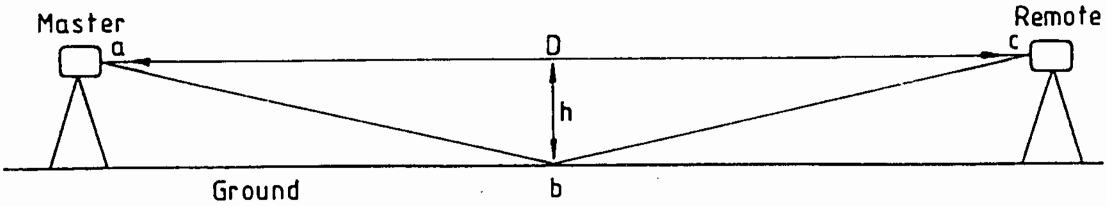


Fig.6-3, Ground Reflection Geometry

The strength of the reflected beam depends on the microwave carrier frequency, the angle of incidence, the plane of polarisation, and the nature of the reflecting surface. The phase difference depends on the excess path length d, and both the microwave carrier and pattern modulation wavelengths (λ_c and λ_m).

For the case shown in Fig.6-3 the error in measured distance is shown (by Bomford, 1971) to be

$$e = \frac{\lambda_m}{2\pi} \arctan\left(\frac{\gamma(\gamma - \cos\beta_c)\sin\beta_m}{1 - \gamma\cos\beta_c(1+\cos\beta_m) + \gamma^2\cos^2\beta_m} \right) \qquad 6.2$$

where

$\beta_c = 2\pi d/\lambda_c$,and

$\beta_m = 2\pi d/\lambda_m$

and where

e = error in measured distance (m)

λ_m = pattern wavelength (m)

γ = ground reflection coefficient (between 0 and 1)

d = path length difference (abc - ac in Fig.6-3)

In cases where the ground reflection coefficient is smaller than 0,3 equation 6.2 can be simplified to

$$e = -(\lambda_m/2\pi) \times \gamma \times \mathrm{Cos}\beta_c \times \mathrm{Sin}\beta_m$$

This formula shows that there are two cyclic components in the function, the cosine term varying rapidly and cycling through zero every half wavelength of the microwave carrier, and the sine term varying slowly cycling through zero every half wavelength of the modulated-pattern frequency.
It also shows that the maximum error is $\pm\gamma \times \lambda_m/2\pi$.

Fig.6-4 and Fig.6-5 show the errors that can be expected with
a ground reflection coefficient of 0,1 ,
a carrier wavelength of λ_c = 29,1 mm
and the 20 MHz fine pattern of the Micromin (λ_m = 14,99 m).

Fig.6-4 shows the first few cycles of the function, and Fig.6-5 shows the envelope of that function.

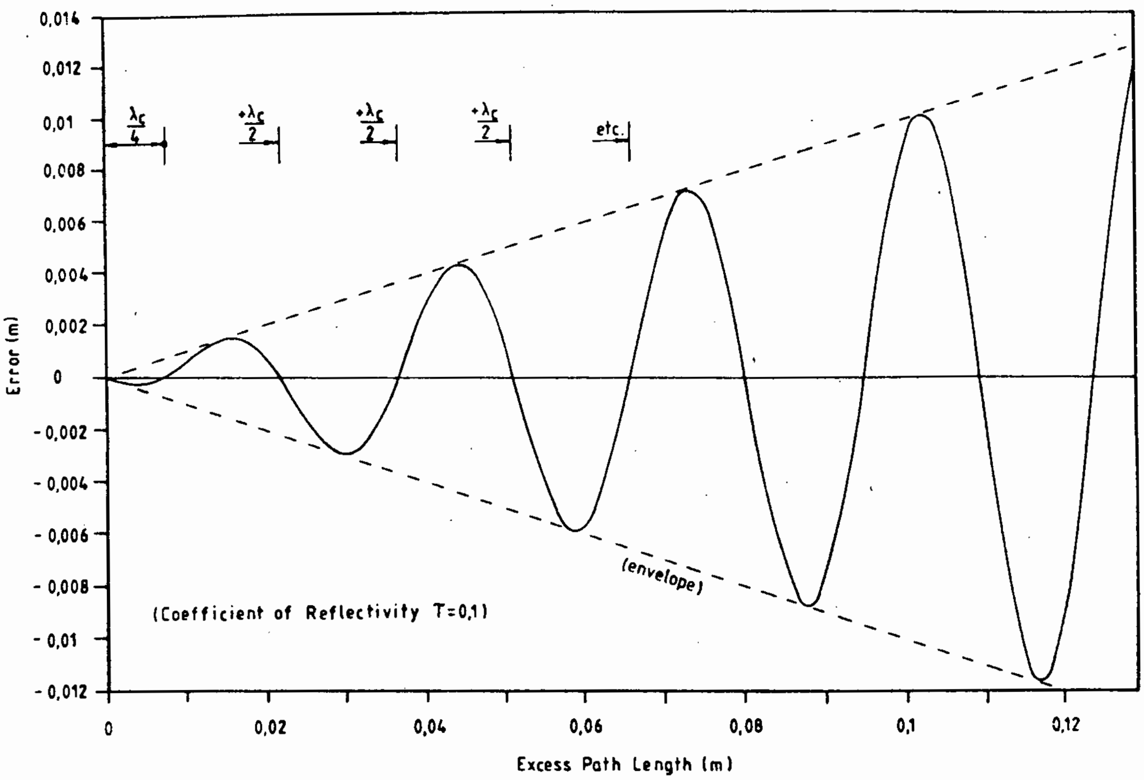


Fig.6-4, Ground Reflection Error vs. Excess Path Length

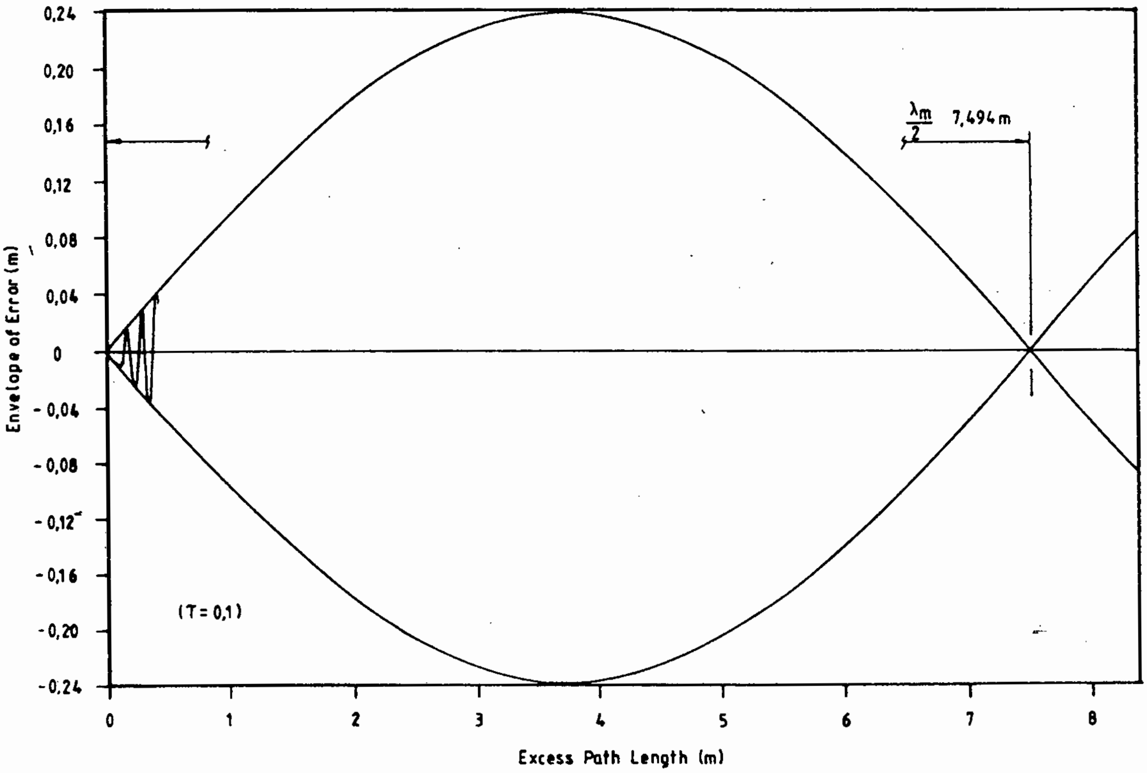


Fig.6-5, Envelope of Ground Reflection Error

For coefficients of reflection other than 0,1 the Y-axes of Fig.6-4 and Fig.6-5 can be proportionally scaled.

The excess path length d, drops off rapidly as the separation between the two instruments is increased and can be defined by the relationship,

$$d = [2(h^2+(D/2)^2)]^{-\frac{1}{2}} - D$$

The value of d, for a height h of 1 m and an instrument separation D of up to 60 m, is shown by the solid line Fig.6-6.

The situation at very close ranges (less than 10 m) is improved by the narrow beamwidth of the horn antenna which limits the amount of microwave signal illuminating the ground.

The beamwidths at half-power points in the E & H-fields are given by;

½-power beamwidth in E-field = $56/A_{e\lambda}$ = 14,05°
½-power beamwidth in H-field = $67/A_{h\lambda}$ = 15,96° **6.3**

and the angle between the first nulls is given by;

angle between nulls E-field = $115/A_{e\lambda}$ = 28,85° **6.3**
angle between nulls H-field = $172/A_{h\lambda}$ = 44,15°

where $A_{e\lambda}$ & $A_{h\lambda}$ are the horn apertures in the E and H fields respectively, expressed in units of free-space wavelengths.

In the E-field the half power beamwidth is 14,05° and for an instrument height of 1 m, the ground illumination is 3 dB less than the main beam at a distance of 8,1 m away from the base of the tripod.

There is a null in the radiation at an angle of ½x44,15° away from the line of the direct beam in the E-field so there will be no illumination of the ground at a distance of 3,88 m away from the base of the tripod.

The change in ground illumination with change in instrument separation at a height of 1 m is shown by the dotted line in Fig.6-6.

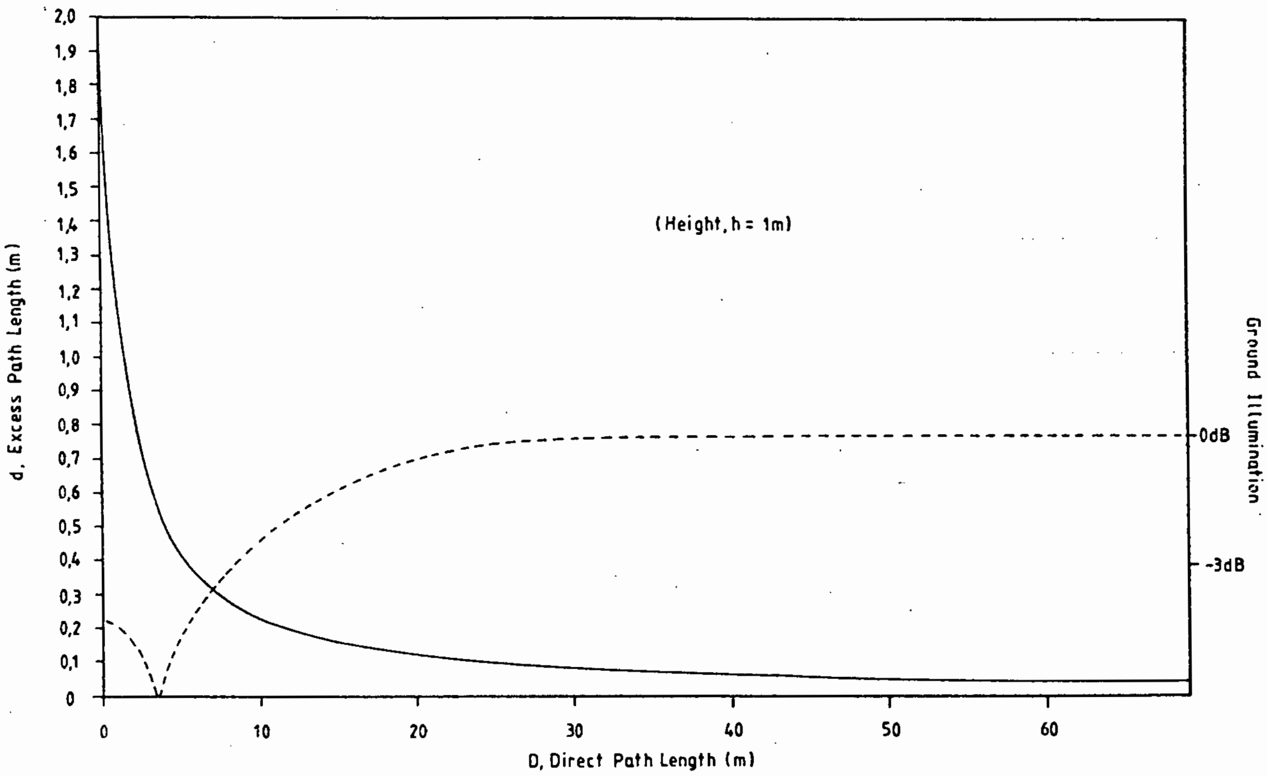


Fig.6-6, Excess Path Length and Ground Illumination

In practice there can be multiple reflections and then the results do not in general bear much resemblance to the theoretical ones. Sometimes reflections can make a measurement very inaccurate and special measures must be taken to reduce the strength of the reflected beam.

For example on hilltops the instruments can be moved back from the top or lowered so that the ground absorbs some of the reflected signal. On flat terrain the instruments can be lowered so as to reduce h and d.
Two special cases of ground swing that produce particularly large errors are worth noting.

The first is the case where the reflected beam cancels out the direct beam allowing a third beam to become dominant. This situation is readily identifiable by a loss of signal strength (if the operator is experienced enough with the Micromin and knows what sort of signal strength to expect over the range), accompanied by significant scatter on readings. If this occurs the operator can alter the instruments height, tilt the instrument or if necessary move the position of the line to get out of the interference area.

Another case is when measuring over a smooth dip in the ground such as down the length of a road that drops away from the operator and rises again as shown in Fig.6-7. The surface of the road can act as a collimating mirror and the reflected path can be much stronger than the direct path. The operator is likely to "beam up" on the strongest beam, (especially if he is not "beaming up" by line of sight). There will be significant scatter between adjacent readings, and an experienced operator may see that the signal strength is greater than should be expected over the operating range.

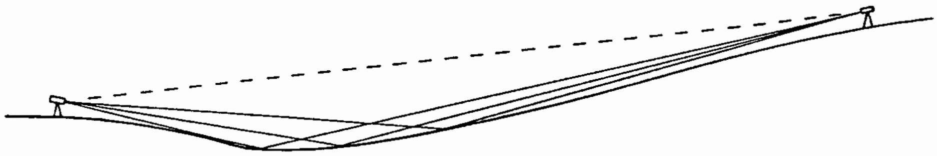


Fig.6-7, Error due to Instruments Aligned on a Reflection

Contamination

The accuracy and range performance of the Micromin can be impaired by noise and contaminating signals. The main causes described here have been systematically reduced to within acceptable levels.

Cyclic Error

Error in the measured distance varying cyclically with respect to distance is termed Cyclic Error.
Distance measurement is achieved by comparison of the phase of a 39KHz signal recovered from the IFs in both instruments which are the product of two high frequency modulations, (i.e. 10-21,25 MHz).
The squarer of the IF is a highly selective amplifier tuned to 39,062 KHz to recover this signal.
In the absence of any contaminating signals the phase of this recovered signal with respect to the internal reference will vary linearly with a change in distance between the two instruments.
However any baseband modulation at 39,062 KHz will also be readily amplified by the squarer and be presented to the phase counter with the recovered 39KHz-Phase and will affect the phase.
The phase of the internal contaminating signal does not vary in phase with change in distance because it does not travel the path, (the other contaminating signal from the far instrument travels the path at baseband and the phase cycles slowly with change in distance).
The resultant phase is the vector sum of these signals varying with change in distance with a cyclic error.

The magnitude of error depends on the relative amplitudes of the contamination and the recovered comparison signal.
Cyclic error in the Micromin is reduced by the 39,062 KHz series resonant trap of L7 and C31 of the Modusynth.
An experiment to determine the magnitude of this contamination is described in Appendix C.

Synthesiser Noise

The output spectra of the Modusynths are important factors in the accuracy of the Micromin. Any sidebands on the output of the Modusynth will add noise to the final phase reading of the comparison signal (39KHz-Phase).

A typical output spectrum of the Modusynth is shown in Fig.4-6. Particular attention was paid to the following areas:

1) Supplying power to the VCO and the modulator via a dedicated regulator, IC5 and isolating the supply rail from any disturbance (particularly the sample-and-hold switching circuitry).

2) Filtering the loop control signal at the sampling frequency (2,441 KHz, see Fig.4-4).

3) Adequate decoupling of supply lines.

4) Consideration of earth loops, circuit board layout and screening of the VCO coil (L1).

Microprocessor Noise

Noise generated by the microprocessor covers a wide frequency spectrum and can interfere with the IF, desensitising the receiver and reducing the maximum range of the instruments.
In the Micromin this noise has been minimised by having separate voltage regulators for the IF and the Microprocessor, and taking the power leads for these boards directly to the voltage source.
The level of interference in the prototype instruments has been determined by listening to the noise level of the receiver (with the other instrument switched off), and switching the microprocessor on and off. There is a slight noticeable increase in the noise level when this is done, but testing the IF sensitivity using a signal generator shows that the IF achieves full quieting with a 10,76 MHz input signal of 3 µV independent of the microprocessor being on or off.
This indicates that the microprocessor noise level is low, but could be reduced in future instruments to give a slight improvement in range performance.
The "star" arrangement of power distribution, effective in reducing mutual interference is shown in Fig.6-8.

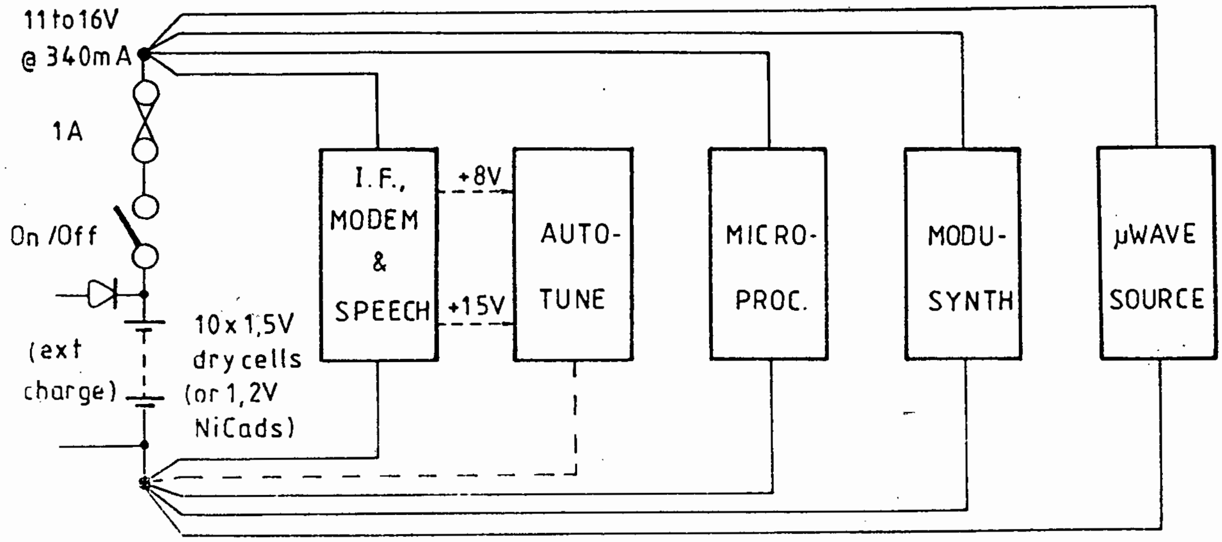


Fig.6-8, "Star" Power Supply Distribution

Data and Speech

Baseband speech modulation disturbs the phase measurement.
Although the press-to-talk switches can be used during measurement the audio amplifiers are muted so there is no speech link available during measurement.

Measurement of Phase Noise on the Comparison Signal

All these sources of noise combine to corrupt 39kHz-Phase which can be measured by the following bench test.
A 39,062 kHz reference (Microprocessor IC10 pin 4) triggers one channel of a dual channel oscilloscope, and the other channel monitors the recovered 39kHz-Phase.
With the instruments tuned into each other the patterns are selected one at a time using the Test switch on the microprocessor.
Typical signals found are shown in Fig.6-9. The width of the phase noise is typically 1 % of a cycle of 39kHz-Phase. This corresponds to approximately 5 cm peak-to-peak scatter on each phase reading of pattern 7 (ambiguity = 3,747 m).

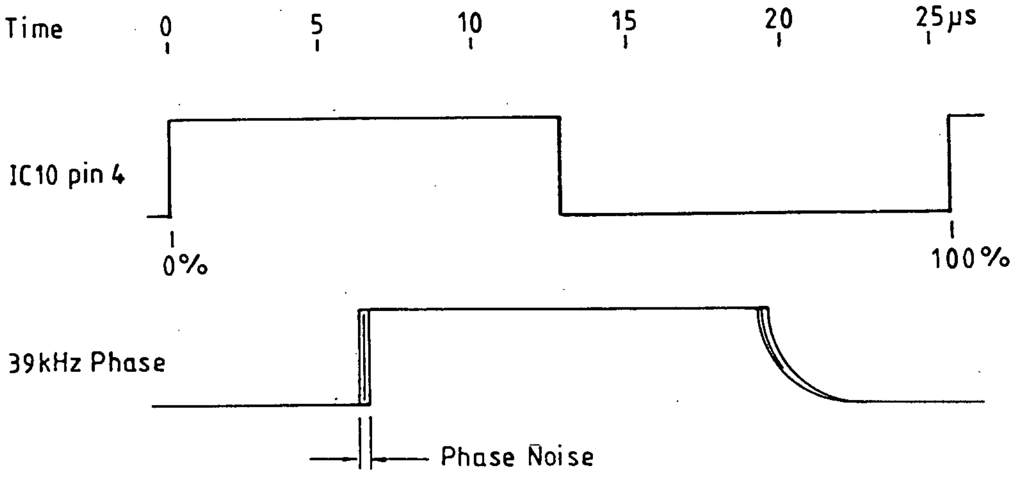


Fig.6-9, Phase Noise on the 39kHz-Phase Comparison Signal

References for the formulae

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6.2 Bomford, G. (1971), "Geodesy", Oxford University Press.

6.3 Kraus, (1950)
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CONCLUSION

This thesis describes the results of three years of work on a Tellurometer, that has included the fields of software, microprocessor, digital and analogue design, low noise frequency-synthesis, microwaves and meteorology. The value-engineering inherent in this design comes as a result of the author's last seven years of industrial experience in the development of Tellurometer products.

During this time, terrestrial-survey equipment sales to the developed countries has been in decline, and the focus of attention has shifted to hydrographic survey (particularly of rivers and coastlines) and satellite navigation.
Satellite position-fixing equipment is relatively inaccurate and expensive compared to the instrument described here.

The author believes that this instrument, in the Tellurometer configuration, could create a new market for itself due to the survey needs of the under-developed nations. The simplicity of operation and repair, the excellent price/performance ratio and the latest market trends give substance to this belief.

In the datalink configuration, the Micromin could find applications particularly in the developed nations, 9 600 Baud duplex being a common modem data-rate for computer-based applications.

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APPENDIX A

Mathematical Analysis of the Measurement Process in the Micromin

Two Micromin instruments are used to measure distance, the Remote X-band carrier signal being locked to the Master with an AFC loop. The Remote instrument, when locked to the Master, is at a frequency 10,76 MHz lower than the Master.

The carriers of both the Master and the Remote are frequency modulated with PATTERN frequencies. By measuring the phase of the product of these patterns (present as amplitude modulation of the IF signal) simultaneously at both instruments, the distance between the two instruments can be calculated.

Pattern Modulations

Two classes of pattern are used, Absolute Pattern pairs, and Difference Pattern pairs. The way of measuring distance from the phase measurements of these patterns is similar, though the mathematical description of each is different. The two classes are therefore discussed separately.

Assumptions and Symbols

In the discussions of both Absolute and Difference Pattern pairs, the following assumptions and symbols are used:

1) Phase measurements will be taken simultaneously in both the Master and the Remote instruments.

2) All frequencies used will be derived from a reference frequency oscillator, ω_m in the Master and ω_r in the Remote (in both cases this frequency is 2,441 kHz).

3) The distance between the Master and the Remote at a time t is D. The rate of increase of distance with time between the Master and the Remote is S.

4) The propagation speed of the carriers is C.

5) +Patterns are modulations at the basic pattern frequency plus $8\omega_m$ at the Master and minus $8\omega_r$ at the Remote (i.e. ±19,031 kHz).

6) -Patterns are modulations at the basic pattern frequency minus $8\omega_m$ at the Master and plus $8\omega_r$ at the Remote (i.e. ±19,031 kHz).

Absolute Pattern Pairs

Absolute Pattern pairs consist of a +Pattern and a -Pattern, each of the same basic pattern frequency $N\omega$.

These two Patterns are called the Straddle Pattern and the Centre Pattern respectively. The Straddle Pattern is applied a time δt before and a time δt after the Centre Pattern to cancel out terms due to δt. The mechanism for this will be analysed later.

At the mixer of the Master the following signals are present.

Straddle Pattern:

Lo: $\omega_m(N+8)t + \Phi_{sm}$
Rx: $\omega_r(N-8)(t-D/(C+S)) + \Phi_{sr}$ **A.1M**

Centre Pattern:

Lo: $\omega_m(N-8)(t+\delta t) + \Phi_{cm}$
Rx: $\omega_r(N+8)(t+\delta t-D/(C+S)) + \Phi_{cr}$ **A.2M**

where 'Lo' is the locally generated sideband and 'Rx' is the received sideband of the other instrument, and where δt is the time difference between the measurements of the Straddle Pattern and the Centre Pattern. The Φ-terms are the random starting phase for each synthesiser when loaded with a new frequency. It is also assumed that S is small in comparison to the resolution of $D/\delta t$.

At the mixer of the Remote the following signals are present

Straddle Pattern:

Lo: $\omega_r(N-8)t + \Phi_{sr}$
Rx: $\omega_m(N+8)(t-D/C) + \Phi_{sm}$ **A.1R**

Centre Pattern:

$$\begin{aligned} &\text{Lo: } \omega_r(N+8)(t+\delta t) + \Phi_{cr} \\ &\text{Rx: } \omega_m(N-8)(t+\delta t-D/C) + \Phi_{cm} \qquad \mathbf{A.2R} \end{aligned}$$

Signals detected at the mixer of the Master

Straddle Pattern: The locally generated sideband minus the received sideband, (from the components of **A.1M**),
(Lo-Rx)=

$$\begin{aligned} &\omega_m(N+8)t + \Phi_{sm} - \\ &\omega_r(N-8)(t-D/(C+S)) - \Phi_{sr} \qquad \mathbf{A.3M} \end{aligned}$$

Centre Pattern: The received sideband minus the locally generated sideband, (from the components of **A.2M**),
(Rx-Lo)=

$$\begin{aligned} &-\omega_m(N-8)(t+\delta t) - \Phi_{cm} \\ &+\omega_r(N+8)(t+\delta t-D/(C+S)) + \Phi_{cr} \qquad \mathbf{A.4M} \end{aligned}$$

These signals are passed through the IF (with a delay δm at the Master) and measured with respect to the local reference frequency ω_m at the Master.

The result is :

Straddle Pattern:

$$\begin{aligned} &[\ \omega_m Nt + 8(\omega_m t) + \Phi_{sm} - \omega_r Nt \\ &+ 8(\omega_r t) + \omega_r ND/(C+S) - 8(\omega_r D/(C+S)) \\ &- \Phi_{sr} - \delta m\ ] - \omega_m t \qquad \mathbf{A.3M}^{1} \end{aligned}$$

Centre Pattern:

$$\begin{aligned}
&[\, - \omega_m N t - \omega_m N \delta t + 8(\omega_m t) \\
&+ 8(\omega_m \delta t) - \Phi_{cm} + \omega_r N t \\
&+ \omega_r N \delta t - \omega_r N D/(C+S) + 8(\omega_r t) \\
&+ 8(\omega_r \delta t) - 8(\omega_r D/(C+S)) \\
&+ \Phi_{cr} - \delta m\,] - \omega_m t \qquad \mathbf{A.4M^{1}}
\end{aligned}$$

These two phase differences are measured by the phase counter in the Micromin and then the two results are subtracted in the microprocessor. The difference between them is:

(S-Pattern) - (C-Pattern) = $\mathbf{A.3M^{1}} - \mathbf{A.4M^{1}}$ =

$$\begin{aligned}
&2\omega_m N t - 2\omega_r N t + 2\omega_r N D/(C+S) \\
&+ \Phi_{sm} - \Phi_{sr} + \Phi_{cm} - \Phi_{cr} \\
&+ \omega_m N \delta t - 8(\omega_m \delta t) \\
&- \omega_r N \delta t - 8(\omega_r \delta t) \qquad \mathbf{A.5M}
\end{aligned}$$

Rewriting equation **A.5M** gives :

$$\begin{aligned}
&2N(\omega_m - \omega_r)\,t \\
&+ 2\omega_r N D/(C+S) \\
&- \Phi_{sr} + \Phi_{sm} - \Phi_{cr} + \Phi_{cm} \\
&+ [\, \omega_m (N-8) - \omega_r (N+8)\,]\,\delta t \qquad \mathbf{A.5M^{1}}
\end{aligned}$$

The first term is due to the 'slipping' between the reference oscillators of the two instruments.

The second term is of interest, from which the distance is derived.

The third term is a random phase value that results from the loading of the synthesisers. These values also occur in the Remote and later cancel out as shown in equation A.6.

The fourth term is the error due to the two patterns being applied at times differing by δt. The δt term is compensated for by a measuring technique called 'Straddling' (as will be explained later), and can be ignored for now.

Similarly at the Remote, neglecting the δt effects, the following signals are detected at the mixer;

Straddle Pattern, (from the components of **A.1R**),
(Rx - Lo) =

$$\begin{aligned}&-\omega_r(N-8)t - \Phi_{sr} + \\ &\omega_m(N+8)(t-D/C) + \Phi_{sm}\end{aligned} \qquad \textbf{A.3R}$$

Centre Pattern, (from the components of **A.2R**, neglecting δt),
(Lo - Rx) =

$$\begin{aligned}&\omega_r(N+8)t + \Phi_{cr} - \\ &\omega_m(N-8)(t-D/C) - \Phi_{cm}\end{aligned} \qquad \textbf{A.4R}$$

These two patterns are measured with respect to the local reference in the phase counter (9,7 kHz), and then subtracted in the microprocessor to give, (ignoring the δt terms):

(S-Pattern) - (C-Pattern) : **A.3R** - **A.4R** =

$$\begin{aligned}&2N(\omega_m - \omega_r)t - 2\omega_m ND/C \\ &-\Phi_{sr} + \Phi_{sm} - \Phi_{cr} + \Phi_{cm}\end{aligned} \qquad \textbf{A.5R}^1$$

This result is transmitted from the Remote to the Master where it is subtracted from the result **A.5M**^{1} obtained at the Master (again by ignoring the δt terms).
N.B. all the Φ-terms cancel.

The difference is : **A.5M^1** - **A.5R^1** =

$(S\text{-}Patt_m - C\text{-}Patt_m) - (S\text{-}Patt_r - C\text{-}Patt_r) =$

$$2\omega_r ND/(C+S) + 2\omega_m ND/C \qquad \textbf{A.6}$$

From which the distance can be calculated (assuming C is known and that S is small with respect to C).

Difference Pattern Pairs

Difference Pattern pairs consist of two -Patterns, each differing in its frequency by the Difference Frequency which distinguishes the particular pattern.

Again the two patterns are called the Straddle Pattern and the Centre Pattern.

In the following discussion the synthesiser loading phases (Φ_{sm},etc) will not be considered as they disappear from the final results in exactly the same way as for the Absolute Pattern case.
Also the effects of the δt seen in equation **A.5M**[1] will not be shown, as the same method for compensating for these terms (to be discussed later) is used in this case as is used for the Absolute Pattern case.

The Difference Pattern frequency will be written as ωM:

At the mixer of the Master instrument the following signals are present:

Straddle Pattern:

$$\begin{aligned} &\text{Lo: } \omega_m(N-8)t \\ &\text{Rx: } \omega_r(N+8)(t+D/(C+S)) \end{aligned} \qquad \textbf{A.8M}$$

Centre Pattern:

$$\begin{aligned} &\text{Lo: } \omega_m(N+M-8)t \\ &\text{Rx: } \omega_r(N+M+8)(t+D/(C+S)) \end{aligned} \qquad \textbf{A.9M}$$

These are detected, passed through the IF and measured with respect to the local reference in exactly the same way as for the Absolute Patterns.

This gives:
Straddle Pattern: (Lo-Rx)=

$$\omega_m(N-8)t - \omega_r(N+8)(t+D/(C+S)) - \omega_m t - \delta m \qquad \textbf{A.10M}$$

Centre Pattern: (Lo-Rx)=

$$\omega_m(N+M-8)t - \omega_r(N+M+8)(t+D/(C+S)) - \omega_m t - \delta m \qquad \textbf{A.11M}$$

Note that the Centre Pattern difference is (Lo-Rx) and not (Rx-Lo) as for the ABSOLUTE PATTERN case. This is a consequence of the frequency relationship between the modulation applied at the Remote and at the Master.
In the ABSOLUTE PATTERN case the Remote modulation is of lower frequency than the Master, the reverse being true in the DIFFERENCE PATTERN case.

Subtracting these two results in the microprocessor gives the result:
A.11M - A.10M =

$$(\omega_r M - \omega_m M)t + \omega_r M(D/(C+S)) \qquad \textbf{A.12M}$$

The first term is minimised by locking the Master and Remote references and the second term is the one of interest.

Similarly, at the mixer of the Remote instrument the following signals are present:

Straddle Pattern:

Lo: $\omega_r(N+8)t$
Rx: $\omega_m(N-8)(t+D/C)$ **A.8R**

Centre Pattern:

Lo: $\omega_r(N+M+8)t$
Rx: $\omega_m(N+M-8)(t+D/C)$ **A.9R**

These are detected, passed through the IF and measured with respect to the local reference in exactly the same way as for the Absolute Patterns. This gives:

Straddle Pattern: (Lo-Rx)=

$$\omega_r(N+8)t - \omega_m(N-8)(t+D/C)$$
$$- \omega_r t - \delta m$$ **A.10R**

Centre Pattern: (Lo-Rx)=

$$\omega_r(N+M+8)t - \omega_m(N+M-8)(t+D/C)$$
$$- \omega_r t - \delta m$$ **A.11R**

Subtracting these two results in the microprocessor gives the result:

A.11R - A.10R =

$$-(\omega_m M - \omega_r M)t - \omega_m M(D/C)$$ **A.12R**

This result is transmitted to the Master and subtracted from the result **A.12M**, which yields,

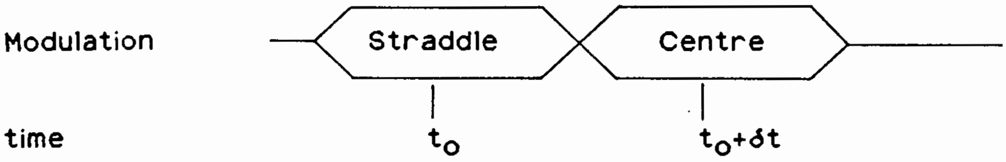
$$(S\text{-}Patt_m - C\text{-}Patt_m) - (S\text{-}Patt_r - C\text{-}Patt_r)$$

$$= \omega_r M(D/(C+S)) + \omega_m M(D/C) \qquad \textbf{A.13}$$

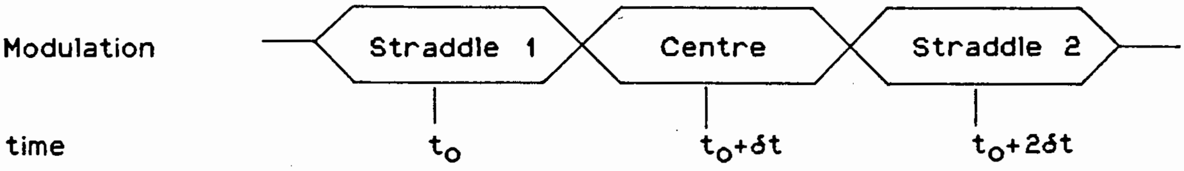
Which is very similar in form to the equation **A.6** derived for the Absolute Patterns, from which the distance D can be calculated. The only difference is a factor of 2 which has to be taken into account when calculating the distance.

Compensating For δt Errors by Straddling:

Referring to equation A.5M[1], the last term, which is just $K\delta t$, where K is a constant (in the short term) for the particular pattern, represents an error introduced by measuring the phase of the Centre Pattern after the Straddle Pattern:



this error can be removed by repeating the Straddle Pattern and effectively measuring two pairs of phase measurements:



Now if the measurements are made at :

t_o, $t_o+\delta t$, and $t_o+2\delta t$, from equation A.6, by calculating:

$$[\ (\mathrm{Straddle}_m{}^1 - \mathrm{Centre}_m) - (\mathrm{Straddle}_r{}^1 - \mathrm{Centre}_r)\ ]$$

We get:

$$2\omega_r N(D/(C+S)) + 2\omega_m N(D/C) + K_m\delta t + K_r\delta t \qquad \mathrm{A.6}^1$$

and by calculating:

$[(S\text{-}Patt_m{}^2 - C\text{-}Patt_m) - (S\text{-}Patt_r{}^2 - C\text{-}Patt_r)]$

We get:

$$2\omega_r N(D/(C+S)) + 2\omega_m N(D/C) + K_m(-\delta t) + K_r(-\delta t) \qquad \textbf{A.6}^2$$

Adding (or averaging) **A.6^1** and **A.6^2** yields a result without any δt error terms.

$$4\omega_r N(D/(C+S)) + 4\omega_m N(D/C) \qquad \textbf{A.14}$$

From which the distance can be calculated.

APPENDIX B

Meteorological Formulae

For Tellurometer phase readings to be interpreted as a distance the velocity of the microwave radiation must be known. This requires a knowledge of the refractive index of the atmosphere through which the waves travel. The following formulae are used in the determination of the atmospheric refractive index at microwave frequencies and are applicable to the Micromin.

$$(RI-1)10^6 = 77{,}62(P-E)/TK + 64{,}70(1+(5\ 748/TK))E/TK \qquad B.1$$

Where;

RI = refractive index

T_K = dry bulb temperature in degrees Kelvin

P = atmospheric pressure in millibars

E = partial pressure in millibars

$$E = SVP - \delta P \qquad B.2$$

$$SVP = a+T_w(b+T_w(c+T_w(d+T_w(e+T_w(f+gT_w))))) \qquad B.3$$

$$\delta P = 0{,}000\ 66(1+0{,}001\ 15T_w)(P)(T_d-T_w) \qquad B.4$$

SVP = saturation vapour pressure in millibars

δP = depression pressure in millibars

T_w = wet bulb temperature in degrees Centigrade

T_d = dry bulb temperature in degrees Centigrade

a = 6,107 799 961

b = $4{,}436\ 518\ 521 \times 10^{-1}$

c = $1{,}428\ 945\ 805 \times 10^{-2}$

d = $2{,}650\ 648\ 471 \times 10^{-4}$

e = $3{,}031\ 240\ 396 \times 10^{-6}$

f = $2{,}034\ 080\ 948 \times 10^{-8}$

g = $6{,}136\ 820\ 929 \times 10^{-11}$

Met. Calculation Program for the Hewlett Packard HP41CV

This calculation is performed by the following program for the HP41CV calculator which calculates the atmospheric refractive index given the parameters of dry bulb temperature ('C), wet bulb temperature ('C) & atmospheric pressure (millibars):

```
01   LBL "MET"
02   "Td IN C?"
03   PROMPT
04   STO 01
05   "TW IN C?"
06   PROMPT
07   STO 02
08   "P IN MB?"
09   PROMPT
10   STO 03
11   RCL 02
12   1.15 E-3
13   *
14   1
15   +
16   ENTER
17   RCL 01
18   RCL 02
19   -
20   *
21   6.6 E-4
22   *
23   RCL 03
24   *
25   STO 04
26   RCL 02
27   6.136820920 E-11
28   *
29   2.034080948 E-8
30   +
31   RCL 02
32   *
33   3.031240396 E-6
34   +
35   RCL 02
36   *
37   2.650648471 E-4
38   +
39   RCL 02
40   *
41   1.428945805 E-2
42   +
43   RCL 02
44   *
45   4.436518521 E-1
46   +
47   RCL 02
48   *
49   6.107799961
50   +
51   STO 05
52   273.16
53   ST+ 01
54   RCL 05
55   RCL 04
56   -
57   STO 06
58   5748
59   RCL 01
60   /
61   1
62   +
63   RCL 06
64   *
65   64.7
66   *
67   RCL 01
68   /
69   ENTER
70   RCL 03
71   RCL 06
72   -
73   77.62
74   *
75   RCL 01
76   /
77   +
78   STO 07
79   RCL 07
80   FIX 1
81   "RI="
82   ARCL X
83   "┤PPM"
84   AVIEW
85   END
```

If the operator of the Micromin wishes to apply meteorological correction to the readings made, then the HP41CV program listed here can be used to calculate the refractive index.

The meteorological measurements necessary can be made with a barometer to measure pressure, and a psychrometer to measure the wet and dry-bulb temperatures.

A more accurate determination of the RI can be made by measuring the meteorological conditions at both instruments, the calculation is then performed for both sets of readings and the average of the two results is used.

Note that the Micromin already assumes a default value of 1,000 325 for the refractive index. So if a distance of D is indicated by the Micromin and a true value of, for example 1,000 375 is measured for RI, then the correction should be applied thus;

True distance = D x (1,000 325/1,000 375).

Constants and Conversions for use with the Micromin

The following constants and conversions are used in surveying and given here for convenient reference.

Velocity of radiation in vacuo,	299 792,5 Km/s	**B.5**
UK to Metric length conversion,	1 inch (UK) = 25,4 mm	**B.6**
US to Metric length conversion,	39,37 inches (US) =1 m	**B.7**
Temperature Conversion,	Kelvin = °C + 273,16 °C = 5/9 x (°F-32)	**B.8**
Pressure Conversion, (1 millibar = 100 Pascals)	1 bar = 29,53 in Hg 1 millibar = 0,750 062 mm Hg	**B.8**

References for the Formulae

B.1 & B.5	Essen, L. & Froome, K.D. "Bulletin Geodesique, New Series, Number 58", 1 Dec 1960, page 413 International Union of Geodesy & Geophysics.
B.2, B.4 & B.8	List R.J., "Smithsonian Meteorological Tables", 6th Revised Edition, page 366 Smithsonian Institution Press, Washington.
B.3	Weather Bureau, Pretoria.
B.6	Kaye, G.W.C. & Laby, T.H. (1975) "Table of Physical & Chemical Constants, 14th edition" Longmanns, page 11.
B.7	Kaye, G.W.C. & Laby, T.H. (1962), "Table of Physical & Chemical Constants, 12th edition" Longmanns, page 2.

APPENDIX C

Field-Trial Results

The field-trials described were performed to evaluate the cyclic error, accuracy and range performance of the prototype instruments.

Cyclic Error

As described in Chapter 6, cyclic error is caused by contamination of the recovered Comparison-Signal with signals internal to the Tellurometer. Such contamination affects the resultant phase of the Comparison-Signal such that it does not vary linearly in phase with change in distance. The Fine-Pattern of the Micromin is 20 MHz, and can be expected to give errors of a cyclic nature with a cycle of error every wavelength of this frequency, i.e. every 14,990 m.

An experiment was set up where the two instruments were separated by approximately 100 m, over a grass surface. The instruments were placed close to the ground to avoid any ground-reflections that might affect the readings. The Master instrument was moved along a straight line towards the Remote in steps of 0,5 m at a time. The 0,5 m steps were measured with a 5 m tape measure. Six readings were made at each of 32 positions, the Master being moved a total of 15,5 m.
The accuracy of this experiment was limited by the positioning of the Master instrument; it is estimated that the placement was performed with an accuracy of ±2 cm.

The results of this exercise shown in Fig.C-1, show no evidence of a 15 m cycle of error, and that the distance was determined with a tolerance of 6 cm peak-to-peak. Scatter found between successive determinations of each distance was a maximum of 3 cm.

```
Cyclic-Error, Plessey Sports Field        Date....3 Aug 1987
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

::::::::::::::::::::0,5 m Increments::::::::::::::::::::

99.24   99.24   99.25   Average   99.243          98.75   98.76   98.76   Average   98.752
99.24   99.25   99.24   Scatter    0.01           98.75   98.75   98.74   Scatter    0.02

98.23   98.22   98.23   Average   98.228          97.71   97.71   97.71   Average   97.722
98.24   98.21   98.24   Scatter    0.03           97.73   97.74   97.73   Scatter    0.03

97.21   97.21   97.21   Average   97.215           96.7   96.72   96.73   Average   96.723
97.21   97.23   97.22   Scatter    0.02           96.73   96.73   96.73   Scatter    0.03

96.25   96.26   96.24   Average   96.248          95.72   95.72   95.72   Average   95.723
96.26   96.24   96.24   Scatter    0.02           95.73   95.73   95.72   Scatter    0.01

95.23   95.23   95.22   Average   95.232          94.73   94.73   94.74   Average   94.727
95.24   95.23   95.24   Scatter    0.02           94.72   94.72   94.72   Scatter    0.02

94.23    94.2   94.21   Average   94.213          93.73   93.74   93.74   Average   93.730
94.22   94.21   94.21   Scatter    0.03           93.72   93.72   93.73   Scatter    0.02

93.23   93.21   93.21   Average   93.217          92.76   92.74   92.73   Average   92.752
93.21   93.22   93.22   Scatter    0.02           92.76   92.76   92.76   Scatter    0.03

92.26   92.26   92.26   Average   92.258          91.74   91.74   91.74   Average   91.740
92.25   92.26   92.26   Scatter    0.01           91.74   91.74   91.74   Scatter    0.00

91.21   91.24   91.23   Average   91.230          90.71   90.71   90.72   Average   90.710
91.23   91.23   91.24   Scatter    0.03           90.72    90.7    90.7   Scatter    0.02

90.22    90.2   90.21   Average   90.217          89.74   89.72   89.73   Average   89.723
90.22   90.23   90.22   Scatter    0.03           89.72   89.72   89.71   Scatter    0.03

89.23   89.24   89.23   Average   89.232          88.74   88.77   88.76   Average   88.755
89.23   89.23   89.23   Scatter    0.01           88.75   88.76   88.75   Scatter    0.03

88.28   88.27   88.28   Average   88.277          87.74   87.75   87.74   Average   87.743
88.29   88.27   88.27   Scatter    0.02           87.74   87.75   87.74   Scatter    0.01

87.23   87.23   87.25   Average   87.240          86.74   86.75   86.74   Average   86.743
87.24   87.24   87.25   Scatter    0.02           86.75   86.75   86.73   Scatter    0.02

86.26   86.27   86.26   Average   86.260          85.76   85.75   85.76   Average   85.765
86.25   86.25   86.27   Scatter    0.02           85.78   85.77   85.77   Scatter    0.03

85.26   85.25   85.26   Average   85.257          84.72   84.72   84.71   Average   84.713
85.26   85.26   85.25   Scatter    0.01           84.71   84.71   84.71   Scatter    0.01

84.22   84.24   84.23   Average   84.235          83.75   83.75   83.75   Average   83.752
84.23   84.24   84.25   Scatter    0.03           83.75   83.76   83.75   Scatter    0.01
```

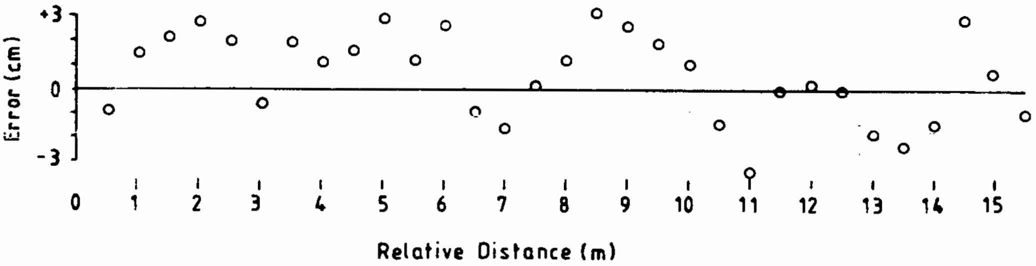


Fig.C-1, Cyclic Contamination

Accuracy, Calibration of the Instruments

To determine the accuracy of the Micromin a five standard lines were measured.
These lines are between the Plessey towers, and between three ground-level posts on the back-field of the Plessey factory site. They have been measured for many years using a wide range of distance measuring equipment. The lines are regularly calibrated with high-precision optical instruments and the distances are known to an accuracy of 1 mm.

Fig.C-2 lists the measurements of these lines and records readings between 13,9 cm and 20,6 cm greater than the true distances. The resultant correction ("zero-calibration") of the prototype instruments is taken to be the average of these five corrections, i.e. **17,3 cm**.

When 17,3 cm is subtracted from each of the measurements shown in Fig.C-2 the error is between +3,3 cm to -3,4 cm. This is consistent with the results of the Cyclic-Error test and forms the basis of the provisional accuracy specification for this instrument.

```
           Zero-Correction, Plessey Towers  Date....12 Aug 1987
           ====================================================

      S Tower, E Pole to N Tower E Pole                         S Tower, E Pole to N Tower E Pole
=================================================         =================================================

  100.19   100.13   100.13     Average   100.168            100.21   100.22   100.21     Average   100.203
  100.13   100.13   100.15     Scatter     0.06             100.21   100.23   100.21     Scatter     0.07
  100.15   100.14   100.18                                  100.25   100.25   100.23
  100.19   100.18   100.19     Actual     99.962            100.23   100.24   100.22     Actual    100.064
  100.17   100.16   100.17     =================            100.22   100.21   100.21     =================
  100.18   100.18   100.18     Zero        0.206            100.21   100.23   100.21     Zero        0.139
  100.18   100.17   100.17                                  100.20   100.20   100.21
  100.17   100.17   100.19                                  100.22   100.21   100.20
  100.15   100.16   100.17                                  100.21   100.21   100.20
  100.19   100.18   100.18                                  100.21   100.20   100.19
  100.19   100.18   100.18                                  100.20   100.19   100.20
  100.18   100.18   100.16                                  100.19   100.19   100.18
  100.18   100.19   100.19                                  100.18   100.19   100.19
  100.18   100.19   100.16                                  100.18   100.19   100.18
  100.15   100.16   100.16                                  100.20   100.18   100.19
  100.16   100.16   100.15                                  100.19   100.19   100.18
  100.16   100.16   100.17                                  100.18   100.18   100.19
  100.17   100.17   100.15                                  100.18   100.18   100.19
```

```
           Zero-Correction, Plessey Sports Field      Date....14 Aug 1987
           ============================================================

   East Post to Middle Post                                  East Post to West Post
=================================================         =================================================

   35.27    35.26    35.26     Average    35.266             83.15    83.18    83.18     Average    83.159
   35.27    35.27    35.27     Scatter     0.03              83.14    83.17    83.15     Scatter     0.04
   35.28    35.27    35.27                                   83.16    83.18    83.15
   35.26    35.27    35.28     Actual     35.099             83.16    83.18    83.16     Actual     82.960
   35.25    35.27    35.26     =================             83.15    83.17    83.16     =================
   35.27    35.28    35.26     Zero        0.167             83.17    83.16    83.14     Zero        0.199
   35.27    35.26    35.26                                   83.16    83.16    83.15
   35.27    35.27    35.28                                   83.17    83.17    83.14
   35.27    35.25    35.26                                   83.17    83.15    83.16
   35.27    35.26    35.26                                   83.16    83.16    83.15
   35.26    35.27    35.26                                   83.17    83.17    83.15
   35.27    35.27    35.26                                   83.14    83.15    83.15

                      West Post to Middle Post
                ======================================================

                   48.02    48.02    48.02          Average    48.014
                   48.01    48.01    48.02          Scatter     0.03
                   48.00    48.01    48.03
                   48.01    48.02    48.02          Actual     47.861
                   48.01    48.01    48.02          =================
                   48.01    48.00    48.01          Zero        0.153
                   48.01    48.01    48.01
                   48.01    48.02    48.01
                   48.02    48.02    48.02
                   48.01    48.01    48.02
                   48.00    48.02    48.02
                   48.03    48.01    48.00
```

Fig.C-2, Zero-Correction

Pointing Error

Error in the measured distance caused by antenna misalignment is called "pointing-error". The pointing-error of the instruments was measured by taking angle readings of pattern 7 whilst progressively pointing the Master instrument away from the Remote.

The line used was between the East pole of the South tower to the West pole of the North tower where the instruments were 100,064 m apart.

The Remote instrument was kept aimed directly at the Master, the Master instrument was aimed between 40 degrees to the left and 40 degrees to the right of the Remote, in steps of 10 degrees.
The results are shown in Fig.C-3.
The angle readings are converted to a relative distance reading shown on the right-hand side of the graph.

There is a "well-behaved" characteristic between ±30 degrees with -5 cm error. If the instrument is aligned to within ±10 degrees then there is typically 1 cm error.

```
                  Pointing Error, Plessey Towers      Date....12 Aug 1987
                  ===============================================

                         S.Tower, E.Pole to N.Tower, W.Pole
                         ==============================

                  Measuring Angle of Pattern 7 (3,747 m Ambiguity)

==================LEFT==================CENTRE================RIGHT==================
 -40 deg  -30 deg  -20 deg -10 deg   0 deg   10 deg   20 deg   30 deg   40 deg

    274      262      263     263     262      263      262      264      273
    271      261      265     266     266      264      263      266      275
    278      265      261     264     266      257      260      260      275
    271      262      263     266     269      266      254      264      276
    271      261      259     268     266      265      262      263      274
    275      259      261     264     265      265      260      264      276
    274      261      262     261     267      265      261      264      274
    273      259      264     265     264      265      261      264      274
    273      261      261     264     266      265      261      264      274
    271      259      262     265     264      264      257      261      274
    273      262      262     262     263      263      261      262      276
    274      259      261     264     267      263      260      262      274
=====================================================================================
  273.2    260.9    262.0   264.3   265.4    263.8    260.2    263.2    274.6 Average (degrees)
      7        6        6       7       7        9        9        6        3 Scatter (degrees)
    3.5      4.0      4.5     5.0     5.0      5.0      4.5      4.0      3.5 Signal Strength
```

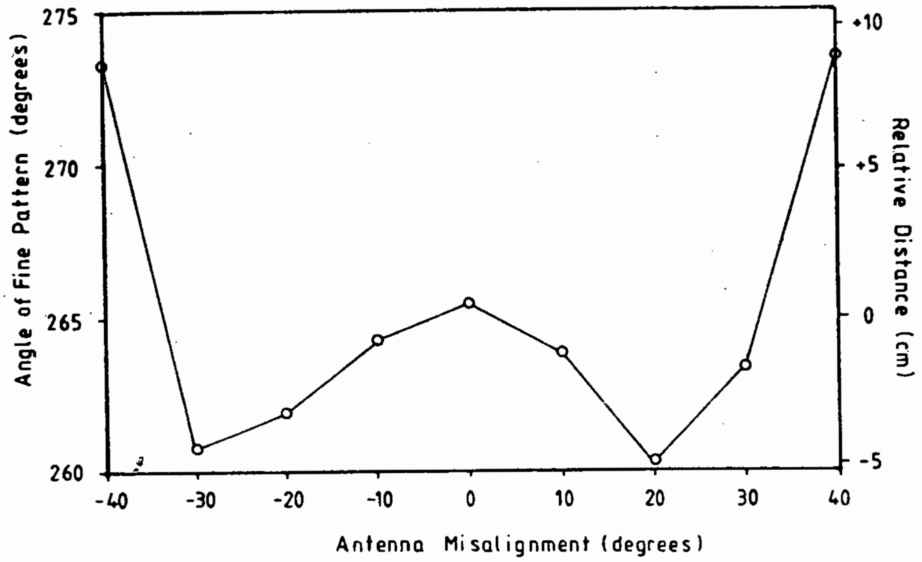


Fig.C-3, Pointing Error

Analysis of Each Pattern

The accuracy of measurement of the eight patterns and the binary ratio between the patterns was measured over a standard line.
The line used was between the Plessey towers, from the East pole of the South Tower, to the East pole of the North tower, a distance of 99,962 m.

Fig.C-4 shows the results of each pattern angle being measured thirty times.

The average is shown at the right of each set of readings. When this average is multiplied by the appropriate pattern ratio (x2, x4 or x8) the "prediction" of the next pattern can be seen to be in agreement with the result of the next pattern.

The tolerance with which the patterns are fitted together is ±90 degrees, this can be seen on line 788 of the software listing.

```
                 Pattern Analysis, Plessey Towers       Date....12 Aug 1987
                 ::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

          S.Tower, E.Pole to N.Tower, E.Pole (99,962 m): Pattern Angles in degrees
          ::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

Pattern 0          2,441 kHz, 61 397,503 m
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
     0      1       0     358     357     359           Average      -0.3
   357      0       0       0       0       0           Scatter         9
   356      3       0       0       0       0
     0      0     357     358     357       0           times 4
   359      5       0       0       0       3           predicts     -1.2

Pattern 1          9,675 kHz, 15 349,376 m
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
     4      2       2       2       3     355           Average       2.1
     4      3       7       3       0       0           Scatter        13
     2      3     356       0       3     357
     2      2       4       3       5       2           times 4
     3      2       2       2       3       8           predicts      8.4

Pattern 2          39,062 kHz, 3 837,344 m
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
    10     10       7      10       6       8           Average       9.2
     9      8       9       9       9       6           Scatter        10
    14      6       9      10      12      12
     5      9       7      10      10      10           times 4
    11     12       6      15      10       8           predicts     36.8

Pattern 3          156,25 kHz, 959,336 m
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
    37     39      40      36      37      41           Average      38.2
    40     38      37      37      41      38           Scatter        14
    35     38      33      38      35      37
    37     39      37      38      39      40           times 4
    38     38      43      37      35      47           predicts    152.8

Pattern 4          625 kHz, 239,834 m
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
   151    150     150     150     149     151           Average     149.5
   150    147     151     151     151     151           Scatter         6
   150    150     149     149     151     149
   150    149     150     148     145     150           times 2
   147    148     150     151     150     146           predicts    299.0

Pattern 5          1,25 MHz, 119,917 m
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
   307    308     309     298     305     310           Average     307.0
   299    306     304     309     305     309           Scatter        13
   309    305     309     306     308     308
   306    306     308     308     309     307           times 8
   309    306     311     308     307     310           predicts    296.0

Pattern 6          10 MHz, 14,990 m
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
   245    245     244     248     244     244           Average     245.3
   245    245     244     245     245     245           Scatter        15
   244    245     245     244     245     243
   246    244     246     239     246     254           times 4
   254    245     247     249     239     245           predicts    261.2

Pattern 7          2 x 20 MHz, 3,747 m
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
   261    272     268     264     258     266           Average     262.8
   262    263     263     261     262     261           Scatter        15
   263    262     257     258     262     263
   262    263     262     263     265     263
   261    262     265     262     267     262
```

Fig.C-4, Pattern Analysis

Range Performance

As calculated in Chapter 3 the range of the Micromin is approximately 15 km. This has been shown to be the case and range trial results are shown in Fig.C-5 showing signal-strength as a function of distance.

In order to maximise the range-performance of the prototype instruments, the matching of the source mixer assemblies was optimised by fitting waveguide shims between the Gunn source and the mixer assembly. In this way reflections from the Gunn source are used as constructive interference to augment the received signal. This was done by measuring the signal-strength output voltage with a digital voltmeter and fitting shims of varying thickness and noting the trend in received signal-strength. The shims inserted were up to 30 mm deep, and the additions were made in steps of 1 mm. Both instruments were adjusted in this manner.

A signal improvement of 3,5% was achieved in the Master by fitting 6 mm of shims. A change in signal-strength reading from 2 to 9 is equivalent to a change in input signal level from 10 µV to 1 mV, (from Fig.C-5). This is a 40 dB change in signal amplitude for a 70% change in meter reading. The meter thus responds at 5,7 dB/division, or 0,57 dB/% of full scale deflection. From this it follows that a change of 3,5% is equivalent to an increase of 2,0 dB.
Likewise, a signal improvement of 3,85% was achieved at the Remote by fitting 3 mm of shims, this is equivalent to 2,2 dB improvement.

The signal-strength meters of the instruments were calibrated by injecting a 1,5 mV, 10,76 MHz signal into each IF (from a signal generator), and adjusting R23 of the IF (see Fig.3-9) for full-scale-deflection of the signal-strength meter.
With the IFs calibrated this way the response of the signal-strength meters to a signal varying from 3 µV to 1,5 mV is as shown by the △ and o symbols in Fig.C-5.

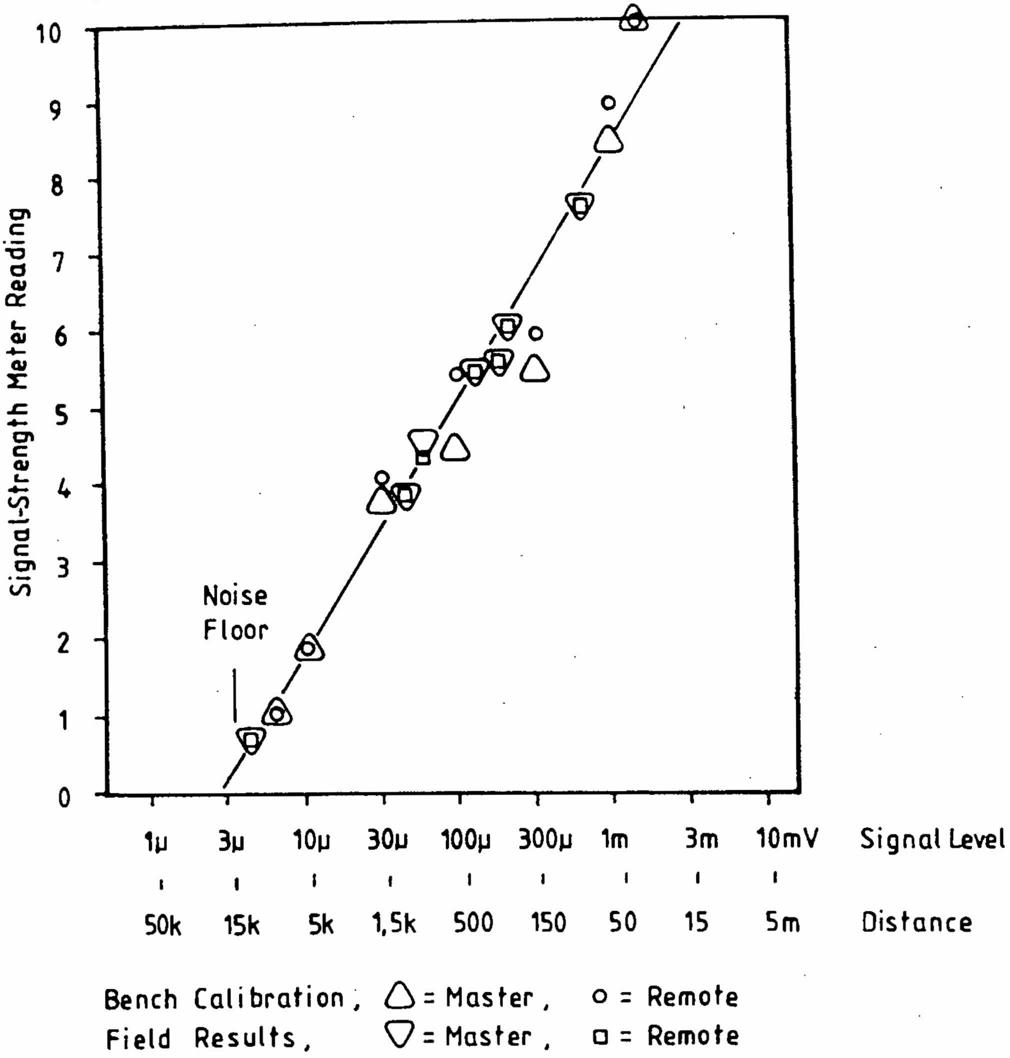


Fig.C-5, Range Performance

The equivalent distance for this range of voltages was calculated as for the analysis of the "Dynamic Range of the Receiver" in Chapter 3, and is shown by the "Distance" abscissa of Fig.C-5.
This calculated-function of signal strength vs. distance was then compared with the signal-strength readings found at various ranges in the field. These results are shown by the ▽ and □ symbols in Fig.C-5, and as can be seen there is agreement between the theory and the field results.

At 10 Km the instruments tune in and work with a good signal to noise ratio but fall out of tune easily during measurement.

At 25 Km the instruments were unable to tune in, although at the Master instrument there was a faint sound of the Remote sweeping through the band. The Master signal received by the Remote was not strong enough to halt the Autotune sweep.

It has been the experience of the author that with prototype instruments, in any development of this nature, the first pair of instruments invariably do not perform as well as later models due to an accumulation of many small shortcomings in performance. This is particularly so with long-range performance, and it is felt that if more instruments are made, these models could improve on the performance of the prototypes.

An alternative mixer arrangement using horizontal polarisation in one instrument and vertical polarisation in the other would offer an improvement in range performance. There would be no receiver losses due to an offset of the mixer diode from the centre of the waveguide, and there would be less absorption of transmitted power. These two factors would give approximately an extra 6 dB signal strength, doubling the range performance to 30 Km. This could be achieved by tapering the horn to a square waveguide to accommodate the mixer diode assembly, and then tapering down to rectangular waveguide to mate with the Gunn source. The Gunn source in one instrument would then have to be turned through 90 degrees. This extra complexity would increase the materials cost of the instruments, but may very well be worthwhile.
Such a change could be made if further commercial interest were shown in this design as a marketable product, and market-research were to suggest an increase in range was necessary.

APPENDIX D

Software Listing

The following assembled software listing is the latest version of the Micromin program, written in assembly language. The processor used is a Hitachi 63701VOC; the microprocessor hardware and software is described in Chapter 5.

The memory map of the microprocessor is shown in Fig.D-1.

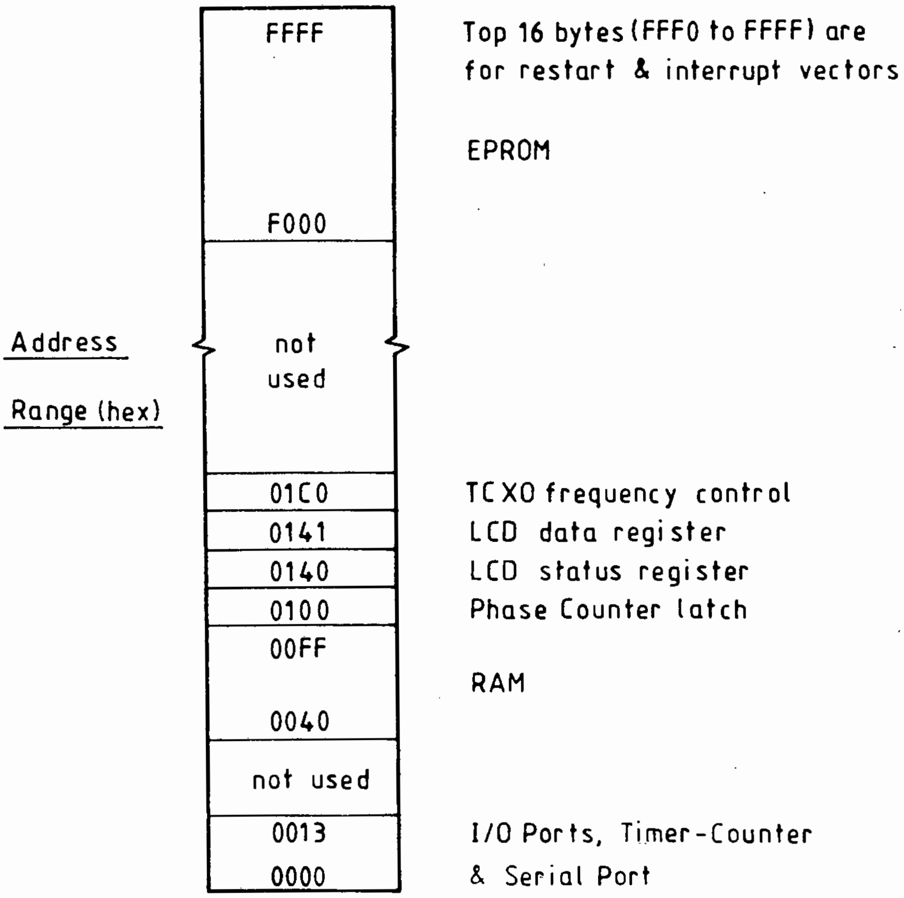


Fig.D-1, Memory Map of the Microprocessor

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                       1 "6801"
                       2
                       3 *      ******************************************
                       4 *      *                                        *
                       5 *      * Author      Mark Marsden               *
                       6 *      * Title       Micromin                   *
                       7 *      * Issue       1.00                       *
                       8 *      * Date        September 1987             *
                       9 *      *                                        *
                      10 *      *                                        *
                      11 *      ******************************************
                      12 *
                      13 *
                      14 * set interrupt vectors
                      15
                      16        ORG     0FFF0H
  FFF0 F04A           17        FDB     RESTRT   keyboard int
  FFF2 F042           18        FDB     LONGTM   timer overflow
  FFF4 F038           19        FDB     OCI      timer output compare
  FFF6 F04A           20        FDB     RESTRT   timer input compare
  FFF8 F041           21        FDB     IRQ      irq
  FFFA F04A           22        FDB     RESTRT   swi
  FFFC F041           23        FDB     NMI      nmi
  FFFE F04A           24        FDB     RESTRT   reset
                      25
                      26 *      memory mapped devices
                      27
          <01C0>      28 DTOA   EQU     1C0H     tcxo
          <0100>      29 PHSCNT EQU     100H     phase counter latch
          <0140>      30 STATUS EQU     140H     lcd status
          <0141>      31 LCD    EQU     141H     lcd data
          <0180>      32 SYNEN  EQU     180H     synthesiser enable data strobe
                      33
                      34
                      35        ORG     0
                      36
  0000                37 DDR1   RMB     1        data direction reg 1
  0001                38 DDR2   RMB     1        data direction reg 2
  0002                39 PORT1  RMB     1        port 1
  0003                40 PORT2  RMB     1        port 2
  0004                41 DDR3   RMB     1        data direction reg 3
  0005                42 DDR4   RMB     1        data direction reg 4
  0006                43 PORT3  RMB     1        port 3
  0007                44 PORT4  RMB     1        port 4
  0008                45 TCSR   RMB     1        timer con/stat reg
  0009                46 CNTR   RMB     2        counter
  000B                47 OCR    RMB     2        output compare reg
  000D                48 ICR    RMB     3        input capture reg
  0010                49 RMCR   RMB     1        rate/mode cont reg
  0011                50 TRCSR  RMB     1        tx/rx con & stat reg
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

    0012                 52 RXDATA RMB    1        rx data reg
    0013                 53 TXDATA RMB    1        tx data reg
                         54
                         55        ORG    40H
                         56
    0040                 57 XTEMP  RMB    2        temp store for x reg
    0042                 58 COUNT  RMB    2        temp store for counter
    0044                 59 XTEMP1 RMB    2        temp store for x reg
    0046                 60 ERROR0 RMB    1        error flag for phase measurement
    0047                 61 COUNTR RMB    1        counter/flag for measurement routines
    0048                 62 PHSTOT RMB    2        partial result from PATFAS
    004A                 63 DELPHS RMB    2        slip measured in PATFAS
    004C                 64 STRDL1 RMB    2        location for saving 1st straddle patt phase
    004E                 65 DIFPHS RMB    2        location for saving difference patt phase
    0050                 66 STRDL2 RMB    2        location for saving 2nd straddle patt phase
    0052                 67 PRVPHS RMB    2        location for saving previous phase
    0054                 68 REMST1 RMB    2        for master to store remote st1-ref phase
    0056                 69 REMST2 RMB    2        for master to store remote st2-ref phase
    0058                 70 PATPHS RMB    2        location for resultant pattern phase in meas
                         71 * patphs is used as 3 bytes in AVERAG spilling over into ADDHLF
    005A                 72 ADDHLF RMB    2        counter for phase ambiguity correction
    005C                 73 SUBHLF RMB    2        counter for phase ambiguity correction
    005E                 74 DIST   RMB    5        distance (or phase)
    0063                 75        RMB    3        3 bytes for dhifting NEWDST into
    0066                 76 SPEED  RMB    5        speed (or phase change in 1/8 s)
    006B                 77 PATCNT RMB    1        pattern counter
    006C                 78 FINALP RMB    1        final pattern
    006D                 79 SYNC   RMB    1        sync flag, set every time an OCI occurs
    006E                 80 SYNCH  RMB    2        used with SYNC to store time derived from CNTR
    0070                 81 TEMPER RMB    1        temp storage of ERROR0 count
    0071                 82 SIDSLP RMB    1        # places RANGE is shifted left
    0072                 83        RMB    3        space to shift RANGE left
    0075                 84 RANGE  RMB    5        range as measured in this breakout
    007A                 85 AMBIGF RMB    1        ambiguity flag used in AVDIST
    007B                 86 CHKSUM RMB    1        holds checksum for data tx/rx'd
    007C                 87 MEASKY RMB    1        key code entered during measurement
    007D                 88 MANUAL RMB    1        manual meas flag - no breakout if <>0
    007E                 89 BROKEN RMB    1        flag set <> 0 if b'kout completed in stake
    007F                 90 RELREG RMB    3        ram area if MANT is called from eprom
    0082                 91 MANT   RMB    3        mantissa
    0085                 92 EXP    RMB    1        exponent
    0086                 93 SIGN   RMB    1        sign of mantissa
    0087                 94 IXP    RMB    2        index register pointer
                         95 INTBIN SET    MANT     int part of fixed point number
                         96 FRBIN  SET    EXP      frac part
    0089                 97 SAVEX3 RMB    2        temp storage for X reg
    008B                 98 SAVEX2 RMB    2          "      "      "    "
    008D                 99        RMB    2          "      "      "    "
    008F                100        RMB    2          "      "      "    "
    0091                101 COUNT1 RMB    3
    0094                102 DBUF1  RMB    11       usually dispaly data
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

  009F                104 DPNT1  RMB    1         1st point associated with DBUF1
  00A0                105 DPNT2  RMB    1         2nd  "     "     "    "
  00A1                106 STAKEF RMB    1         flag set to indicate stakeout mode
  00A2                107 STPCNT RMB    1         number of measurements on this pattern
  00A3                108 LIST   RMB    32        list of pattern phases on repeated readings
  00C3                109 LNGTIM RMB    1         timer extension
  00C4                110 SYNREG RMB    5         holds data loaded into synth
                      111
                      112        ORG    0F000H
                      113
                      114 *             ************************
                      115 *              SYNTHESISER DATA TABLE
                      116 *             ************************
                      117
                      118 * reference pattern data
                      119
  F000 A000A000       120 INITSY FCB    0A0H,0,0A0H,0                20,000 MHz mod-off
  F004 1FF9200928     121 PATTAB FCB    01FH,0F9H,020H,009H,028H   20-M+2k44
  F009 1FFC200C28     122        FCB    01FH,0FCH,020H,00CH,028H   20-M+9k76
  F00E 2008201828     123        FCB    020H,008H,020H,018H,028H   20-M+39K06
  F013 2038204828     124        FCB    020H,038H,020H,048H,028H   20-M+156k25
  F018 20F8210828     125        FCB    020H,0F8H,021H,008H,028H   20-M+625k
  F01D 21F8220828     126        FCB    021H,0F8H,022H,008H,028H   20-M+1M25
  F022 1FF820082C     127        FCB    01FH,0F8H,020H,008H,02CH   10-M+10M
  F027 1FF8200830     128        FCB    01FH,0F8H,020H,008H,030H   20-M
                      129
                      130 * straddle pattern data
                      131
  F02C 1FF82008       132        FCB    01FH,0F8H,020H,008H        20-M
  F030 5FF06010       133        FCB    05FH,0F0H,060H,010H        10-M
  F034 20081FF8       134        FCB    020H,008H,01FH,0F8H        20+M
                      135
                      136 *      constants for measuring routines
                      137
                      138 *  !_MSTTIM_!_PHSTIM_!_PHSTIM_!_RXTIM________!_CYCTIM_!
                      139 *  !rx,synth!straddl1!cent-phs!straddl2,,rx-data,calc.!
                      140 *  0  20     49,2     113,2   177,2          !237,2   300 ms
                      141 *                                           !latest start
                      142 *                                           !of 2nd rx byte
                      143
                      144 * times in E-cycles (1,0 us) till/between-
         <C350>       145 MSTIM1 EQU    50000     phase can be measured in M 69,2 ms
         <4B00>       146 MSTIM2 EQU    19200
                      147 * 69,2 = 48,6(rem) + 20(data-lead-in) + 0,6(propogation delay)
         <BDD8>       148 REMTIM EQU    48600     phase can be measured in R 48,6 ms
         <FA00>       149 PHSTIM EQU    64000     phase measurements (64 ms)
         <EA60>       150 RXTIM  EQU    60000     rx phase data return from rem 60ms
         <A730>       151 CYCTIM EQU    42800     beginning of next frame 42,8ms
                      152
         <0050>       153 PATCOM EQU    050H      command to tx patterns
                      154 *                       (ls 4 bits hold pattern number)
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     156
                     157 *          ************************
                     158 *           SUBROUTINE NMI,IRQ,OCI
                     159 *          ************************
                     160
                     161 * routine services timer output compare ints
  F038 9608          162 OCI   LDAA  08H     dummy read of TCSR
  F03A DC08          163       LDD   0BH     & dummy write to OCR
  F03C DD0B          164       STD   0BH     to clear OCF flag
  F03E 7A006D        165       DEC   SYNC    SET SYNC FLAG
  F041               166 NMI
  F041 3B            167 IRQ   RTI           return
                     168
                     169 *          *******************
                     170 *           SUBROUTINE LONGTM
                     171 *          *******************
                     172
                     173 * timer overflow int routine increments LNGTIM which
                     174 * forms an 8-bit extension to the timer (period=16,77 s @ 4 MHz)
                     175
  F042 9608          176 LONGTM LDAA 08H     dummy read TCSR & counter
  F044 DC09          177       LDD   09H     to reset Timer Overflow Flag
  F046 7C00C3        178       INC   LNGTIM  increment LNGTIM when timer overflows
  F049 3B            179       RTI
                     180
                     181 *          *******************
                     182 *           SUBROUTINE RESTRT
                     183 *          *******************
                     184
                     185 * init system
                     186
  F04A 8E00FF        187 RESTRT LDS  #0FFH   init stack pointer
  F04D 867E          188       LDAA  #7EH
  F04F 9700          189       STAA  DDR1    port1 I/O direction
  F051 864E          190       LDAA  #4EH
  F053 9702          191       STAA  PORT1   init port1
  F055 86C1          192       LDAA  #0C1H   1,2,3,4,& 5 as inputs
  F057 9705          193       STAA  DDR4
  F059 8614          194       LDAA  #014H
  F05B 9701          195       STAA  DDR2    timer, clock, serial data output
  F05D 8609          196       LDAA  #09H
  F05F 9710          197       STAA  RMCR    nrz; clock = 7812 Hz
  F061 861A          198       LDAA  #1AH
  F063 9711          199       STAA  TRCSR   tx/rx enabled
  F065 860C          200       LDAA  #0CH
  F067 9708          201       STAA  TCSR    tof enabled
                     202 * init tcxo to centre of range
  F069 8664          203       LDAA  #100
  F06B F601C0        204 TCXO_1 LDAB DTOA    read 100 times
  F06E 4A            205       DECA
  F06F 26FA          206       BNE   TCXO_1
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

   F071 8632          208          LDAA   #50
   F073 F701C0        209 TCXO_2 STAB   DTOA     write 50 times
   F076 4A            210          DECA
   F077 26FA          211          BNE    TCXO_2
                      212
                      213 * init synth
   F079 CEF000        214          LDX    #INITSY
   F07C BDF87D        215          JSR    SYNTH
                      216
                      217 * if we are a master then init the datalink
   F07F 9602          218          LDAA   PORT1
   F081 8480          219          ANDA   #80H
   F083 271D          220          BEQ    REMOTE
   F085 9602          221          LDAA   PORT1
   F087 84FD          222          ANDA   #0FDH    P11 low
   F089 9702          223          STAA   PORT1
                      224
                      225 * init the lcd
   F08B CEF1A7        226          LDX    #LCDSET
   F08E C604          227          LDAB   #4
   F090 A600          228 NEXT     LDAA   X
   F092 B70140        229          STAA   STATUS
   F095 BDF50C        230          JSR    WORM_W
   F098 08            231          INX
   F099 5A            232          DECB
   F09A 26F4          233          BNE    NEXT
                      234
                      235 * display introductory message on lcd
   F09C CEF197        236          LDX    #MESSG1
   F09F BDF1AB        237          JSR    LCDMSG
                      238
                      239 * wait for 1 second
   F0A2 8604          240 REMOTE LDAA   #4
   F0A4 CE0000        241          LDX    #0
   F0A7 09            242 WAIT2    DEX
   F0A8 26FD          243          BNE    WAIT2
   F0AA 4A            244          DECA
   F0AB 26FA          245          BNE    WAIT2
                      246
                      247 * switch off the synth to conserve battery
   F0AD 9602          248          LDAA   PORT1
   F0AF 84BF          249          ANDA   #0BFH    P16 low
   F0B1 9702          250          STAA   PORT1
                      251 * dummy reads
   F0B3 9611          252          LDAA   TRCSR
   F0B5 9612          253          LDAA   RXDATA
                      254 * init distance display to 'no dist'
   F0B7 86FF          255          LDAA   #0FFH
   F0B9 975E          256          STAA   DIST
                      257 * clear the interrupt mask
   F0BB 0E            258          CLI
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     260 * link monitor routine LINK
                     261
   F0BC 9602         262 LINK   LDAA   PORT1
   F0BE 8480         263        ANDA   #80H
   F0C0 2744         264        BEQ    RLINK
                     265
                     266 * master:
                     267 * enable the datalink
                     268
   F0C2 9602         269 MLINK  LDAA   PORT1
   F0C4 8A04         270        ORAA   #04H     P12  trdata high
   F0C6 84FD         271        ANDA   #0FDH    P11  muteda low
   F0C8 9702         272        STAA   PORT1
                     273 * IF the test line is low THEN do test
   F0CA 9607         274        LDAA   PORT4
   F0CC 8420         275        ANDA   #20H
   F0CE 2603         276        BNE    NOTEST
   F0D0 BDF1BF       277        JSR    TEST
                     278 * IF the meas line is low THEN
   F0D3 9607         279 NOTEST LDAA   PORT4
   F0D5 8402         280        ANDA   #02H     P41
   F0D7 2625         281        BNE    SYNOFF
                     282 * .contact debounce for 20 ms
   F0D9 CE1388       283        LDX    #5000
   F0DC 09           284 D_BNC  DEX
   F0DD 26FD         285        BNE    D_BNC
                     286 * wait for meas to go high again
   F0DF 9607         287 SW_UP  LDAA   PORT4
   F0E1 8402         288        ANDA   #02H
   F0E3 27FA         289        BEQ    SW_UP
                     290 * IF the track line is low (Pin 27 of 6301) THEN.
   F0E5 9607         291        LDAA   PORT4
   F0E7 8404         292        ANDA   #04H
   F0E9 2605         293        BNE    TESTMS
                     294 * .start stakeout
   F0EB BDF241       295        JSR    STAKE
   F0EE 200E         296        BRA    SYNOFF
                     297 * .ELSE IF the test line is low THEN
   F0F0 9607         298 TESTMS LDAA   PORT4
   F0F2 8420         299        ANDA   #20H
   F0F4 2605         300        BNE    STATMS
                     301 * .start the manual breakout
   F0F6 BDF25E       302        JSR    VELCTY
   F0F9 2003         303        BRA    SYNOFF
                     304 * ELSE start static meas
   F0FB BDF24F       305 STATMS JSR    STATIC
                     306 * ELSE switch off the synth
   F0FE 9602         307 SYNOFF LDAA   PORT1
   F100 84BF         308        ANDA   #0BFH   P16 low
   F102 9702         309        STAA   PORT1
   F104 20BC         310        BRA    MLINK
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                      312 * remote:
                      313 * this routine listens for a message from the master
                      314 * wait for data (pin 26,carrier detect falling)
                      315
  F106 96C3           316 RLINK  LDAA   LNGTIM    init timer
  F108 8B06           317        ADDA   #6        (300 ms)
  F10A 9791           318        STAA   COUNT1
  F10C 9602           319 RLOOP  LDAA   PORT1
  F10E 8A02           320        ORAA   #02H      P11 high
  F110 9702           321        STAA   PORT1     ensure own datalink off
  F112 CE0280         322        LDX    #640      2,5 ms for data decay
  F115 09             323 PATNCE DEX
  F116 26FD           324        BNE    PATNCE
  F118 C608           325        LDAB   #08H      08 while waiting for rising edge
                      326
                      327 * IF the TEST line is low THEN do test
  F11A 9607           328 EDGE   LDAA   PORT4
  F11C 8520           329        BITA   #20H
  F11E 2603           330        BNE    TMROW
  F120 BDF1BF         331        JSR    TEST
  F123 96C3           332 TMROW  LDAA   LNGTIM    time up?
  F125 9191           333        CMPA   COUNT1
  F127 2B0C           334        BMI    EDGE2
                      335
                      336 * A timeout has occured, the instruments are out of tune
                      337 * or the measurement has finished. Switch off the synth.
  F129 9602           338        LDAA   PORT1
  F12B 84BF           339        ANDA   #0BFH     P16 low
  F12D 9702           340        STAA   PORT1
  F12F 96C3           341        LDAA   LNGTIM    restart the timer (200 ms)
  F131 8B05           342        ADDA   #5
  F133 9791           343        STAA   COUNT1
  F135 9607           344 EDGE2  LDAA   PORT4     look for the falling edge of CDET
  F137 8408           345        ANDA   #08H
  F139 11             346        CBA
  F13A 26DE           347        BNE    EDGE
  F13C C008           348        SUBB   #08H
  F13E 27DA           349        BEQ    EDGE      eq hi detected, now wait for low
                      350
                      351 * start the timer to time out audio mute
  F140 96C3           352        LDAA   LNGTIM
  F142 8B06           353        ADDA   #6
  F144 9791           354        STAA   COUNT1
                      355
                      356 * IF the TEST line is low THEN do test
  F146 9607           357 BYTCUM LDAA   PORT4
  F148 8520           358        BITA   #20H
  F14A 2603           359        BNE    NO_TST
  F14C BDF1BF         360        JSR    TEST
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     362 * rx the data, wait for the falling edge of rxdata
  F14F 9607          363 NO_TST LDAA   PORT4
  F151 8410          364        ANDA   #10H      RX DATA pin 25?
  F153 270E          365        BEQ    GOT_IT
  F155 96C3          366        LDAA   LNGTIM    has the timer timed out yet?
  F157 9191          367        CMPA   COUNT1
  F159 26EB          368        BNE    BYTCUM    no, carry on
  F15B 9602          369        LDAA   PORT1     yes, switch off the synth
  F15D 84BF          370        ANDA   #0BFH
  F15F 9702          371        STAA   PORT1     P16 low
  F161 20E3          372        BRA    BYTCUM
                     373
  F163 DC09          374 GOT_IT LDD    CNTR
  F165 DD6E          375        STD    SYNCH
  F167 7F0046        376        CLR    ERROR0
  F16A BDF9E3        377        JSR    RXINFO
  F16D 7D0046        378        TST    ERROR0
  F170 2703          379        BEQ    OKTOGO
  F172 7EF10C        380        JMP    RLOOP     if data error - keep waiting
  F175 17            381 OKTOGO TBA
                     382
                     383
                     384 * IF data was command to measure THEN note pattern no.
                     385 * & start measure task
  F176 84F0          386        ANDA   #0F0H      top bits define command
  F178 8150          387        CMPA   #PATCOM
  F17A 2618          388        BNE    DONTMS
  F17C C40F          389        ANDB   #0FH      save pattern number
  F17E D76B          390        STAB   PATCNT
                     391 * switch off the remote datalink
  F180 9602          392        LDAA   PORT1
  F182 8A02          393        ORAA   #02H     P11 high
  F184 9702          394        STAA   PORT1
                     395 * switch on the synth
  F186 9602          396        LDAA   PORT1
  F188 8A40          397        ORAA   #40H     P16 high
  F18A 9702          398        STAA   PORT1
  F18C CEF000        399        LDX    #INITSY
  F18F BDF87D        400        JSR    SYNTH
  F192 8D77          401        BSR    REM
  F194 7EF106        402 DONTMS JMP    RLINK
                     403
  F197 2A2A2A204D    404 MESSG1 ASC    "*** MICROMIN ***"
  F1A7 34060C01      405 LCDSET FCB    34H,6,0CH,1
```

```
                407 *             *******************
                408 *              SUBROUTINE LCDMSG
                409 *             *******************
                410
                411 * The 16 ascii charachter message is pointed to by
                412 * the index register; display it on the lcd.
                413
  F1AB 8601     414 LCDMSG LDAA   #1
  F1AD B70140   415        STAA   STATUS
  F1B0 C610     416        LDAB   #16
  F1B2 BDF50C   417 DSP_1  JSR    WORM_W
  F1B5 A600     418        LDAA   X
  F1B7 B70141   419        STAA   LCD
  F1BA 08       420        INX
  F1BB 5A       421        DECB
  F1BC 26F4     422        BNE    DSP_1
  F1BE 39       423        RTS
                424
                425 *             *****************
                426 *              SUBROUTINE TEST
                427 *             *****************
                428
                429 * switch on the synth & the modulation
  F1BF 9602     430 TEST   LDAA   PORT1
  F1C1 8A40     431        ORAA   #40H
  F1C3 84F7     432        ANDA   #0F7H
  F1C5 9702     433        STAA   PORT1
                434
                435 * init PATCNT to 0
  F1C7 7F006B   436 TESTRT CLR    PATCNT
                437
                438 * wait for the falling edge of the test line
  F1CA 9607     439 TSTDN  LDAA   PORT4
  F1CC 8420     440        ANDA   #20H
  F1CE 26FA     441        BNE    TSTDN
                442
                443 * debounce for 40 ms
  F1D0 CE2710   444        LDX    #10000
  F1D3 09       445 TSTBNC DEX
  F1D4 26FD     446        BNE    TSTBNC
                447
                448 * wait for the rising edge of the test line
  F1D6 9607     449 TSTUP  LDAA   PORT4
  F1D8 8420     450        ANDA   #20H
  F1DA 27FA     451        BEQ    TSTUP
                452 * calculate the address of the synth data
  F1DC CEF004   453        LDX    #PATTAB
  F1DF 8605     454        LDAA   #5
  F1E1 D66B     455        LDAB   PATCNT
  F1E3 3D       456        MUL
  F1E4 3A       457        ABX
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                        459 * IF we are on patt 7 THEN
   F1E5 8607            460         LDAA   #7
   F1E7 916B            461         CMPA   PATCNT
   F1E9 2603            462         BNE    USUAL
                        463
                        464 * the reference of patt 7 is the same as patt 6
                        465 * so use this opportunity to test the 10 MHz
                        466 * straddle for patt 6
   F1EB C609            467         LDAB   #9
   F1ED 3A              468         ABX
                        469
                        470 * ELSE load the synth
   F1EE BDF87D          471 USUAL  JSR    SYNTH
                        472
                        473 * wait for 100 ms
   F1F1 CE61A8          474         LDX    #25000
   F1F4 09              475 SYNFIN DEX
   F1F5 26FD            476         BNE    SYNFIN
                        477
                        478 * IF master THEN display the pattern #
   F1F7 9602            479         LDAA   PORT1
   F1F9 8580            480         BITA   #80H
   F1FB 2703            481         BEQ    WRONG1
   F1FD BDF4F5          482         JSR    WORM
                        483
                        484 * increment the pattern #, (rollover to 0 after 7)
   F200 966B            485 WRONG1 LDAA   PATCNT
   F202 4C              486         INCA
   F203 8107            487         CMPA   #FINEP
   F205 2EC0            488         BGT    TESTRT
   F207 976B            489         STAA   PATCNT
   F209 20BF            490         BRA    TSTDN
                        491
                        492 *              ****************
                        493 *               SUBROUTINE REM
                        494 *              ****************
                        495
                        496 * If the instrument is a remote,
                        497 * it will execute this routine on command from the
                        498 * MEAS routine running in the master
                        499
                        500 * set up the OCR so that SYNC will be set at the right time
   F20B DC6E            501 REM    LDD    SYNCH
   F20D C3BDD8          502         ADDD   #REMTIM
   F210 DD6E            503         STD    SYNCH
   F212 DD0B            504         STD    OCR
   F214 7F006D          505         CLR    SYNC
                        506 * load pattern number
   F217 966B            507         LDAA   PATCNT
   F219 840F            508         ANDA   #0FH
   F21B 976B            509         STAA   PATCNT
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                    511 * measure phase of this pattern
   F21D BDF70D      512       JSR   PHASE
                    513 * transmit phase to master
   F220 964C        514       LDAA  STRDL1   ms 8 bits of ST1-REF
   F222 BDF982      515       JSR   TXPLUS
   F225 9650        516       LDAA  STRDL2   ms 8 bits of ST2-REF
   F227 BDF99C      517       JSR   TXINFO
   F22A 964D        518       LDAA  STRDL1+1 pack ls 2 bits ST1-REF..
   F22C 84C0        519       ANDA  #0C0H
   F22E D651        520       LDAB  STRDL2+1 ls 2 bits of ST2-REF..
   F230 57          521       ASRB
   F231 57          522       ASRB
   F232 C430        523       ANDB  #30H
   F234 1B          524       ABA
   F235 9A6B        525       ORAA  PATCNT   & pattern number
   F237 BDF99C      526       JSR   TXINFO   transmit the data &
   F23A 9602        527       LDAA  PORT1    then mute the datalink
   F23C 8A02        528       ORAA  #02H     P11 high
   F23E 9702        529       STAA  PORT1
   F240 39          530       RTS
                    531
                    532 FINEP SET   7        finest pattern (20 MHz) number
                    533
                    534 *           ******************
                    535 *            SUBROUTINE STAKE
                    536 *           ******************
                    537
                    538 * This is the entry point for stakeout
                    539 * The routine simply sets STAKEF & starts MEAS
                    540
   F241 8601        541 STAKE LDAA  #1
   F243 97A1        542       STAA  STAKEF   (to steer averaging)
   F245 8607        543       LDAA  #FINEP   select '7' as final pattern
   F247 7F007C      544       CLR   MEASKY
   F24A 7F007D      545       CLR   MANUAL
   F24D 200B        546       BRA   STAT4
                    547
                    548 *           *******************
                    549 *            SUBROUTINE STATIC
                    550 *           *******************
                    551
                    552 * This is the entry point for STATIC
                    553 * Thisroutine simply clears STAKEF & starts MEAS
                    554
   F24F 7F00A1      555 STATIC CLR  STAKEF
   F252 7F007D      556       CLR   MANUAL       clear MANUAL flag
   F255 7F007C      557       CLR   MEASKY
   F258 8607        558 STAT3 LDAA  #FINEP
   F25A 976C        559 STAT4 STAA  FINALP
   F25C 2009        560       BRA   MEAS
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                    *           *******************
                    *            SUBROUTINE VELCTY
                    *           *******************

                    * FOR TESTING this is a manual measure (angles)
                    * no breakout is incorperated

  F25E 86FF         VELCTY LDAA   #0FFH       set MANUAL flag
  F260 977D                STAA   MANUAL
  F262 7F00A1              CLR    STAKEF
  F265 20F1                BRA    STAT3

                    *           *****************
                    *            SUBROUTINE MEAS
                    *           *****************

                    * This is the entry point for MEAS. STATIC & STAKE both
                    * come here after clear/set-ing STAKEF to show
                    * which function is required

                    * home the cursor
  F267 8602         MEAS   LDAA   #2
  F269 B70140              STAA   STATUS
  F26C BDF50C              JSR    WORM_W
                    * switch on the synth
  F26F 9602                LDAA   PORT1
  F271 8A40                ORAA   #40H    P16 high
  F273 9702                STAA   PORT1
  F275 CEF000              LDX    #INITSY
  F278 BDF87D              JSR    SYNTH

                    * init SYNCH & OCR for frame timing
  F27B DC09                LDD    CNTR     read counter
  F27D C361A8              ADDD   #25000   to start in 25 ms
  F280 DD6E                STD    SYNCH    save value
  F282 DD0B                STD    OCR      set up OCR
  F284 7F006D              CLR    SYNC     clear SYNC flag
  F287 7F007E              CLR    BROKEN   clear 'breakout completed'
  F28A CE005E              LDX    #DIST    get address of distance
  F28D 6F00         INITRG CLR    0,X      clear location
  F28F 08                  INX             clear dist,speed,
  F290 8C006B              CPX    #PATCNT  patcnt.
  F293 23F8                BLS    INITRG
  F295 86FF                LDAA   #-1      accum count=-1 to cause 2 patt 0's
  F297 97A2                STAA   STPCNT
  F299 7C0046              INC    ERROR0   fake error (prevent speed 1st time)
  F29C 7F006D              CLR    SYNC     just in case that took too long

```

```
                * FOR all patterns or UNTIL aborted DO.
                * IF the switch has been pressed THEN we must stop the meas
F29F 9607       ADINF  LDAA   PORT4
F2A1 8402              ANDA   #02H     P41 low ?
F2A3 265F              BNE    AUTOBR
                * debounce for 5 ms
F2A5 CE1388            LDX    #5000
F2A8 09         DE_BNC DEX
F2A9 26FD              BNE    DE_BNC

                * put on datalink to prevent falling out of tune
F2AB 9602              LDAA   PORT1
F2AD 8A04              ORAA   #04H    P12 high
F2AF 84FD              ANDA   #0FDH   P11 low
F2B1 9702              STAA   PORT1

                * wait for the MEAS line to go high
F2B3 9607       GO_HI  LDAA   PORT4
F2B5 8402              ANDA   #02H    P41 low ?
F2B7 27FA              BEQ    GO_HI
                * THEN exit
F2B9 7EF453            JMP    MEAOUT

                * IF manual breakout THEN wait here till next instruction
F2BC 7D007D            TST    MANUAL
F2BF 2743              BEQ    AUTOBR
                * 1st time in so wait for the rising edge of TEST line
F2C1 9607       TESTU  LDAA   PORT4
F2C3 8520              BITA   #20H
F2C5 27FA              BEQ    TESTU
                * debounce for 20 ms
F2C7 CE1388            LDX    #5000
F2CA 09         DBNITS DEX
F2CB 26FD              BNE    DBNITS
                * init the datalink
F2CD 9602       WOTNXT LDAA   PORT1
F2CF 8A04              ORAA   #04H
F2D1 84FD              ANDA   #0FDH
F2D3 9702              STAA   PORT1

                * manual breakout, wait for falling edge of test line
F2D5 9607       TESTDN LDAA   PORT4
F2D7 8520              BITA   #20H
F2D9 2706              BEQ    DBNTST
F2DB 8502              BITA   #02H
F2DD 2719              BEQ    DBNMES
F2DF 20F4              BRA    TESTDN
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                         659 * debounce for 20 ms
   F2E1 CE1388           660 DBNTST LDX    #5000
   F2E4 09               661 TST_BN DEX
   F2E5 26FD             662        BNE    TST_BN
                         663 * wait for the test line to go high again
   F2E7 9607             664 TESTUP LDAA   PORT4
   F2E9 8420             665        ANDA   #20H
   F2EB 27FA             666        BEQ    TESTUP
                         667
                         668 * go to the next pattern but not beyond FINEP
   F2ED 966B             669        LDAA   PATCNT
   F2EF 4C               670        INCA
   F2F0 8107             671        CMPA   #FINEP
   F2F2 2E10             672        BGT    AUTOBR
   F2F4 976B             673        STAA   PATCNT
   F2F6 200C             674        BRA    AUTOBR
                         675
                         676 * debounce for 20 ms
   F2F8 CE1388           677 DBNMES LDX    #5000
   F2FB 09               678 MES_BN DEX
   F2FC 26FD             679        BNE    MES_BN
                         680
                         681 * wait for the MEAS line to go high again
   F2FE 9607             682 MESUP  LDAA   PORT4
   F300 8502             683        BITA   #02H
   F302 27FA             684        BEQ    MESUP
                         685
                         686 * transfer DIST to RANGE
   F304 DC60             687 AUTOBR LDD    DIST+2
   F306 DD77             688        STD    RANGE+2
   F308 DC5E             689        LDD    DIST
   F30A DD75             690        STD    RANGE
                         691 * .measure new DIST
   F30C 9646             692        LDAA   ERROR0   remember error count
   F30E 9770             693        STAA   TEMPER
   F310 BDF589           694        JSR    MASTPH
   F313 BDF4F5           695        JSR    WORM     display the pattern number
   F316 7D007D           696        TST    MANUAL   ok to display <0 deg on pat0 in manual
   F319 260D             697        BNE    AWD
   F31B 7D006B           698        TST    PATCNT   any reading > 60 km is an error
   F31E 2608             699        BNE    AWD
   F320 9658             700        LDAA   PATPHS
   F322 84E0             701        ANDA   #0E0H
   F324 81E0             702        CMPA   #0E0H
   F326 27DC             703        BEQ    AUTOBR   retry if the phase is < 0 (ie~359) to prevent
                         704 *                   60 km readings at short range
   F328 9646             705 AWD    LDAA   ERROR0   if any errors then try again
   F32A 9170             706        CMPA   TEMPER
   F32C 2708             707        BEQ    INTUNE
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

  F32E 7D006D        709 RETUNE TST    SYNC     wait till remote is finished
  F331 27FB          710        BEQ    RETUNE
  F333 7EF29F        711        JMP    ADINF
                     712
  F336 BDF842        713 INTUNE JSR    TCXO
                     714
                     715 * .IF in manual mode THEN display the result in degrees
  F339 7D007D        716        TST    MANUAL
  F33C 277C          717        BEQ    NOTMAN
  F33E DC58          718        LDD    PATPHS   get phase
  F340 DD82          719        STD    MANT
  F342 7F0084        720        CLR    MANT+2
  F345 7F0086        721        CLR    SIGN
  F348 7F0085        722        CLR    EXP
  F34B CEF3B5        723        LDX    #DEGREE  in float point degrees
  F34E BDFB42        724        JSR    MULT
  F351 C600          725        LDAB   #0
  F353 BDFC6F        726        JSR    DFLOAT
  F356 8601          727        LDAA   #1       clear the display & reset the cursor
  F358 B70140        728        STAA   STATUS
  F35B BDF50C        729        JSR    WORM_W
                     730
                     731 * display the angle with the 1st 2 leading 0's suppressed
  F35E 9698          732        LDAA   DBUF1+4
  F360 840F          733        ANDA   #0FH
  F362 2707          734        BEQ    YES0
  F364 8A30          735        ORAA   #30H
  F366 BDF515        736        JSR    WORM_N
  F369 200E          737        BRA    KEIN0
  F36B BDF513        738 YES0   JSR    WORM_S
  F36E 9699          739        LDAA   DBUF1+5
  F370 840F          740        ANDA   #0FH
  F372 2605          741        BNE    KEIN0
  F374 BDF513        742        JSR    WORM_S
  F377 2009          743        BRA    BUF1_6
  F379 9699          744 KEIN0  LDAA   DBUF1+5
  F37B 840F          745        ANDA   #0FH
  F37D 8A30          746        ORAA   #30H
  F37F BDF515        747        JSR    WORM_N
  F382 969A          748 BUF1_6 LDAA   DBUF1+6
  F384 840F          749        ANDA   #0FH
  F386 8A30          750        ORAA   #30H
  F388 BDF515        751        JSR    WORM_N
                     752
                     753 * display "'_on_patt_"
  F38B CEF3AB        754        LDX    #DEGSON
  F38E C60A          755        LDAB   #10
  F390 A600          756 THRU   LDAA   X
  F392 BDF515        757        JSR    WORM_N
  F395 08            758        INX
```

```
  F396 5A            760          DECB
  F397 26F7          761          BNE    THRU
                     762
                     763 * then the pattern #__
  F399 966B          764          LDAA   PATCNT
  F39B 840F          765          ANDA   #0FH
  F39D 8A30          766          ORAA   #30H
  F39F BDF515        767          JSR    WORM_N
  F3A2 BDF513        768          JSR    WORM_S
  F3A5 BDF513        769          JSR    WORM_S
                     770
                     771 * wait for the next pattern-measure instruction
  F3A8 7EF2CD        772          JMP    WOTNXT
                     773
  F3AB DF            774 DEGSGN FCB    0DFH              ascii for degrees sign
  F3AC 206F6E2070    775          ASC    " on patt "
  F3B5 B400000900    776 DEGREE FCB    0B4H,0,0,9,0   360 in flp
                     777
                     778 * .END (ELSE)
  F3BA BDF454        779 NOTMAN JSR    WINDOW   scale RANGE for this pattern
  F3BD 96A2          780          LDAA   STPCNT   skip test if first measure
  F3BF 4C            781          INCA
  F3C0 2729          782          BEQ    PHSOK
  F3C2 DC75          783          LDD    RANGE    get old distance bits
  F3C4 9358          784          SUBD   PATPHS   subtract the new ones (msb = 180 deg)
                     785
                     786 *        static
  F3C6 8B40          787          ADDA   #040H     if msb's = 11XXH or 00XXH then ok
  F3C8 8580          788          BITA   #080H     else error>90 deg
  F3CA 271F          789          BEQ    PHSOK
                     790
                     791 * ..dec average counter, if zero then
                     792 *   dec counter, but not below 0
                     793
  F3CC 7A00A2        794 BADPHS DEC    STPCNT
  F3CF 2F03          795          BLE    TOOFAR
  F3D1 7EF29F        796          JMP    ADINF
  F3D4 7A006B        797 TOOFAR DEC    PATCNT
  F3D7 2E05          798          BGT    BAKPAT
  F3D9 2709          799          BEQ    BACK2
  F3DB 7C006B        800          INC    PATCNT
  F3DE 7F00A2        801 BAKPAT CLR    STPCNT
  F3E1 7EF29F        802          JMP    ADINF
  F3E4 86FF          803 BACK2  LDAA   #-1      pat 0: count=-1 to prevent averaging
  F3E6 97A2          804          STAA   STPCNT
  F3E8 7EF29F        805          JMP    ADINF
                     806 * .ELSE
                     807 * ..RANGE = RANGE so far with low bits from this measurement
  F3EB 96A2          808 PHSOK  LDAA   STPCNT    inc average count to max of 16
  F3ED 8110          809          CMPA   #16
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

   F3EF 2703            811         BEQ    GETON
   F3F1 4C              812         INCA
   F3F2 97A2            813         STAA   STPCNT
   F3F4 BDF693          814 GETON   JSR    USEPH
   F3F7 BDF481          815         JSR    BLIND   normalise RANGE
                        816
                        817 * ..increment pattern count, but not above FINALP
                        818 *   (pattern 0 to be repeated twice)
   F3FA 966B            819         LDAA   PATCNT
   F3FC 916C            820         CMPA   FINALP
   F3FE 270A            821         BEQ    CALCSP
   F400 9BA2            822         ADDA   STPCNT   1st time on pattern 0?
   F402 2706            823         BEQ    CALCSP
   F404 7C006B          824         INC    PATCNT
   F407 7F00A2          825         CLR    STPCNT   cleaer counts of measurements on this pattern
                        826 * ..calculate new speed (2's complement)
   F40A 7D0046          827 CALCSP TST     ERROR0   if any errors timing disturbed
   F40D 260E            828         BNE    CLRERR   so keep old speed
   F40F DC77            829         LDD    RANGE+2  get ls bytes of new distance
   F411 9360            830         SUBD   DIST+2   subtract previous distance
   F413 DD68            831         STD    SPEED+2  2 ls bytes of speed
   F415 DC75            832         LDD    RANGE    get 2 ms bytes
   F417 D25F            833         SBCB   DIST+1   subtract with carry 3rd byte
   F419 925E            834         SBCA   DIST     subtract with carry ms byte
   F41B DD66            835         STD    SPEED    ms bytes of speed
   F41D 7F0046          836 CLRERR CLR     ERROR0
                        837
                        838 * ..display the pattern number
   F420 0F              839         SEI
   F421 DC75            840         LDD    RANGE
   F423 DD5E            841         STD    DIST
   F425 DC77            842         LDD    RANGE+2
   F427 DD60            843         STD    DIST+2
   F429 0E              844         CLI
   F42A BDF49E          845         JSR    DEBUG
                        846 * .END
                        847 * REP
                        848 * never end if in stakeout mode
   F42D 966B            849         LDAA   PATCNT   if final pattern..
   F42F 916C            850         CMPA   FINALP
   F431 260B            851         BNE    ADIINF
   F433 7D00A1          852         TST    STAKEF   ..& not in stakeout mode
   F436 2606            853         BNE    ADIINF
   F438 8610            854         LDAA   #16      ..& done 16
   F43A 91A2            855         CMPA   STPCNT
   F43C 2703            856         BEQ    WRAPUP   ..then display the reading
   F43E 7EF29F          857 ADIINF JMP     ADINF
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                      859 * IF the breakout went to FINALP THEN
   F441 966C          860 WRAPUP LDAA   FINALP
   F443 916B          861        CMPA   PATCNT
   F445 2E0C          862        BGT    MEAOUT
   F447 BDF8CB        863        JSR    ANSWER   format the answer
                      864 * put the datalink back on to stop falling out of tune
   F44A 9602          865        LDAA   PORT1
   F44C 84FD          866        ANDA   #0FDH    P11 low
   F44E 9702          867        STAA   PORT1
   F450 BDF523        868        JSR    LCDRNG   display the answer on the lcd
                      869
                      870 * .display the result & get out
   F453 39            871 MEAOUT RTS
                      872
                      873 *             *******************
                      874 *              SUBROUTINE WINDOW
                      875 *             *******************
                      876
                      877 * Shifts the data in RANGE so that bits
                      878 * in 'window' (RANGE, RANGE+1) correspond to
                      879 * bits in PATPHS
                      880 * calc # of times approx dist to be
                      881 * shifted for comparison with phase (PATPHS)
   F454 CEF479        882 WINDOW LDX    #SLIDE
   F457 D66B          883        LDAB   PATCNT
   F459 3A            884        ABX
   F45A E600          885        LDAB   0,X
   F45C D771          886        STAB   SIDSLP   save # of times to be shifted
                      887 * shift approx dist left for comparison with measured phase
   F45E 5A            888 SHIFTL DECB
   F45F 2B17          889        BMI    COMPAR   if shifted enough, stop
   F461 780078        890        ASL    RANGE+3
   F464 790077        891        ROL    RANGE+2
   F467 790076        892        ROL    RANGE+1
   F46A 790075        893        ROL    RANGE
   F46D 790074        894        ROL    RANGE-1
   F470 790073        895        ROL    RANGE-2
   F473 790072        896        ROL    RANGE-3  shift left (max 18 times)
   F476 20E6          897        BRA    SHIFTL   repeat
   F478 39            898 COMPAR RTS
                      899 * # of times that RANGE must be shifted for
                      900 * comparison with measured phase, PATPHS
   F479 00            901 SLIDE  FCB    0          2k44  effective pattern frequencies
   F47A 02            902        FCB    2          9k76
   F47B 04            903        FCB    4         39k06
   F47C 06            904        FCB    6        156k
   F47D 08            905        FCB    8        625k
   F47E 09            906        FCB    9          1M25
   F47F 0C            907        FCB    12        10M
   F480 0E            908        FCB    14        40M
```

```
                    910 *           ******************
                    911 *            SUBROUTINE BLIND
                    912 *           ******************
                    913
                    914 * Shifts RANGE data back to where WINDOW
                    915 * found them. It assumes SIDSLP has been
                    916 * set by WINDOW
                    917
                    918 * Shift approx dist back to proper position
   F481 D671        919 BLIND  LDAB SIDSLP  recover # of times to be shifted
   F483 5A          920 SHIFTR DECB
   F484 2B17        921        BMI  DRAWN   if shifted enough stop
   F486 770072      922        ASR  RANGE-3
   F489 760073      923        ROR  RANGE-2
   F48C 760074      924        ROR  RANGE-1
   F48F 760075      925        ROR  RANGE
   F492 760076      926        ROR  RANGE+1
   F495 760077      927        ROR  RANGE+2
   F498 760078      928        ROR  RANGE+3 shift right (max 18 times)
   F49B 20E6        929        BRA  SHIFTR  repeat
   F49D 39          930 DRAWN  RTS
                    931
                    932
                    933 *           ******************
                    934 *            SUBROUTINE DEBUG
                    935 *           ******************
                    936
   F49E 7D0046      937 DEBUG  TST  ERROR0   no display if an error has occurred
   F4A1 2621        938        BNE  FORGT
   F4A3 7D00A1      939        TST  STAKEF   or in STATIC meas mode
   F4A6 271C        940        BEQ  FORGT
   F4A8 966B        941        LDAA PATCNT  STAKEOUT ,so show distance
   F4AA 916C        942        CMPA FINALP  are we on final pattern?
   F4AC 2616        943        BNE  FORGT
   F4AE 96A2        944        LDAA STPCNT  if so skip on the 1st one
   F4B0 8101        945        CMPA #1
   F4B2 2610        946        BNE  FORGT
   F4B4 86FF        947        LDAA #0FFH   flag that we now have a breakout
   F4B6 977E        948        STAA BROKEN
   F4B8 7F00A2      949        CLR  STPCNT  clear the count of how long on this pattern
   F4BB BDF8CB      950        JSR  ANSWER  display the result
   F4BE BDF523      951        JSR  LCDRNG
   F4C1 7A006B      952        DEC  PATCNT  go back to patt #FINALP-1
   F4C4 39          953 FORGT  RTS
                    954
                    955 * messages
   F4C5 2A2A2A2A2A  956 TO1ERR ASC  "********ERROR1**"
   F4D5 2A2A2A2A2A  957 TO2ERR ASC  "********ERROR2**"
   F4E5 2A2A2A2A2A  958 HSERR  ASC  "********HS-ERR**"
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                      960 *           *****************
                      961 *            SUBROUTINE WORM
                      962 *           *****************
                      963
                      964 * copy "__N___" into the first 6 positions of the lcd
                      965 * where N is the pattern number
                      966
  F4F5 8D24           967 WORM   BSR    WORM_R
  F4F7 8D1A           968        BSR    WORM_S
  F4F9 8D18           969        BSR    WORM_S
  F4FB 966B           970        LDAA   PATCNT
  F4FD 840F           971        ANDA   #0FH
  F4FF 8A30           972        ORAA   #30H
  F501 8D12           973        BSR    WORM_N
  F503 8D0E           974        BSR    WORM_S
  F505 8D0C           975        BSR    WORM_S
  F507 8D0A           976        BSR    WORM_S
  F509 8D10           977        BSR    WORM_R
  F50B 39             978        RTS
                      979
  F50C B60140         980 WORM_W LDAA   STATUS      wait for BF
  F50F 48             981        ASLA
  F510 25FA           982        BCS    WORM_W
  F512 39             983        RTS
                      984
  F513 8620           985 WORM_S LDAA   #20H        space
  F515 B70141         986 WORM_N STAA   LCD         number
  F518 8DF2           987        BSR    WORM_W
  F51A 39             988        RTS
                      989
  F51B 8602           990 WORM_R LDAA   #2          reset cursor
  F51D B70140         991        STAA   STATUS
  F520 8DEA           992        BSR    WORM_W
  F522 39             993        RTS
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                      995 *              *******************
                      996 *               SUBROUTINE LCDRNG
                      997 *              *******************
                      998
                      999
   F523 8DF6         1000 LCDRNG BSR   WORM_R        reset cursor
   F525 8644         1001        LDAA  $44H          D
   F527 8DEC         1002        BSR   WORM_N
   F529 8649         1003        LDAA  $49H          I
   F52B 8DE8         1004        BSR   WORM_N
   F52D 8653         1005        LDAA  $53H          S
   F52F 8DE4         1006        BSR   WORM_N
   F531 8654         1007        LDAA  $54H          T
   F533 8DE0         1008        BSR   WORM_N
   F535 863D         1009        LDAA  $3DH          =
   F537 8DDC         1010        BSR   WORM_N
   F539 8DD8         1011        BSR   WORM_S        sp
   F53B 7F0040       1012        CLR   XTEMP
   F53E 9694         1013        LDAA  DBUF1
   F540 8D33         1014        BSR   SLZ           10000's
   F542 8DD1         1015        BSR   WORM_N
   F544 9695         1016        LDAA  DBUF1+1
   F546 8D2D         1017        BSR   SLZ           1000's
   F548 8DCB         1018        BSR   WORM_N
   F54A 9696         1019        LDAA  DBUF1+2
   F54C 8D27         1020        BSR   SLZ           100's
   F54E 8DC5         1021        BSR   WORM_N
   F550 9697         1022        LDAA  DBUF1+3
   F552 8D21         1023        BSR   SLZ           10's
   F554 8DBF         1024        BSR   WORM_N
   F556 9698         1025        LDAA  DBUF1+4
   F558 8D23         1026        BSR   REST          1's
   F55A 8DB9         1027        BSR   WORM_N
   F55C 862E         1028        LDAA  $2EH          dp
   F55E 8DB5         1029        BSR   WORM_N
   F560 9699         1030        LDAA  DBUF1+5
   F562 8D19         1031        BSR   REST          dm
   F564 8DAF         1032        BSR   WORM_N
   F566 969A         1033        LDAA  DBUF1+6
   F568 8D13         1034        BSR   REST          cm
   F56A 8DA9         1035        BSR   WORM_N
   F56C 866D         1036        LDAA  $6DH          m
   F56E 8DA5         1037        BSR   WORM_N
   F570 8DA1         1038        BSR   WORM_S        sp
   F572 8DA7         1039        BSR   WORM_R        reset cursor
   F574 39           1040        RTS
                     1041
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     1043 *            *********************
                     1044 *            SUBROUTINE SLZ & REST
                     1045 *            *********************
                     1046
                     1047 * IF a digit has already been found THEN
   F575 7D0040       1048 SLZ    TST    XTEMP    xtemp is a memory of the first occurence
   F578 2603         1049        BNE    REST     of a non zero digit
   F57A 4D           1050        TSTA            zero detected
   F57B 2709         1051        BEQ    LDZ
                     1052 * .display zeroes as digits
   F57D 840F         1053 REST   ANDA   #0FH     convert unpacked bcd to ascii
   F57F 8A30         1054        ORAA   #30H     return with ascii in ACCA
   F581 C6FF         1055        LDAB   #0FFH
   F583 D740         1056        STAB   XTEMP
   F585 39           1057        RTS
                     1058 * ELSE this is a zero string at the beginning of a number
   F586 8620         1059 LDZ    LDAA   #020H     replace leading zero with space
   F588 39           1060        RTS
                     1061
                     1062
                     1063 *            *******************
                     1064 *             SUBROUTINE MASTPH
                     1065 *            *******************
                     1066
                     1067 * This subroutine does all the necessary synth setting,
                     1068 * timing & data transfers required to obtain one
                     1069 * measurement on one phase when a master instrument
                     1070
                     1071 * Wait till command should be transmitted
   F589 7D006D       1072 MASTPH TST    SYNC     1st check that we're not late
   F58C 270C         1073        BEQ    COMTX1
   F58E DC09         1074        LDD    CNTR     too late..
   F590 C30140       1075        ADDD   #320     wait a further 320 us
   F593 DD6E         1076        STD    SYNCH
   F595 DD0B         1077        STD    OCR
   F597 7F006D       1078        CLR    SYNC
   F59A 7D006D       1079 COMTX1 TST    SYNC
   F59D 27FB         1080        BEQ    COMTX1   wait till command should be transmitted
                     1081 * tx command
   F59F 9602         1082        LDAA   PORT1    set the datalink to a 1 & enable
   F5A1 8A04         1083        ORAA   #04H     P12 high
   F5A3 84FD         1084        ANDA   #0FDH    P11 low
   F5A5 9702         1085        STAA   PORT1
   F5A7 966B         1086        LDAA   PATCNT   get pattern #
   F5A9 8A50         1087        ORAA   #PATCOM  add measure command
   F5AB BDF982       1088        JSR    TXPLUS   tx command
```

```
LOCATION OBJECT CODE LINE    SOURCE LINE

                     1090 * set up OCR to set SYNC at the right time
  F5AE DC6E          1091        LDD    SYNCH    get prev value of SYNC time
  F5B0 C3C350        1092        ADDD   #MSTIM1  + time till start of next wait period
  F5B3 DD08          1093        STD    OCR      set up OCR
  F5B5 DD6E          1094        STD    SYNCH    save time
  F5B7 7F006D        1095        CLR    SYNC     clear SYNC flag
                     1096 * turn datalink off (remote should tx phase data later)
  F5BA 9602          1097        LDAA   PORT1
  F5BC 8A02          1098        ORAA   #02H     P11 high
  F5BE 9702          1099        STAA   PORT1
                     1100
                     1101 * measure effective pattern phase (from 3 patterns)
  F5C0 BDF70D        1102        JSR    PHASE
                     1103 * set up OCR to set SYNC at the right time
  F5C3 DC6E          1104        LDD    SYNCH    get prev value of SYNC time
  F5C5 C3EA60        1105        ADDD   #RXTIM   + time till the 2nd byte should be rx'd
  F5C8 DD08          1106        STD    OCR      set up OCR
  F5CA DD6E          1107        STD    SYNCH    save time
  F5CC 7F006D        1108        CLR    SYNC     clear SYNC flag
                     1109 * rx phase data from remote
  F5CF CEF4C5        1110 WAITRX LDX    #T01ERR  wait for the falling edge of CDET
  F5D2 7D006D        1111        TST    SYNC
  F5D5 2664          1112        BNE    RERROR
  F5D7 8608          1113        LDAA   #08H     P43 ?
  F5D9 9507          1114        BITA   PORT4
  F5DB 26F2          1115        BNE    WAITRX
                     1116 * 1st byte
  F5DD CEF4D5        1117 RX1BYT LDX    #T02ERR
  F5E0 7D006D        1118        TST    SYNC     wait for start bit (falling edge of RXDATA)
  F5E3 2656          1119        BNE    RERROR
  F5E5 8610          1120        LDAA   #10H     P44 ?
  F5E7 9507          1121        BITA   PORT4
  F5E9 26F2          1122        BNE    RX1BYT
  F5EB 7F0046        1123        CLR    ERROR0
  F5EE BDF9E3        1124        JSR    RXINFO
  F5F1 7D0046        1125        TST    ERROR0
  F5F4 2645          1126        BNE    RERROR
  F5F6 D754          1127        STAB   REMST1   1st byte (STRADDLE1-REF)
                     1128 * 2nd byte
  F5F8 CEF4D5        1129 RX2BYT LDX    #T02ERR
  F5FB 7D006D        1130        TST    SYNC     must rx the start of this 2nd byte
  F5FE 2638          1131        BNE    RERROR   before SYNC to avoid a timeout
  F600 8610          1132        LDAA   #10H     P44 ?
  F602 9507          1133        BITA   PORT4
  F604 26F2          1134        BNE    RX2BYT
  F606 7F0046        1135        CLR    ERROR0
  F609 BDF9E3        1136        JSR    RXINFO
  F60C 7D0046        1137        TST    ERROR0
  F60F 262A          1138        BNE    RERROR
  F611 D756          1139        STAB   REMST2
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                    1141 * 3rd byte
    F613 8610       1142 RX3BYT LDAA   #10H      P44 ?
    F615 9507       1143        BITA   PORT4
    F617 26FA       1144        BNE    RX3BYT
    F619 7F0046     1145        CLR    ERROR0
    F61C BDF9E3     1146        JSR    RXINFO
    F61F 7D0046     1147        TST    ERROR0
    F622 2617       1148        BNE    RERROR
                    1149
                    1150 * 3rd byte rx'd. Check handshake nibble in the ls 4 bits
                    1151 * of the 2nd byte, it should = pattern #
                    1152
    F624 17         1153        TBA              duplicate rx'd byte in acca
    F625 C40F       1154        ANDB   #0FH      get handshake nibble
    F627 CEF4E5     1155        LDX    #HSERR
    F62A D16B       1156        CMPB   PATCNT    check if = pattern #
    F62C 260D       1157        BNE    RERROR    if not then error
    F62E 16         1158        TAB              ls 2 bits of rem st1 & st2 in top nibble
    F62F 84C0       1159        ANDA   #0C0H     get the 2 lsb's of rem's st1 & save
    F631 9755       1160        STAA   REMST1+1
    F633 58         1161        ASLB             get 2 lsb's of rem's st2
    F634 58         1162        ASLB
    F635 C4C0       1163        ANDB   #0C0H
    F637 D757       1164        STAB   REMST2+1 & save
    F639 200E       1165        BRA    SETSNC    synchronise
                    1166
                    1167 * an error has occurred
    F63B 7C0046     1168 RERROR INC    ERROR0    inc error flag
    F63E BDF1AB     1169        JSR    LCDMSG    display the error message pointed
    F641 D6C3       1170        LDAB   LNGTIM    to by the index register
    F643 CB03       1171        ADDB   #3        to time 200 ms
    F645 D1C3       1172 LETSEE CMPB   LNGTIM
    F647 2AFC       1173        BPL    LETSEE
                    1174
                    1175 * turn datalink off
    F649 9602       1176 SETSNC LDAA   PORT1
    F64B 8A06       1177        ORAA   #06H      P11 & P12 high
    F64D 9702       1178        STAA   PORT1     tx a 1
                    1179 * set up OCR to set SYNC at the proper time
    F64F 7D006D     1180 SYNDEL TST    SYNC
    F652 27FB       1181        BEQ    SYNDEL
    F654 DC6E       1182        LDD    SYNCH
    F656 C3A730     1183        ADDD   #CYCTIM
    F659 DD6E       1184        STD    SYNCH
    F65B DD0B       1185        STD    OCR
    F65D 7F006D     1186        CLR    SYNC
                    1187 * calculate the phase angle for this pattern
    F660 7F007A     1188        CLR    AMBIGF    clear ambiguity flag
    F663 DC4C       1189        LDD    STRDL1    get 1st straddle result
    F665 9354       1190        SUBD   REMST1
    F667 DD4C       1191        STD    STRDL1    (10 bits are significant)
```

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LOCATION OBJECT CODE LINE     SOURCE LINE

    F669 DC50          1193        LDD    STRDL2   2nd ditto
    F66B 9356          1194        SUBD   REMST2
    F66D DD50          1195        STD    STRDL2
    F66F 934C          1196        SUBD   STRDL1   now check for rollover
    F671 46            1197        RORA            test:(C XOR N)=1 if rollover
    F672 8B40          1198        ADDA   #040H
    F674 2A04          1199        BPL    NOROL
    F676 8680          1200        LDAA   #080H    set ambiguity flag
    F678 977A          1201        STAA   AMBIGF
    F67A DC4C          1202 NOROL  LDD    STRDL1   find av st1 & st2
    F67C D350          1203        ADDD   STRDL2
    F67E 46            1204        RORA
    F67F 56            1205        RORB
    F680 9B7A          1206        ADDA   AMBIGF   correct for rollover ambiguity
    F682 DD58          1207        STD    PATPHS
                       1208
                       1209 * check for disagreement between straddles
    F684 DC4C          1210        LDD    STRDL1
    F686 9350          1211        SUBD   STRDL2
    F688 2B01          1212        BMI    ABSC
    F68A 40            1213        NEGA
    F68B 8110          1214 ABSC   CMPA   #010H
    F68D 2D03          1215        BLT    LOKEPT
    F68F 7C0046        1216        INC    ERROR0
    F692 39            1217 LOKEPT RTS
                       1218
                       1219 *             ******************
                       1220 *              SUBROUTINE USEPH
                       1221 *             ******************
                       1222
                       1223 * IF enough readings have been taken on this pattern THEN
                       1224 * use the result else add the result to the phase list
                       1225
                       1226 * IF final pattern THEN
    F693 966B          1227 USEPH  LDAA   PATCNT
    F695 916C          1228        CMPA   FINALP
    F697 262F          1229        BNE    NOTFNL
                       1230 * .add the result to the phase list
    F699 CE00A3        1231        LDX    #LIST
    F69C D6A2          1232        LDAB   STPCNT
    F69E 5A            1233        DECB
    F69F 3A            1234        ABX
    F6A0 3A            1235        ABX
    F6A1 DC58          1236        LDD    PATPHS
    F6A3 ED00          1237        STD    0,X
                       1238 * .IF in static mode THEN
    F6A5 7D00A1        1239        TST    STAKEF
    F6A8 2610          1240        BNE    STAKEM
```

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LOCATION OBJECT CODE LINE     SOURCE LINE

                     1242 * ..IF 16 readings already THEN
    F6AA D6A2        1243        LDAB   STPCNT
    F6AC C110        1244        CMPB   #16
    F6AE 2608        1245        BNE    MOREPH
                     1246 * ...average all of them
    F6B0 C610        1247        LDAB   #16
    F6B2 BDF93A      1248        JSR    AVERAG
                     1249 * ...incorporate in answer
    F6B5 BDF6CC      1250        JSR    APPEND
                     1251 * END
    F6B8 200C        1252 MOREPH BRA    KEEPON
                     1253 * .ELSEIF in dynamic mode THEN
    F6BA             1254 STAKEM RMB    0
                     1255 * ..IF 1 reading THEN
    F6BA D6A2        1256        LDAB   STPCNT
    F6BC C101        1257        CMPB   #1
    F6BE 2606        1258        BNE    KEEPON
                     1259 * ...average & incorporate them
    F6C0 BDF93A      1260        JSR    AVERAG
    F6C3 BDF6CC      1261        JSR    APPEND
                     1262 * END
    F6C6 2003        1263 KEEPON BRA    AVOUT
                     1264 * ELSE incorporate into measurement
    F6C8 BDF6CC      1265 NOTFNL JSR    APPEND
                     1266 * END
    F6CB 39          1267 AVOUT  RTS
                     1268
                     1269
                     1270 *             ###################
                     1271 *              SUBROUTINE APPEND
                     1272 *             ###################
                     1273
                     1274 * Replaces the low bits of DIST with the result
                     1275 * for this pattern, (PATPHS)
                     1276 * Range has been scaled for this pattern before entry
                     1277
                     1278 * correct high bits for rollover & append new bits
    F6CC DC75        1279 APPEND LDD    RANGE
    F6CE 9358        1280        SUBD   PATPHS
    F6D0 2409        1281        BCC    THUMP    carry clear = new-dist < old-dist
    F6D2 8580        1282        BITA   #80H     dec hi bits if net disturbance is less
    F6D4 260C        1283        BNE    JUMP
    F6D6 BDF6E7      1284        JSR    DECHI
    F6D9 2007        1285        BRA    JUMP
    F6DB 8580        1286 THUMP  BITA   #80H     inc hi bits if disturbance is less
    F6DD 2703        1287        BEQ    JUMP
    F6DF BDF6FA      1288        JSR    INCHI
    F6E2 DC58        1289 JUMP   LDD    PATPHS
    F6E4 DD75        1290        STD    RANGE
    F6E6 39          1291        RTS
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

    F6E7 9674          1293 DECHI  LDAA   RANGE-1  dec high bits
    F6E9 8001          1294        SUBA   #1
    F6EB 9774          1295        STAA   RANGE-1
    F6ED 9673          1296        LDAA   RANGE-2
    F6EF 8200          1297        SBCA   #0
    F6F1 9773          1298        STAA   RANGE-2
    F6F3 9672          1299        LDAA   RANGE-3
    F6F5 8200          1300        SBCA   #0
    F6F7 9772          1301        STAA   RANGE-3
    F6F9 39            1302        RTS
                       1303
    F6FA 9674          1304 INCHI  LDAA   RANGE-1  inc high bits
    F6FC 8B01          1305        ADDA   #1
    F6FE 9774          1306        STAA   RANGE-1
    F700 9673          1307        LDAA   RANGE-2
    F702 8900          1308        ADCA   #0
    F704 9773          1309        STAA   RANGE-2
    F706 9672          1310        LDAA   RANGE-3
    F708 8900          1311        ADCA   #0
    F70A 9772          1312        STAA   RANGE-3
    F70C 39            1313        RTS
                       1314
                       1315 *             ******************
                       1316 *              SUBROUTINE PHASE
                       1317 *             ******************
                       1318
                       1319 * Measures the phase of the current pattern.
                       1320 * Measures the phases of the straddles & subtracts
                       1321 * them from the phase of the reference frequency to
                       1322 * give the partial results for each straddle.
                       1323 * (In the MEAS routine the phase at the master is subtracted
                       1324 * from the remote phase to give the final pattern phase.)
                       1325
                       1326 * Calculate addresses where synth data is stored in table
    F70D CEF004        1327 PHASE  LDX    #PATTAB  get address of pattern table
    F710 8605          1328        LDAA   #5
    F712 D66B          1329        LDAB   PATCNT
    F714 3D            1330        MUL             offset address = 6 * pattern #
    F715 3A            1331        ABX             add offset to start of table
    F716 DF44          1332        STX    XTEMP1   save address of reference pattern
                       1333 * calculate address of straddle freq data
    F718 E604          1334        LDAB   4,X      get offset for straddle freq data
    F71A CEF004        1335        LDX    #PATTAB
    F71D 3A            1336        ABX             get address of straddle freq
    F71E 3C            1337        PSHX            save for the 2nd straddle
                       1338 * set up the synth for the 1st straddle
    F71F BDF87D        1339        JSR    SYNTH    load synth
                       1340 * If remote then don't add delay
    F722 9602          1341        LDAA   PORT1
    F724 8480          1342        ANDA   #80H     P17 ?
    F726 2711          1343        BEQ    NOWAIT
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                       1345 * wait a little longer if master
 F728 7D006D           1346 FRSTWT TST    SYNC
 F72B 27FB             1347        BEQ    FRSTWT
 F72D DC6E             1348        LDD    SYNCH
 F72F C34B00           1349        ADDD   #MSTIM2
 F732 DD6E             1350        STD    SYNCH
 F734 DD0B             1351        STD    OCR
 F736 7F006D           1352        CLR    SYNC
                       1353
                       1354 * calc phase of 1st straddle pattern
 F739 4F               1355 NOWAIT CLRA          clear phase slip
 F73A 5F               1356        CLRB
 F73B DD4A             1357        STD    DELPHS
 F73D BDF79E           1358        JSR    PATFAS
 F740 DC48             1359        LDD    PHSTOT get straddle phase
 F742 DD4C             1360        STD    STRDL1 & save
                       1361 * wait for 1 ms to ensure other inst has finished measuring
 F744 CE00FA           1362        LDX    #250
 F747 09               1363 S1     DEX
 F748 26FD             1364        BNE    S1
                       1365 * load synth with reference pattern
 F74A DE44             1366        LDX    XTEMP1
 F74C BDF87D           1367        JSR    SYNTH
                       1368 * set up OCR to set SYNC at right time
 F74F DC6E             1369        LDD    SYNCH  get previous value of SYNC time
 F751 C3FA00           1370        ADDD   #PHSTIM add time till start of next measurement
 F754 DD0B             1371        STD    OCR    update OCR
 F756 DD6E             1372        STD    SYNCH  update SYNC
 F758 7F006D           1373        CLR    SYNC   clear SYNC flag
                       1374 * calc phase of reference pattern
 F75B BDF79E           1375        JSR    PATFAS
 F75E DC48             1376        LDD    PHSTOT get average phase
 F760 DD4E             1377        STD    DIFPHS & save
                       1378 * wait for 1 ms to ensure other inst has finished measuring
 F762 CE00FA           1379        LDX    #250
 F765 09               1380 S2     DEX
 F766 26FD             1381        BNE    S2
                       1382 * set up synth with 2nd straddle pattern
 F768 38               1383        PULX
 F769 BDF87D           1384        JSR    SYNTH
                       1385 * set up OCR to set SYNC at the right time
 F76C DC6E             1386        LDD    SYNCH
 F76E C3FA00           1387        ADDD   #PHSTIM
 F771 DD0B             1388        STD    OCR
 F773 DD6E             1389        STD    SYNCH
 F775 7F006D           1390        CLR    SYNC
                       1391 * calc phase of 2nd straddle pattern
 F778 BDF79E           1392        JSR    PATFAS
 F77B DC48             1393        LDD    PHSTOT get average phase
 F77D DD50             1394        STD    STRDL2 & save
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     1396 * wait for 1 ms to ensure other inst has finished measuring
  F77F CE00FA        1397         LDX    #250
  F782 09            1398 S3      DEX
  F783 26FD          1399         BNE    S3
                     1400 * switch off the modulator
  F785 CEF000        1401         LDX    #INITSY
  F788 BDF87D        1402         JSR    SYNTH
                     1403 * do the sums
  F78B DC4E          1404         LDD    DIFPHS   get ref - 1st straddle phase
  F78D 934C          1405         SUBD   STRDL1
  F78F 05            1406         ASLD            left justify
  F790 05            1407         ASLD
  F791 05            1408         ASLD
  F792 DD4C          1409         STD    STRDL1
  F794 DC4E          1410         LDD    DIFPHS    get ref - 2nd straddle phase
  F796 9350          1411         SUBD   STRDL2
  F798 05            1412         ASLD
  F799 05            1413         ASLD
  F79A 05            1414         ASLD
  F79B DD50          1415         STD    STRDL2
  F79D 39            1416         RTS
                     1417
                     1418 *               ###################
                     1419 *                 SUBROUTINE PATFAS
                     1420 *               ###################
                     1421
                     1422 * Measures phase of one pattern
                     1423 * 2 * 128 samples are measured & the sum of the results
                     1424 * is placed in PHSTOT.
                     1425 * The slip between the 1st & 2nd samples is added
                     1426 * to a running counter to be used later to lock tcxo's
                     1427 * The routine starts at the 1st occurence of SYNC being set
                     1428
  F79E 966D          1429 PATFAS LDAA   SYNC     wait for SYNC flag
  F7A0 27FC          1430         BEQ    PATFAS
  F7A2 7F006D        1431         CLR    SYNC
  F7A5 8680          1432         LDAA   #128     # of samples
  F7A7 BDF7E0        1433         JSR    PHSMES   measure the phase
  F7AA DE48          1434         LDX    PHSTOT   save
  F7AC DF50          1435         STX    STRDL2   (use STRDL2 as scratch)
  F7AE 8680          1436         LDAA   #128     meas 2nd time
  F7B0 BDF7E0        1437         JSR    PHSMES
                     1438 * The following will form   SLIP1-SLIP2+SLIP3    after
                     1439 * 3 calls of this subr if DELPHS is cleared
                     1440 * before the 1st call (result in DELPHS)
                     1441 * & corrects slip & phase for ambiguity between halves
                     1442
  F7B3 DC48          1443         LDD    PHSTOT
  F7B5 9350          1444         SUBD   STRDL2
  F7B7 2A08          1445         BPL    POSLIP   PL: slip appears +ve
  F7B9 8508          1446         BITA   #08H     is slip really -ve?
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

  F7BB 2618         1448        BNE    NO_AMB   (ie. is ABS(slip) < pi?)
  F7BD 8B10         1449        ADDA   #10H     NO!, add 2*PI to make +ve
  F7BF 2006         1450        BRA    AMBIG
  F7C1 8508         1451 POSLIP BITA   #08H     is slip really +ve?
  F7C3 2710         1452        BEQ    NO_AMB   (ie. is ABS(slip) < pi?)
  F7C5 8010         1453        SUBA   #10H     NO!, subt 2*PI to make -ve
  F7C7 934A         1454 AMBIG  SUBD   DELPHS   DELPHS = -DELPHS + slip
  F7C9 DD4A         1455        STD    DELPHS
  F7CB DC48         1456        LDD    PHSTOT   correct PHSTOT
  F7CD 8010         1457        SUBA   #10H     (subtract 360 deg)
  F7CF D350         1458        ADDD   STRDL2   add 2nd half
  F7D1 DD48         1459        STD    PHSTOT
  F7D3 200A         1460        BRA    PATOUT
  F7D5 934A         1461 NO_AMB SUBD   DELPHS   DELPHS = -DELPHS + slip
  F7D7 DD4A         1462        STD    DELPHS
  F7D9 DC48         1463        LDD    PHSTOT   add 1st & 2nd halves of reading
  F7DB D350         1464        ADDD   STRDL2
  F7DD DD48         1465        STD    PHSTOT   (now in 13 bits)
  F7DF 39           1466 PATOUT RTS
                    1467
                    1468 *             *******************
                    1469 *              SUBROUTINE PHSMES
                    1470 *             *******************
                    1471
                    1472 * Routine to measure phase of one pattern.
                    1473
                    1474 * The synth should already be loaded.
                    1475 * The loop is synchronised to the falling edge of the
                    1476 * 9,7656 kHz signal so as to take the phase values in step
                    1477 * with the transfer of the counter value to the latch.
                    1478 * The loop then sums (A-reg) readings of the counter
                    1479 * & corrects this sum for ambiguity by adding or subtracting
                    1480 * 64 to the total depending on how many counts were made
                    1481 * after or before the rollover.
                    1482
  F7E0 9747         1483 PHSMES STAA   COUNTR   store # of samples required
  F7E2 07           1484        TPA             save ststus (int mask in particular)
  F7E3 36           1485        PSHA
  F7E4 0F           1486        SEI             do not disturb
  F7E5 8620         1487        LDAA   #020H    init previous phase to equal
  F7E7 9752         1488        STAA   PRVPHS   half of the maximum possible count
  F7E9 CE0000       1489        LDX    #0       init ACCX for summing phases
  F7EC 4F           1490        CLRA             "   ACCA (add-or-subtract flag)
  F7ED 7F005A       1491        CLR    ADDHLF    "   ambiguity correction register
  F7F0 7F005C       1492        CLR    SUBHLF    "       "         "          "
  F7F3 C601         1493        LDAB   #01H     wait for the falling edge of 9,7656 kHz
  F7F5 D502         1494 UP19   BITB   PORT1
  F7F7 26FC         1495        BNE    UP19
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     1497 * Loop to collect "COUNTR" phase readings.
                     1498 * COUNTR=128 if PHSMES is called from PATFAS (MEAS)
                     1499 * The value of each reading lies between 0 & 3FH.
                     1500
                     1501 * ! THE TIMING OF THIS LOOP MUST NOT BE CHANGED !
                     1502
  F7F9 C601          1503 LOOP   LDAB   #01H    Wait for the falling edge of 9,76 kHz
  F7FB D502          1504 LATCH  BITB   PORT1   this latches the counters value to
  F7FD 27FC          1505        BEQ    LATCH   the latch
  F7FF F60100        1506        LDAB   PHSCNT  read the counter value
  F802 D740          1507        STAB   XTEMP   save in scratchpad for later
  F804 3A            1508        ABX            add it to the running sum
  F805 D052          1509        SUBB   PRVPHS  subtract the previous phase value
  F807 59            1510        ROLB           before shifting.....
  F808 59            1511        ROLB           If msb's of diff=X10 then rollover..
  F809 8900          1512        ADCA   #0      ..so inc ambiguity flag
  F80B 59            1513        ROLB           If msb's of diff=X01 then rollunder..
  F80C 8200          1514        SBCA   #0      ..so dec ambiguity flag
  F80E D640          1515        LDAB   XTEMP   recover saved counter value
  F810 D752          1516        STAB   PRVPHS  to update previous phase register
  F812 4D            1517        TSTA           check ambiguity flag
  F813 2E0C          1518        BGT    PH3     If +ve increment ADDHLF
  F815 270D          1519        BEQ    PH4     If  0  do not adjust
  F817 7C005C        1520        INC    SUBHLF  If -ve increment SUBHLF
  F81A 7A0047        1521        DEC    COUNTR  Finished yet?
  F81D 26DA          1522        BNE    LOOP
  F81F 2008          1523        BRA    AV_RAG
  F821 7C005A        1524 PH3    INC    ADDHLF
  F824 7A0047        1525 PH4    DEC    COUNTR  decrement count until COUNTR phases read
  F827 26D0          1526        BNE    LOOP    ie, until COUNTR=0
                     1527 *
                     1528 * This is the end of the phase reading loop. The x-reg
                     1529 * now contains the sum of COUNTR phase readings ,ADDHLF &
                     1530 * SUBHLF contain the # of readings that were different
                     1531 * by more than +32 or -32 respectively.
                     1532
                     1533
  F829 DF48          1534 AV_RAG STX    PHSTOT  store sum of phases
  F82B 4F            1535        CLRA           form ADDHLF-SUBHLF in d-reg
  F82C D65A          1536        LDAB   ADDHLF
  F82E D05C          1537        SUBB   SUBHLF
  F830 8200          1538        SBCA   #0      (sign extend)
  F832 05            1539        ASLD           times 64
  F833 05            1540        ASLD
  F834 05            1541        ASLD
  F835 05            1542        ASLD
  F836 05            1543        ASLD
  F837 05            1544        ASLD
  F838 D348          1545        ADDD   PHSTOT  adjust sum
  F83A 841F          1546        ANDA   #1FH    preserve the 13 meaningful phase bits
  F83C 04            1547        LSRD           scrap least bit, result in 12 bits
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

   F83D DD48          1549          STD    PHSTOT   store phase result
   F83F 32            1550          PULA            restore status
   F840 06            1551          TAP
   F841 39            1552          RTS             return from measurement
                      1553
                      1554 *               *****************
                      1555 *                SUBROUTINE TCXO
                      1556 *               *****************
                      1557
                      1558 * this subroutine pulls the master tcxo
                      1559
                      1560 * get absolute value of phase difference
   F842 DC4A          1561 TCXO  LDD    DELPHS   DELPHS holds sum of 3
   F844 05            1562          ASLD            readings of slip
   F845 05            1563          ASLD            each of +/-11bits (+/- PI)
   F846 CEF875        1564          LDX    #PATPUL  init the amount of pulling depending
   F849 D66B          1565          LDAB   PATCNT   on what pattern we are currently on
   F84B C40F          1566          ANDB   #0FH
   F84D 3A            1567          ABX
   F84E E600          1568          LDAB   0,X
                      1569
   F850 4D            1570          TSTA
   F851 2A02          1571          BPL    ABSA
   F853 40            1572          NEGA            change the direction of the tcxo pulling
   F854 50            1573          NEGB            depending on the direction of the phase change
                      1574
   F855 8102          1575 ABSA  CMPA   #2       if the phase diff is less than the noise
   F857 2D1B          1576          BLT    PULOUT   threshold (2) then don't pull tcxo
                      1577
                      1578 * from the pattern number decide the required direction of pulling
   F859 966B          1579          LDAA   PATCNT
   F85B 840F          1580          ANDA   #0FH     mask off the higher nibble
   F85D 8006          1581          SUBA   #6       diff patts (0-6) have opposite sense
   F85F 2E01          1582          BGT    BUMP     to absolute patterns, so change the
   F861 50            1583          NEGB            direction of pulling for pattern 7
                      1584
                      1585 * now pull the tcxo
   F862 5D            1586 BUMP  TSTB
   F863 270F          1587          BEQ    PULOUT
   F865 2B07          1588          BMI    INCPOT
   F867 B701C0        1589 DECPOT STAA  DTOA    write to decrement pot
   F86A 5A            1590          DECB           B times
   F86B 26FA          1591          BNE    DECPOT
   F86D 39            1592          RTS
   F86E B601C0        1593 INCPOT LDAA  DTOA    read to increment pot
   F871 5C            1594          INCB           B times
   F872 26FA          1595          BNE    INCPOT
   F874 39            1596 PULOUT RTS
                      1597
   F875 0403030202    1598 PATPUL FCB   4,3,3,2,2,1,1,1
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     1600 *              ******************
                     1601 *               SUBROUTINE SYNTH
                     1602 *              ******************
                     1603
                     1604 * Routine to load synth.
                     1605 * Address of data is in X-reg.
   F87D 07           1606 SYNTH  TPA              Remember the state of the I-mask
   F87E 36           1607        PSHA             Save on stack
   F87F 37           1608        PSHB
   F880 0F           1609        SEI
                     1610 * IF remote THEN
   F881 9602         1611        LDAA   PORT1
   F883 8480         1612        ANDA   #80H
   F885 2602         1613        BNE    MSYN
                     1614 * .inc X by 2 to get the remote freq data
   F887 08           1615        INX
   F888 08           1616        INX
                     1617 * ELSE get master freq data
   F889 EC00         1618 MSYN   LDD    0,X      save synth data for later ref
   F88B DDC4         1619        STD    SYNREG
   F88D 8610         1620        LDAA   #16      counter for 16 bits
   F88F 9742         1621        STAA   COUNT
                     1622
   F891 DCC4         1623 MORBIT LDD    SYNREG
   F893 05           1624        ASLD
   F894 DDC4         1625        STD    SYNREG
   F896 2406         1626        BCC    ITSA0
   F898 9602         1627        LDAA   PORT1    data out high
   F89A 8A10         1628        ORAA   #10H     P14
   F89C 2004         1629        BRA    CLOK
                     1630
   F89E 9602         1631 ITSA0  LDAA   PORT1    data out low
   F8A0 84EF         1632        ANDA   #0EFH
   F8A2 9702         1633 CLOK   STAA   PORT1
   F8A4 9602         1634        LDAA   PORT1
   F8A6 8A20         1635        ORAA   #20H     clock pulse high
   F8A8 9702         1636        STAA   PORT1    P15
   F8AA 9602         1637        LDAA   PORT1
   F8AC 84DF         1638        ANDA   #0DFH    clock pulse low
   F8AE 9702         1639        STAA   PORT1
   F8B0 7A0042       1640        DEC    COUNT
   F8B3 26DC         1641        BNE    MORBIT
                     1642
   F8B5 9602         1643        LDAA   PORT1    clear synth data
   F8B7 84CF         1644        ANDA   #0CFH    clear synth clock
   F8B9 9702         1645        STAA   PORT1    P14,P15 low
                     1646
   F8BB B70180       1647        STAA   SYNEN    strobe the data into the synth
   F8BE B70180       1648        STAA   SYNEN
   F8C1 B70180       1649        STAA   SYNEN
   F8C4 B70180       1650        STAA   SYNEN
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

    F8C7 33            1652         PULB
    F8C8 32            1653         PULA
    F8C9 06            1654         TAP
    F8CA 39            1655         RTS
                       1656
                       1657
                       1658
                       1659 *             *******************
                       1660 *              SUBROUTINE ANSWER
                       1661 *             *******************
                       1662
                       1663 * Displays the range answer.
                       1664 * Prepares the result in locations DIST for display after
                       1665 * taking into account the met correction, & the units required.
                       1666
    F8CB 965E          1667 ANSWER LDAA   DIST
    F8CD 84E0          1668        ANDA   #0E0H    if ms bits set then no dist
    F8CF 81E0          1669        CMPA   #0E0H
    F8D1 2601          1670        BNE    DISTIN
    F8D3 39            1671        RTS
    F8D4 4F            1672 DISTIN CLRA
    F8D5 5F            1673        CLRB
    F8D6 DD75          1674        STD    RANGE    use top RANGE as scratch
    F8D8 DC60          1675        LDD    DIST+2
    F8DA 9375          1676        SUBD   RANGE
    F8DC DD77          1677        STD    RANGE+2
    F8DE DC5E          1678        LDD    DIST
    F8E0 C200          1679        SBCB   #0
    F8E2 8200          1680        SBCA   #0
    F8E4 DD75          1681        STD    RANGE
                       1682
                       1683 * Subtract coarse offset of 000 mm due to the horns.
                       1684 * (an offset of 14 cm is #1320H)
    F8E6 DC77          1685        LDD    RANGE+2
    F8E8 830000        1686        SUBD   #0000H     msb =937 mm
    F8EB DD77          1687        STD    RANGE+2
    F8ED DC75          1688        LDD    RANGE
    F8EF C200          1689        SBCB   #0
    F8F1 8200          1690        SBCA   #0
    F8F3 DD75          1691        STD    RANGE
                       1692
                       1693 * RANGE is 4 bytes long though the maths routines only
                       1694 * work in 3 bytes so left justify RANGE
                       1695 * (shift left up to 5 bits until msb is set)
    F8F5 4F            1696        CLRA            shift counter/exponent
    F8F6 D675          1697 SC_LE  LDAB   RANGE    test if msb is set
    F8F8 2B12          1698        BMI    PROD
    F8FA 36            1699        PSHA
    F8FB DC77          1700        LDD    RANGE+2  shift 1 bit
    F8FD 05            1701        ASLD
    F8FE DD77          1702        STD    RANGE+2
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

   F900 DC75          1704           LDD    RANGE
   F902 59            1705           ROLB
   F903 49            1706           ROLA
   F904 DD75          1707           STD    RANGE
   F906 32            1708           PULA              recover shift counter
   F907 4A            1709           DECA
   F908 81FA          1710           CMPA   #-6
   F90A 26EA          1711           BNE    SC_LE
   F90C 5F            1712 PROD      CLRB              to clr sign of RANGE
   F90D DD78          1713           STD    RANGE+3  save exp & sign of RANGE
                      1714
                      1715 * range = range*met factor
   F90F CE0075        1716           LDX    #RANGE
   F912 BDFBB6        1717           JSR    GET
   F915 BDFA9B        1718           JSR    NORM
   F918 CEF930        1719           LDX    #RIFACT
   F91B BDFB42        1720           JSR    MULT
   F91E CE0075        1721           LDX    #RANGE
   F921 BDFBD8        1722           JSR    SAVE
                      1723 * mant = range*units factor
   F924 CEF935        1724           LDX    #CONVRT
   F927 BDFB42        1725           JSR    MULT
                      1726
                      1727 * prepare for display
   F92A C602          1728           LDAB   #2
   F92C BDFC6F        1729           JSR    DFLOAT     metric/static 2 dp acc (1 cm)
   F92F 39            1730           RTS
                      1731
                      1732 * Units conversion, (C= 299 792 500 m/s)
   F930 800AA60100    1733 RIFACT FCB    080H,00AH,0A6H,001H,0       1,000325 (met)
   F935 EFD5811000    1734 CONVRT FCB    0EFH,0D5H,081H,010H,0       Full scale metres
                      1735 *CONVRT FCB    0C4H,0B6H,0BFH,012H,0       Full scale UK feet
                      1736 *CONVRT FCB    0C4H,0B6H,0D8H,012H,0       Full scale US feet
                      1737
                      1738
                      1739 *                ###################
                      1740 *                 SUBROUTINE AVERAG
                      1741 *                ###################
                      1742
                      1743 * Averages (B-reg) pattern readings in LIST
                      1744 * taking ambiguity correction into consideration
                      1745 * returns result in PATPHS
                      1746
                      1747 * B must be a power of 2 !
                      1748
                      1749 * init
   F93A 7F0058        1750 AVERAG CLR    PATPHS
   F93D 7F0059        1751           CLR    PATPHS+1
   F940 7F005A        1752           CLR    PATPHS+2
   F943 CE00A3        1753           LDX    #LIST
   F946 37            1754           PSHB
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     1803 *             *******************
                     1804 *              SUBROUTINE TXPLUS
                     1805 *             *******************
                     1806
                     1807 * Set TXDATA high for 20 ms then jump to TXINFO
  F982 37            1808 TXPLUS PSHB
  F983 3C            1809        PSHX
  F984 36            1810        PSHA
  F985 DC09          1811        LDD    CNTR     to time 20 ms
  F987 C34E20        1812        ADDD   #20000
  F98A 37            1813        PSHB
  F98B 36            1814        PSHA
  F98C 38            1815        PULX
  F98D D602          1816        LDAB   PORT1    transmit a 1
  F98F CA04          1817        ORAB   #04H     P12 high trdata
  F991 C4FD          1818        ANDB   #0FDH    P11 low  muteda
  F993 D702          1819        STAB   PORT1
  F995 9C09          1820 FIVEMS CPX    CNTR
  F997 2AFC          1821        BPL    FIVEMS
  F999 32            1822        PULA
  F99A 2002          1823        BRA    TXIN
                     1824
                     1825 *             *******************
                     1826 *              SUBROUTINE TXINFO
                     1827 *             *******************
                     1828
                     1829 * Routine to tx info to another instrument
                     1830 * Format: start bit, 8 data bits, 2 checksum bits, stop bit
                     1831 * baud rate = 1200. Lsb is tx'd 1st
                     1832 * Output is high for a 1
                     1833 * Byte must be in ACCA. ACCB & X reg are not destroyed.
                     1834 * A bit is moved into the carry flag & then tx'd
                     1835
  F99C 37            1836 TXINFO PSHB            save ACCB
  F99D 3C            1837        PSHX            save X reg
  F99E D602          1838 TXIN   LDAB   PORT1    transmit a 1
  F9A0 CA04          1839        ORAB   #04H     P12 high trdata
  F9A2 C4FD          1840        ANDB   #0FDH    P11 low  muteda
  F9A4 D702          1841        STAB   PORT1
  F9A6 C601          1842        LDAB   #1       init high bit counter
  F9A8 D77B          1843        STAB   CHKSUM   (to 1 so all 0's not valid)
  F9AA C60C          1844        LDAB   #12      # of bits to be tx'd
  F9AC D747          1845        STAB   COUNTR
  F9AE DE09          1846        LDX    CNTR     get current value of counter
  F9B0 0C            1847        CLC             tx start bit = 0
                     1848 * Loop to tx 10 bits
  F9B1 2508          1849 LOOPTX BCS    TXONE    tx one if carry set
                     1850 * Tx 0
  F9B3 D602          1851        LDAB   PORT1
  F9B5 C4FB          1852        ANDB   #0FBH    P12 low
  F9B7 D702          1853        STAB   PORT1
  F9B9 2009          1854        BRA    BITWAT   wait until next bit has to be tx'd
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     1856 * TX 1
  F9BB D602          1857 TXONE  LDAB   PORT1
  F9BD CA04          1858        ORAB   #04H     P12 high
  F9BF D702          1859        STAB   PORT1
  F9C1 7C007B        1860        INC    CHKSUM   inc sum of bits
                     1861 * Wait for 1 bit period
  F9C4 C6D0          1862 BITWAT LDAB   #0D0H     (= 1/4 bit period)
  F9C6 3A            1863        ABX
  F9C7 3A            1864        ABX
  F9C8 3A            1865        ABX
  F9C9 3A            1866        ABX              add period required to X reg (=832 E-cycles)
  F9CA 9C09          1867 WATBIT CPX    CNTR
  F9CC 2AFC          1868        BPL    WATBIT   wait until end of period
                     1869 * Check if end of transmission
  F9CE 7A0047        1870        DEC    COUNTR
  F9D1 270D          1871        BEQ    ENDTX    return if last bit has been tx'd
                     1872 * If end of data THEN tx the checksum & stop bit
  F9D3 C603          1873        LDAB   #3
  F9D5 D147          1874        CMPB   COUNTR
  F9D7 2604          1875        BNE    NXTBIT
  F9D9 967B          1876        LDAA   CHKSUM   ls 2 bits will be tx'd
  F9DB 8A04          1877        ORAA   #4       insert stop bit
  F9DD 46            1878 NXTBIT RORA            move next bit into carry flag
  F9DE 20D1          1879        BRA    LOOPTX   tx next bit
                     1880 * Recover registers, END.
  F9E0 38            1881 ENDTX  PULX
  F9E1 33            1882        PULB
  F9E2 39            1883        RTS
                     1884
                     1885
                     1886 *             ###################
                     1887 *              SUBROUTINE RXINFO
                     1888 *             ###################
                     1889
                     1890 * Subroutine to rx info from another instrument
                     1891 * Format: 1 start bit ,8 data bits, 2 check bits,1 stop bits
                     1892 * Baud rate = 1200. Lsb is rx'd 1st
                     1893 * Input must be high for a 1.
                     1894 * Rx'd byte will be in ACCB. ACCA, X reg not destroyed
                     1895 * Subroutine must only be called after start bit detected
                     1896
                     1897 * Subroutine ends if rx'd start bit is < half period long
                     1898 * ERRORO will be incremented if stop bit is not detected
                     1899 * or if check bits not correct or if bits not 'solid'
                     1900 * Rx'd bit sets or clears. Carry is shifted to give byte
                     1901
                     1902 * Init
  F9E3 3C            1903 RXINFO PSHX
  F9E4 36            1904        PSHA
  F9E5 DE09          1905        LDX    CNTR     set X to time at 3/8 bit
  F9E7 C6FF          1906        LDAB   #0FFH
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

   F9E9 3A            1908         ABX
   F9EA C639          1909         LDAB   #039H
   F9EC 3A            1910         ABX
   F9ED C60D          1911         LDAB   #13        init bit counter
   F9EF D747          1912         STAB   COUNTR
   F9F1 4F            1913         CLRA              init bit rx'd
   F9F2 36            1914         PSHA              to balance stack
   F9F3 9F40          1915         STS    XTEMP      save cond of stack
   F9F5 7F007B        1916         CLR    CHKSUM     start count of hi bits rx'd
   F9F8 7C007B        1917         INC    CHKSUM     (@ 1 so all 0's not valid)
                      1918
                      1919 * FOR all bits DO.
   F9FB 7A0047        1920 RXLOOP DEC    COUNTR
   F9FE 2F35          1921         BLE    RXSTOP
                      1922
                      1923 * .add newest bit to bits rx'd so far, & update checksum
   FA00 33            1924         PULB              recover bits so far
   FA01 4D            1925         TSTA              test new bit
   FA02 2704          1926         BEQ    GOT0
   FA04 7C007B        1927         INC    CHKSUM
   FA07 0D            1928         SEC
   FA08 56            1929 GOT0   RORB
   FA09 37            1930         PSHB
                      1931
                      1932 * .IF the 8 data bits have all been rx'd THEN
                      1933 *  save the checksum. Prepare stack to rx
                      1934 *  the tx'd checksum.
   FA0A 8603          1935         LDAA   #3
   FA0C 9147          1936         CMPA   COUNTR
   FA0E 2607          1937         BNE    ONEQ
   FA10 967B          1938         LDAA   CHKSUM
   FA12 8403          1939         ANDA   #3
   FA14 36            1940         PSHA
   FA15 4F            1941         CLRA
   FA16 36            1942         PSHA
                      1943
                      1944 * .wait till 3/8 way through the current bit
   FA17 9C09          1945 ONEQ   CPX    CNTR
   FA19 2AFC          1946         BPL    ONEQ
                      1947
                      1948 * .read the rxdata line
   FA1B 9607          1949         LDAA   PORT4
   FA1D 8410          1950         ANDA   #10H       P44 ?
   FA1F 16            1951         TAB
                      1952
                      1953 * .IF the bit doesn't stay solid for 1/4 bit time THEN
                      1954 *  GOTO error
   FA20 C6D0          1955         LDAB   #0D0H      (=1/4 bit time)
   FA22 3A            1956         ABX
   FA23 D607          1957 THREEQ LDAB   PORT4
   FA25 C410          1958         ANDB   #10H
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

  FA27 11           1960        CBA
  FA28 261A         1961        BNE    REROR
  FA2A 9C09         1962        CPX    CNTR
  FA2C 2AF5         1963        BPL    THREEQ
                    1964
                    1965 * REP (1st set X-reg for 3/8 next bit time)
  FA2E C6D0         1966        LDAB   #0D0H
  FA30 3A           1967        ABX
  FA31 3A           1968        ABX
  FA32 3A           1969        ABX
  FA33 20C6         1970        BRA    RXLOOP
                    1971
                    1972 * IF the stop bit isn't high THEN GOTO REROR
  FA35 4D           1973 RXSTOP TSTA
  FA36 270C         1974        BEQ    REROR
                    1975
                    1976 * IF the calculated checksum is not = the rx'd
                    1977 * checksum THEN GOTO REROR
  FA38 32           1978        PULA             rx'd checksum
  FA39 49           1979        ROLA
  FA3A 49           1980        ROLA
  FA3B 49           1981        ROLA             right justified
  FA3C 33           1982        PULB             calc'd checksum
  FA3D 11           1983        CBA
  FA3E 2604         1984        BNE    REROR
                    1985
                    1986 * RETURN (result in B-reg)
  FA40 33           1987 RXOUT  PULB
  FA41 32           1988        PULA
  FA42 38           1989        PULX
  FA43 39           1990        RTS
                    1991
                    1992 * Flag error, restore stack & exit
  FA44 7C0046       1993 REROR  INC    ERROR0
  FA47 9E40         1994        LDS    XTEMP
  FA49 20F5         1995        BRA    RXOUT
                    1996
                    1997
                    1998 *  In the following subroutines involving 2
                    1999 *  operands, the 1st operand consists of 5
                    2000 *  contiguous locations with the following format;
                    2001 *    MANT    m.s. byte of mantissa
                    2002 *    MANT+1  middle byte of mantissa
                    2003 *    MANT+2  l.s. byte of mantissa
                    2004 *    EXP     exponent
                    2005 *    SIGN    sign of mantissa
                    2006 *  The 2nd operand is index referenced in
                    2007 *  the following way;
                    2008 *    0,X     m.s. byte of mantissa
                    2009 *    1,X     middle byte of mantissa
                    2010 *    2,X     l.s. byte of mantissa
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     2012 *     3,X     exponent
                     2013 *     4,X     sign of mantissa
                     2014 *   The result always overwrites the 1st operand
                     2015 *   The 2nd operand remains unaltered
                     2016
                     2017 *             ****************
                     2018 *              SUBROUTINE ADD
                     2019 *             ****************
                     2020
                     2021 *  THE addend, the address of which is specified by
                     2022 *  the X reg, is added to the augend in
                     2023 *  MANT (3 bytes), EXP, SIGN
                     2024
   FA4B A604         2025 ADD    LDAA   4,X      test sign of addend
   FA4D 2A04         2026        BPL    ADDP     if sign is -ve then
   FA4F BDFAC3       2027        JSR    SUBP     subtract addend
   FA52 39           2028        RTS
   FA53 DF87         2029 ADDP   STX    IXP      save X reg
   FA55 BDFACD       2030        JSR    ADJEXP   adjust exponents
   FA58 9682         2031        LDAA   MANT
   FA5A 9A83         2032        ORAA   MANT+1
   FA5C 9A84         2033        ORAA   MANT+2
   FA5E 2607         2034        BNE    A1       test if mantissa=0
   FA60 BDFBB6       2035        JSR    GET
   FA63 7F0086       2036        CLR    SIGN     set sign to +ve
   FA66 39           2037        RTS
   FA67 9686         2038 A1     LDAA   SIGN     test sign
   FA69 2703         2039        BEQ    L1
   FA6B BDFAFB       2040        JSR    COMPL    complement mantissa
   FA6E BDFB00       2041 L1     JSR    ADD1     add mantissas
   FA71 250C         2042        BCS    L2       check if overflow occurred
   FA73 9686         2043        LDAA   SIGN     test sign
   FA75 2719         2044        BEQ    OUT1
   FA77 BDFAFB       2045        JSR    COMPL    complement mantissa
   FA7A BDFA9B       2046        JSR    NORM     normalise result
   FA7D 2011         2047        BRA    OUT1
   FA7F 9686         2048 L2     LDAA   SIGN     test sign
   FA81 2610         2049        BNE    L3
   FA83 0D           2050        SEC    SHIFT    in a "1"
   FA84 760082       2051        ROR    MANT
   FA87 760083       2052        ROR    MANT+1
   FA8A 760084       2053        ROR    MANT+2
   FA8D 7C0085       2054        INC    EXP
   FA90 DE87         2055 OUT1   LDX    IXP      restore index value
   FA92 39           2056        RTS
   FA93 7F0086       2057 L3     CLR    SIGN     set sign to +ve
   FA96 BDFA9B       2058        JSR    NORM     normalise result
   FA99 20F5         2059        BRA    OUT1
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                      2061 *           #################
                      2062 *            SUBROUTINE NORM
                      2063 *           #################
                      2064
   FA9B 9682          2065 NORM  LDAA  MANT     check if normalised
   FA9D 2B15          2066       BMI   R2
   FA9F 8619          2067       LDAA  #25
   FAA1 4A            2068 L5    DECA
   FAA2 2718          2069       BEQ   L4
   FAA4 7A0085        2070       DEC   EXP
   FAA7 290C          2071       BVS   ZERO     check for 2's complement overflow
   FAA9 780084        2072       ASL   MANT+2   shift mantissa left
   FAAC 790083        2073       ROL   MANT+1
   FAAF 790082        2074       ROL   MANT
   FAB2 2AED          2075       BPL   L5       repeat if not yet normalised
   FAB4 39            2076 R2    RTS
                      2077
                      2078 *           #################
                      2079 *            SUBROUTINE ZERO
                      2080 *           #################
                      2081
   FAB5 4F            2082 ZERO  CLRA
   FAB6 9782          2083       STAA  MANT     set mantissa =0
   FAB8 9783          2084       STAA  MANT+1
   FABA 9784          2085       STAA  MANT+2
   FABC 9786          2086 L4    STAA  SIGN
   FABE 8680          2087       LDAA  #080H    set exponent to largest
   FAC0 9785          2088       STAA  EXP      ...-ve # allowed
   FAC2 39            2089       RTS
                      2090
                      2091 *           #################
                      2092 *            SUBROUTINE SUBP
                      2093 *           #################
   FAC3 730086        2094 SUBP  COM   SIGN     change sign
   FAC6 BDFA53        2095       JSR   ADDP     add absolute value of subtrahend
   FAC9 730086        2096       COM   SIGN     change sign of result
   FACC 39            2097       RTS
                      2098
                      2099 *           ###################
                      2100 *            SUBROUTINE ADJEXP
                      2101 *           ###################
                      2102 *  Subroutine ADJEXP operates on the smaller of
                      2103 *  the 2 operands. Its mantissa is shifted right
                      2104 *  & its exponent increased until it is equal to
                      2105 *  the exponent of the larger operand.
                      2106
   FACD A603          2107 ADJEXP LDAA 3,X      exponent of addend
   FACF 9185          2108       CMPA  EXP      exponent of augend
   FAD1 2712          2109       BEQ   RET1     test for equal exponents
   FAD3 2D11          2110       BLT   RELOC    (3,X)<(EXP)
```

```
LOCATION OBJECT CODE LINE    SOURCE LINE

  FAD5 740082         2112 ADJ1   LSR    MANT     shift mantissa to right &
  FAD8 760083         2113        ROR    MANT+1   ...increase exponent
  FADB 760084         2114        ROR    MANT+2
  FADE 7C0085         2115        INC    EXP
  FAE1 9185           2116        CMPA   EXP
  FAE3 26F0           2117        BNE    ADJ1
  FAE5 39             2118 RET1   RTS
                      2119
                      2120 *             ******************
                      2121 *              SUBROUTINE RELOC
                      2122 *             ******************
                      2123
                      2124 * Subroutine RELOC is required in case the addend
                      2125 * is a constant in rom. If its exponent is smaller
                      2126 * than that of the augend, it must be transferred to
                      2127 * ram so that its mantissa can be shifted right &
                      2128 * its exponent increased until it equals the
                      2129 * exponent of the augend.
                      2130
  FAE6 BDFBCB         2131 RELOC  JSR    GET1     copy mantissa into RELREG
  FAE9 74007F         2132 ADJ2   LSR    RELREG   shift mantissa to right &
  FAEC 760080         2133        ROR    RELREG+1 ...increase exponent
  FAEF 760081         2134        ROR    RELREG+2
  FAF2 4C             2135        INCA            A contains exp of addend
  FAF3 9185           2136        CMPA   EXP      compare with exp of augend
  FAF5 26F2           2137        BNE    ADJ2
  FAF7 CE007F         2138        LDX    #RELREG  point to RELREG
  FAFA 39             2139        RTS             ...of relocated addend.
                      2140
                      2141 *             ******************
                      2142 *              SUBROUTINE COMPL
                      2143 *             ******************
                      2144
                      2145 * Subroutine COMPL forms the 2's complement of
                      2146 * the 3 byte word in MANT
                      2147
  FAFB 4F             2148 COMPL  CLRA
  FAFC 9284           2149 COMPL1 SBCA   MANT+2
  FAFE 9784           2150        STAA   MANT+2
  FB00 8600           2151        LDAA   #00
  FB02 9283           2152        SBCA   MANT+1
  FB04 9783           2153        STAA   MANT+1
  FB06 8600           2154        LDAA   #00
  FB08 9282           2155        SBCA   MANT
  FB0A 9782           2156        STAA   MANT
  FB0C 39             2157        RTS
```

```
                 * FOR all (B) entries DO.
                 * .add phase to total
F947 37          SUM    PSHB            (loop counter)
F948 EC00               LDD    X
F94A D359               ADDD   PATPHS+1
F94C DD59               STD    PATPHS+1
F94E 9658               LDAA   PATPHS
F950 8900               ADCA   #0

                 * .correct for ambiguity
F952 E600               LDAB   X
F954 D0A3               SUBB   LIST
F956 2406               BCC    BACKWD
F958 5D                 TSTB
F959 2B07               BMI    NOAMB
F95B 4C                 INCA
F95C 2004               BRA    NOAMB
F95E 5D          BACKWD TSTB
F95F 2A01               BPL    NOAMB
F961 4A                 DECA
F962 9758        NOAMB  STAA   PATPHS

                 * REP
F964 08                 INX
F965 08                 INX
F966 33                 PULB
F967 5A                 DECB
F968 26DD               BNE    SUM

                 * now find average & normalise
F96A 33                 PULB
F96B 54          SKALE  LSRB
F96C 270F               BEQ    SCALED
F96E 37                 PSHB
F96F DC58               LDD    PATPHS
F971 47                 ASRA
F972 56                 RORB
F973 DD58               STD    PATPHS
F975 965A               LDAA   PATPHS+2
F977 46                 RORA
F978 975A               STAA   PATPHS+2
F97A 33                 PULB
F97B 20EE               BRA    SKALE
F97D DC59        SCALED LDD    PATPHS+1
F97F DD58               STD    PATPHS
F981 39                 RTS
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     2159 *               *****************
                     2160 *                SUBROUTINE ADD1
                     2161 *               *****************
                     2162
                     2163 * Subroutine ADD1 adds the mantissa of the addend
                     2164 * at the address specified by the X reg to
                     2165 * that of the augend in MANT,EXP,SIGN &
                     2166 * stores the result in MANT,EXP,SIGN
                     2167
    FB0D 4F          2168 ADD1   CLRA
    FB0E 9684        2169 ADD2   LDAA   MANT+2
    FB10 A902        2170        ADCA   2,X
    FB12 9784        2171        STAA   MANT+2
    FB14 9683        2172        LDAA   MANT+1
    FB16 A901        2173        ADCA   1,X
    FB18 9783        2174        STAA   MANT+1
    FB1A 9682        2175        LDAA   MANT
    FB1C A900        2176        ADCA   0,X
    FB1E 9782        2177        STAA   MANT
    FB20 39          2178        RTS
                     2179
                     2180 *               *****************
                     2181 *                SUBROUTINE SUB1
                     2182 *               *****************
                     2183
                     2184 * Subroutine SUB1 subtracts the mantissa of the
                     2185 * subtrahend at the address specified by the X reg
                     2186 * from that of the minuend in
                     2187 * MANT,EXP,SIGN & stores the result in MANT,EXP,SIGN
                     2188
    FB21 4F          2189 SUB1   CLRA
    FB22 9684        2190        LDAA   MANT+2
    FB24 A202        2191        SBCA   2,X
    FB26 9784        2192        STAA   MANT+2
    FB28 9683        2193        LDAA   MANT+1
    FB2A A201        2194        SBCA   1,X
    FB2C 9783        2195        STAA   MANT+1
    FB2E 9682        2196        LDAA   MANT
    FB30 A200        2197        SBCA   0,X
    FB32 9782        2198        STAA   MANT
    FB34 39          2199        RTS
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     2201 *            *****************
                     2202 *             SUBROUTINE MOVE
                     2203 *            *****************
                     2204
                     2205 * Subroutine MOVE transfers the 3 bytes at
                     2206 * RELREG to MANT.
                     2207
    FB35 967F        2208 MOVE   LDAA   RELREG
    FB37 9782        2209        STAA   MANT
    FB39 9680        2210        LDAA   RELREG+1
    FB3B 9783        2211        STAA   MANT+1
    FB3D 9681        2212        LDAA   RELREG+2
    FB3F 9784        2213        STAA   MANT+2
    FB41 39          2214        RTS
                     2215
                     2216 *            ******************
                     2217 *             SUBROUTINE  MULT
                     2218 *            ******************
                     2219
                     2220 * The multiplicand at MANT,EXP,SIGN is
                     2221 * multiplied by the multiplier, the address of which
                     2222 * is specified by the X reg.
                     2223
    FB42 A604        2224 MULT   LDAA   4,X      test sign of multiplier
    FB44 2A03        2225        BPL    MULTP
    FB46 730086      2226        COM    SIGN     change sign
    FB49 BDFBAC      2227 MULTP  JSR    ZTST     test if multiplicand=0
    FB4C 5F          2228        CLRB
    FB4D D77F        2229        STAB   RELREG   clear RELREG
    FB4F D780        2230        STAB   RELREG+1
    FB51 D781        2231        STAB   RELREG+2
    FB53 C618        2232        LDAB   #24      B contains shift count
    FB55 740082      2233        LSR    MANT     shift mantissa of multiplicand
    FB58 760083      2234        ROR    MANT+1   ...to right 1 bit with
    FB5B 760084      2235        ROR    MANT+2   ...ls bit into carry
    FB5E 2412        2236 M1     BCC    SHFT     carry=1?
    FB60 A602        2237        LDAA   2,X      Yes, add mantissa of
    FB62 9B81        2238        ADDA   RELREG+2 ...multiplier to form partial result
    FB64 9781        2239        STAA   RELREG+2
    FB66 A601        2240        LDAA   1,X
    FB68 9980        2241        ADCA   RELREG+1
    FB6A 9780        2242        STAA   RELREG+1
    FB6C A600        2243        LDAA   0,X
    FB6E 997F        2244        ADCA   RELREG
    FB70 977F        2245        STAA   RELREG
    FB72 76007F      2246 SHFT   ROR    RELREG   No, shift mantissa of partial
    FB75 760080      2247        ROR    RELREG+1 ...result & multiplicand
    FB78 760081      2248        ROR    RELREG+2 ...to right 1 bit
    FB7B 760082      2249        ROR    MANT
    FB7E 760083      2250        ROR    MANT+1
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

    FB81 760084       2252        ROR    MANT+2
    FB84 5A           2253        DECB          continue until shift count=0
    FB85 26D7         2254        BNE    M1
    FB87 A603         2255        LDAA   3,X
    FB89 9B85         2256        ADDA   EXP    add exponents
    FB8B 2926         2257        BVS    Z1     check for 2's compliment overflow
    FB8D 9785         2258        STAA   EXP
    FB8F 967F         2259        LDAA   RELREG test if result is normalised
    FB91 2B11         2260        BMI    M2
    FB93 790082       2261        ROL    MANT   rotate left to normalise
    FB96 790081       2262        ROL    RELREG+2
    FB99 790080       2263        ROL    RELREG+1
    FB9C 79007F       2264        ROL    RELREG
    FB9F 7A0085       2265        DEC    EXP
    FBA2 290F         2266        BVS    Z1     check for 2's complement overflow
    FBA4 BDFB35       2267 M2     JSR    MOVE   transfer mantissa of result
    FBA7 9682         2268        LDAA   MANT   to locations MANT
    FBA9 2708         2269        BEQ    Z1     check if result=0
    FBAB 39           2270        RTS
                      2271
                      2272 *             *****************
                      2273 *              SUBROUTINE ZTST
                      2274 *             *****************
                      2275
                      2276 * Subroutine ZTST tests if the 1st operand=0
                      2277 * in which case the operation (multiplication,
                      2278 * division,or square root, is bypassed & the
                      2279 * result is left as 0
                      2280
    FBAC 9682         2281 ZTST   LDAA   MANT
    FBAE 2602         2282        BNE    R1
    FBB0 31           2283        INS
    FBB1 31           2284        INS
    FBB2 39           2285 R1     RTS
    FBB3 7EFAB5       2286 Z1     JMP    ZERO
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     2288 *            ****************
                     2289 *              SUBROUTINE GET
                     2290 *            ****************
                     2291
                     2292 * Transfers 5 bytes of data from
                     2293 * locations specified by the X reg, to
                     2294 * MANT,EXP,SIGN
                     2295
    FBB6 A600        2296 GET    LDAA   0,X
    FBB8 9782        2297        STAA   MANT
    FBBA A601        2298        LDAA   1,X
    FBBC 9783        2299        STAA   MANT+1
    FBBE A602        2300        LDAA   2,X
    FBC0 9784        2301        STAA   MANT+2
    FBC2 A603        2302        LDAA   3,X
    FBC4 9785        2303        STAA   EXP
    FBC6 A604        2304        LDAA   4,X
    FBC8 9786        2305        STAA   SIGN
    FBCA 39          2306        RTS
                     2307
                     2308 *            *****************
                     2309 *              SUBROUTINE GET1
                     2310 *            *****************
                     2311
                     2312 * Transfers 3 bytes of data from location specified
                     2313 * by the X reg to RELREG.
                     2314
    FBCB E600        2315 GET1   LDAB   0,X
    FBCD D77F        2316        STAB   RELREG
    FBCF E601        2317        LDAB   1,X
    FBD1 D780        2318        STAB   RELREG+1
    FBD3 E602        2319        LDAB   2,X
    FBD5 D781        2320        STAB   RELREG+2
    FBD7 39          2321        RTS
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     2323 *          *****************
                     2324 *           SUBROUTINE SAVE
                     2325 *          *****************
                     2326
                     2327 * Transfers 4 bytes of data
                     2328 * from MANT,EXP to locations specified
                     2329 * by the X reg.
    FBD8 9682        2330 SAVE   LDAA   MANT
    FBDA A700        2331        STAA   0,X
    FBDC 9683        2332        LDAA   MANT+1
    FBDE A701        2333        STAA   1,X
    FBE0 9684        2334        LDAA   MANT+2
    FBE2 A702        2335        STAA   2,X
    FBE4 9685        2336        LDAA   EXP
    FBE6 A703        2337        STAA   3,X
    FBE8 9686        2338        LDAA   SIGN
    FBEA A704        2339        STAA   4,X
    FBEC 39          2340        RTS
                     2341
                     2342 *          *******************
                     2343 *           SUBROUTINE FLPFXD
                     2344 *          *******************
                     2345
                     2346 * Floating to fixed point conversion.
                     2347 * The floating point # is at MANT,EXP,SIGN.
                     2348 * The fixed point variable consists of an integer
                     2349 * part at INTBIN,(3 bytes), followed by a fractional
                     2350 * part at FRBIN,(3 bytes). The format is INTBIN.FRBIN.
                     2351 * The exponent of the floating point word is to be
                     2352 * less than or equal to 24.
    FBED BDFA9B      2353 FLPFXD JSR    NORM     normalise
    FBF0 D685        2354        LDAB   EXP
    FBF2 4F          2355        CLRA            clear fractional part
    FBF3 9785        2356        STAA   FRBIN    of the fixed point
    FBF5 9786        2357        STAA   FRBIN+1  variable
    FBF7 9787        2358        STAA   FRBIN+2
    FBF9 C180        2359        CMPB   #080H    small flp value?
    FBFB 2719        2360        BEQ    FLP2     yes, stop conversion
    FBFD C018        2361        SUBB   #24      B fixes the # of right
    FBFF 2715        2362        BEQ    FLP2     rotations
    FC01 740082      2363 FLP1   LSR    INTBIN
    FC04 760083      2364        ROR    INTBIN+1
    FC07 760084      2365        ROR    INTBIN+2
    FC0A 760085      2366        ROR    FRBIN
    FC0D 760086      2367        ROR    FRBIN+1
    FC10 760087      2368        ROR    FRBIN+2
    FC13 5C          2369        INCB
    FC14 26EB        2370        BNE    FLP1
    FC16 39          2371 FLP2   RTS
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     2373 *      *******************
                     2374 *       SUBROUTINE BINBCD
                     2375 *      *******************
                     2376
                     2377 * A 3 byte binary word is to be converted
                     2378 * to a maximum 7 byte bcd word
                     2379 * Binary word stored in INTBIN (3 bytes)
                     2380 * SAVEX2 stores the pointer for the bcd destination
                     2381 * string.
                     2382 * 1st byte in the bcd string (the ms byte) can
                     2383 * be a digit, a blank (code 0F), or a
                     2384 * -ve sign (code 0A)
                     2385
                     2386 * SAVEX3 stores the pointer for the conversion constants
                     2387 * If converting an integer, the X reg should be
                     2388 * loaded with CNST6 & ACCB with 7 before entering
                     2389 * the subroutine.
                     2390
                     2391 * If converting a binary fractional value the X reg
                     2392 * should be loaded with CNST01 &
                     2393 * ACCB with 4 before entering the subroutine.
                     2394
  FC17 DF89          2395 BINBCD STX    SAVEX3   save pointer for constants
  FC19 D791          2396        STAB   COUNT1
  FC1B 5F            2397 BINC2  CLRB
  FC1C DE89          2398        LDX    SAVEX3
  FC1E 5C            2399 BINC1  INCB
  FC1F BDFB21        2400        JSR    SUB1     binary=(binary)-constant
  FC22 24FA          2401        BCC    BINC1    binary>constant
  FC24 5A            2402        DECB
  FC25 BDFB0D        2403        JSR    ADD1     restore binary
  FC28 08            2404        INX             point to next constant
  FC29 08            2405        INX
  FC2A 08            2406        INX
  FC2B DF89          2407        STX    SAVEX3   save pointer
  FC2D DE8B          2408        LDX    SAVEX2   pointer for bcd variable
  FC2F E700          2409        STAB   0,X      store bcd in destinstion string
  FC31 7A0091        2410        DEC    COUNT1
  FC34 2705          2411        BEQ    BINC3    if zero conversion finished
  FC36 08            2412        INX             point to next bcd string
  FC37 DF8B          2413        STX    SAVEX2   & save pointer
  FC39 20E0          2414        BRA    BINC2    repeat
  FC3B 39            2415 BINC3  RTS
                     2416
                     2417 * these constants are used by BINBCD
                     2418
  FC3C 0F4240        2419 CNST6  FCB    00FH,042H,040H 1000,000
  FC3F 0186A0        2420 CNST5  FCB    001H,086H,0A0H  100,000
  FC42 002710        2421 CNST4  FCB    000H,027H,010H   10,000
  FC45 0003E8        2422 CNST3  FCB    000H,003H,0E8H    1,000
```

```
    FC48 000064        2424 CNST2  FCB    000H,000H,064H      100
    FC4B 00000A        2425 CNST1  FCB    000H,000H,00AH       10
    FC4E 000001        2426 CNST0  FCB    000H,000H,001H        1
    FC51 199999        2427 CNST01 FCB    019H,099H,099H      0,1
    FC54 028F5C        2428 CNST02 FCB    002H,08FH,05CH     0,01
    FC57 004189        2429 CNST03 FCB    000H,041H,089H    0,001
    FC5A 00068D        2430 CNST04 FCB    000H,006H,08DH   0,0001
                       2431
                       2432 *             *******************
                       2433 *              SUBROUTINE STRING
                       2434 *             *******************
                       2435
                       2436 * Transfers blocks of data
                       2437 * from a source to a destination string.
                       2438 * SAVEX2 stores the pointer of source string
                       2439 * SAVEX3 stores the pointer of destination string
                       2440 * ACCB dictates # of bytes to be transferred.
                       2441 * The above registers are initialised before
                       2442 * entering this routine.
                       2443
    FC5D DE8B          2444 STRING LDX    SAVEX2
    FC5F A600          2445        LDAA   0,X       source data
    FC61 08            2446        INX
    FC62 DF8B          2447        STX    SAVEX2
    FC64 DE89          2448        LDX    SAVEX3    transferred to destination
    FC66 A700          2449        STAA   0,X       string data
    FC68 08            2450        INX
    FC69 DF89          2451        STX    SAVEX3
    FC6B 5A            2452        DECB             dec counter
    FC6C 26EF          2453        BNE    STRING
    FC6E 39            2454        RTS
                       2455
                       2456 *             *******************
                       2457 *              SUBROUTINE DFLOAT
                       2458 *             *******************
                       2459
                       2460 * Auto ranges & prepares a flp number for display
                       2461 * Number must be in range -999999,+9999999   (-10^6 to 10^7)
                       2462 * entry; number in MANT,EXP,SIGN
                       2463 *         ACCB contains max # d.places to be displayed
                       2464 * exit;  bcd DBUF1, DPNT1 set up, DPNT2 switched off
                       2465
                       2466 * Set left most dec point
    FC6F 7F009F        2467 DFLOAT CLR    DPNT1
    FC72 D7A0          2468        STAB   DPNT2     (scratch!)
                       2469
                       2470 * WHILE max d.places not exceeded & -
    FC74 D6A0          2471 SCALE  LDAB   DPNT2
    FC76 D09F          2472        SUBB   DPNT1
    FC78 2F1B          2473        BLE    NOMORE
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                    2475 * AND WHILE value*10 < full scale DO.
    FC7A CEFCF3     2476        LDX    #FLP6
    FC7D 7D0086     2477        TST    SIGN
    FC80 2703       2478        BEQ    DECIDE
    FC82 CEFCF8     2479        LDX    #FLP5    (1 less dig available IF-)
    FC85 BDFCDA     2480 DECIDE JSR    CMPARE
    FC88 240B       2481        BHS    NOMORE
                    2482
                    2483 * .shift d.point left & multiply value by ten
    FC8A 7C009F     2484        INC    DPNT1
    FC8D CEFD02     2485        LDX    #TEN
    FC90 BDFB42     2486        JSR    MULT
                    2487
                    2488 * REP
    FC93 20DF       2489        BRA    SCALE
    FC95 86FF       2490 NOMORE LDAA   #0FFH    clear 2nd point
    FC97 97A0       2491        STAA   DPNT2
    FC99 9686       2492        LDAA   SIGN     save the sign
    FC9B 36         2493        PSHA
                    2494
                    2495 * now round & display the ranged result
    FC9C 9682       2496        LDAA   MANT     IF any danger of overflow.
    FC9E 8118       2497        CMPA   #24
    FCA0 2C09       2498        BGE    NOROND   ..THEN don't round (error 10E-6)
    FCA2 CEFCFD     2499        LDX    #CP5
    FCA5 7F0086     2500        CLR    SIGN
    FCA8 BDFA4B     2501        JSR    ADD      ..ELSE round
    FCAB BDFBED     2502 NOROND JSR    FLPFXD   convert to binary...
    FCAE CE0094     2503        LDX    #DBUF1   ...THEN to bcd
    FCB1 DF88       2504        STX    SAVEX2
    FCB3 CEFC3C     2505        LDX    #CNST6
    FCB6 C607       2506        LDAB   #7
    FCB8 BDFC17     2507        JSR    BINBCD
                    2508
                    2509 * IF -ve THEN include '-'
    FCBB 32         2510        PULA
    FCBC 4D         2511        TSTA
    FCBD 271A       2512        BEQ    DFLOUT
    FCBF 8606       2513        LDAA   #6       place '-' just before 1st dig
    FCC1 CE0094     2514        LDX    #DBUF1
    FCC4 4A         2515 FIND   DECA
    FCC5 919F       2516        CMPA   DPNT1    only 1 dig before point?
    FCC7 270C       2517        BEQ    PUTINX
    FCC9 6D01       2518        TST    1,X      is next dig a 0?
    FCCB 2608       2519        BNE    PUTINX
    FCCD 8C0099     2520        CPX    #DBUF1+5 only 1 more dig in buffer?
    FCD0 2703       2521        BEQ    PUTINX
    FCD2 08         2522        INX
    FCD3 20EF       2523        BRA    FIND
    FCD5 8640       2524 PUTINX LDAA   #040H
    FCD7 A700       2525        STAA   0,X
    FCD9 39         2526 DFLOUT RTS
```

```
LOCATION OBJECT CODE LINE     SOURCE LINE

                     2528 * Local        SUBROUTINE CMPARE
                     2529
                     2530 * Compare MANT,EXP with (X-reg) - both normalised
    FCDA 9685        2531 CMPARE LDAA    EXP
    FCDC A103        2532        CMPA    3,X
    FCDE 2608        2533        BNE     MODIFY
    FCE0 DC82        2534        LDD     MANT
    FCE2 A300        2535        SUBD    0,X
    FCE4 2604        2536        BNE     CMPD
    FCE6 9684        2537        LDAA    MANT+2
    FCE8 A102        2538        CMPA    2,X
    FCEA 39          2539 CMPD   RTS
    FCEB 2E03        2540 MODIFY BGT     BIGGER    modify so unsigned test
    FCED 0D          2541        SEC               may be used (BHS)
    FCEE 20FA        2542        BRA     CMPD
    FCF0 0C          2543 BIGGER CLC
    FCF1 20F7        2544        BRA     CMPD
                     2545
    FCF3 F424001400  2546 FLP6   FCB     0F4H,024H,000H,014H,0  1000000
    FCF8 C350001100  2547 FLP5   FCB     0C3H,050H,000H,011H,0   100000
    FCFD 8000000000  2548 CP5    FCB     080H,000H,000H,000H,0     0,50
    FD02 A000000400  2549 TEN    FCB     0A0H,000H,000H,004H,0    10,00
                     2550
                     2551        END

Errors=    0
```