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**US ARMY
ELECTRONICS
RESEARCH & DEVELOPMENT
ACTIVITY**

DME DATA REDUCTION

BY

DIETER E. HOLBERG

410281

USA ERDA-1

JANUARY 1963

**WHITE SANDS MISSILE RANGE
NEW MEXICO**

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DA Project 3C16-19-001

**INSTRUMENTATION DEPARTMENT
U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT ACTIVITY
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FOREWORD

The basic outputs of the Distance Measuring Equipment (DME) are the digitized phase delays of four so-called data frequencies. In its initial configuration, the DME contained a small special-purpose digital computer which was to derive a range word from the four phase words. It was soon realized that the fixed-wired program was far inferior to a flexible program which could cope with many situations in which the fixed program would fail. In the absence of any other information, all four phasemeter outputs are required for computation of a nonambiguous range word, but there are many cases where ambiguity resolution can be accomplished on the basis of prior DME data or even data of other systems. While, with the fixed program, data is lost when any one of the four phasemeters fails, a flexible program can continue operating with any combination of one, two, or three phasemeters. In addition, flexible programs may provide higher precision by averaging over the four phasemeter outputs.

All the benefits of flexible programming can be obtained only if the range-word synthesis from phase words is fully understood. Therefore the major part of this report is devoted to describing this range-word synthesis in detail. While the actual DME is based on binary relationships to provide data ideally suited for digital computers, an equivalent decimal system is discussed first in order to show the various computational steps more clearly. At the end, two programs for the binary DME are developed and a description of the DME tapes is included.

A remark pertaining to the symbolism employed in this report seems appropriate. The actual, correct phase delays associated with distances are denoted by small p 's. These p 's are principally unavailable; when they appear in equations, they are to show or prove the mathematical consistence. Conversely, phasemeter outputs and all digital quantities derived from them in the course of the program are denoted by P 's or other capital letters, respectively. While a capital letter stands for a binary number with a definite numerical range and bit weighting, the small p 's may stand for either the total phase delay or that part of the total phase delay dealt within the particular equation.

This report is intended to be the first step to devising intelligent DME data reduction routines. It is hoped that it provides the background for the development of more advanced methods.

ABSTRACT

The ambiguity-resolution problem for a Distance Measuring Equipment (DME), using four independent modulation frequencies in the 500-kc region, is described in mathematical terms. The method is developed for a DME model with decimal modulation-frequency relationships and then applied to the actual system whose modulation frequencies are related by binary numbers. Finally, two digital-computer routines providing for both ambiguity resolution and accuracy increase by averaging over the four phase measurements are developed.

C O N T E N T S

	<u>PAGE</u>
FOREWORD -----	iii
ABSTRACT -----	v
GENERAL -----	1
EQUIVALENT DECIMAL DME -----	1
AMBIGUITY RESOLUTION WITH PERFECTLY ACCURATE PHASEMETER OUTPUTS --	4
FINE-AMBIGUITY RESOLUTION WITH PROVISION FOR PHASEMETER ERRORS ---	7
COARSE-AMBIGUITY RESOLUTION WITH PROVISION FOR PHASEMETER ERRORS -	11
VERY-COARSE-AMBIGUITY RESOLUTION WITH PROVISION FOR PHASEMETER ERRORS -----	13
ACCURACY IMPROVEMENT BY AVERAGING -----	15
AN IMPROVED METHOD OF AMBIGUITY RESOLUTION -----	16
THE BINARY DME -----	19
THE IMPROVED METHOD OF AMBIGUITY RESOLUTION IN BINARY FORM -----	22
SMOOTHING -----	24
DME TAPE FORMAT -----	24

DME DATA REDUCTION

1. GENERAL

In principle, DME range is determined as follows: four "ranging frequencies" are modulated on a UHF carrier, transmitted to the airborne transponder, detected, remodulated on a new UHF carrier, retransmitted to the ground station and demodulated (Fig. 1). The phase delay of the demodulated ranging frequencies yields the range to the target. 360 degrees of phase delay in the loop ground-target-ground correspond to the following one way distances:

<u>Ranging Frequencies</u>			<u>One-Way Distances</u>		(1-1)
Very Fine	= VF = f ₁	480.234 kc	2 ¹⁰ ft =	1,024 ft =	0.19 miles
Fine	= F _n = 2 ⁻⁴ f ₁	30.015 kc	2 ¹⁴ ft =	16,384 ft =	3.1 miles
Coarse	= C _s = 2 ⁻⁸ f ₁	1.875 kc	2 ¹⁸ ft =	262,144 ft =	49.6 miles
Very Coarse	= V _C = 2 ⁻¹² f ₁	0.117 kc	2 ²² ft =	4,194,304 ft =	795 miles

Range information is obtained by combining the data obtained from the four phase meters. If phase can be measured accurate to one degree, $1024/360 = 2.9$ feet range accuracy is obtained. With the given relation of 1:16 between ranging frequencies, the range data of the lower ranging frequencies can be corrected to conform with the range data of the next higher frequencies, as long as the error in the lower (coarser) frequency is less than $\pm \frac{1}{2} 360/16 = \pm 12^\circ$. This process is called ambiguity resolution and is in detail described in the following. The binary relationships of the ranging frequencies make the data particularly suitable for digital computers. For reasons of spectrum conservation and carrier frequency isolation, the following "data frequencies" (being sum and differences of the ranging frequencies) are modulated on the transmitter:

$$\begin{aligned}
 f_1 &= VF &= 480.234 \text{ Kc} & & (1-2) \\
 f_2 &= VF - F_n &= 480.234 - 30.015 &= 450.219 \text{ Kc} \\
 f_3 &= VF + C_s &= 480.234 + 1.875 &= 482.109 \text{ Kc} \\
 f_4 &= VF - C_s - V_C &= 480.234 - 1.875 - 0.117 &= 478.241 \text{ Kc}
 \end{aligned}$$

2. EQUIVALENT DECIMAL DME

In order to spare at this stage the cumbersome notation of a DME with binary-related ranging frequencies we described first an equivalent system with decimal-related frequencies. Thus we choose the basic data

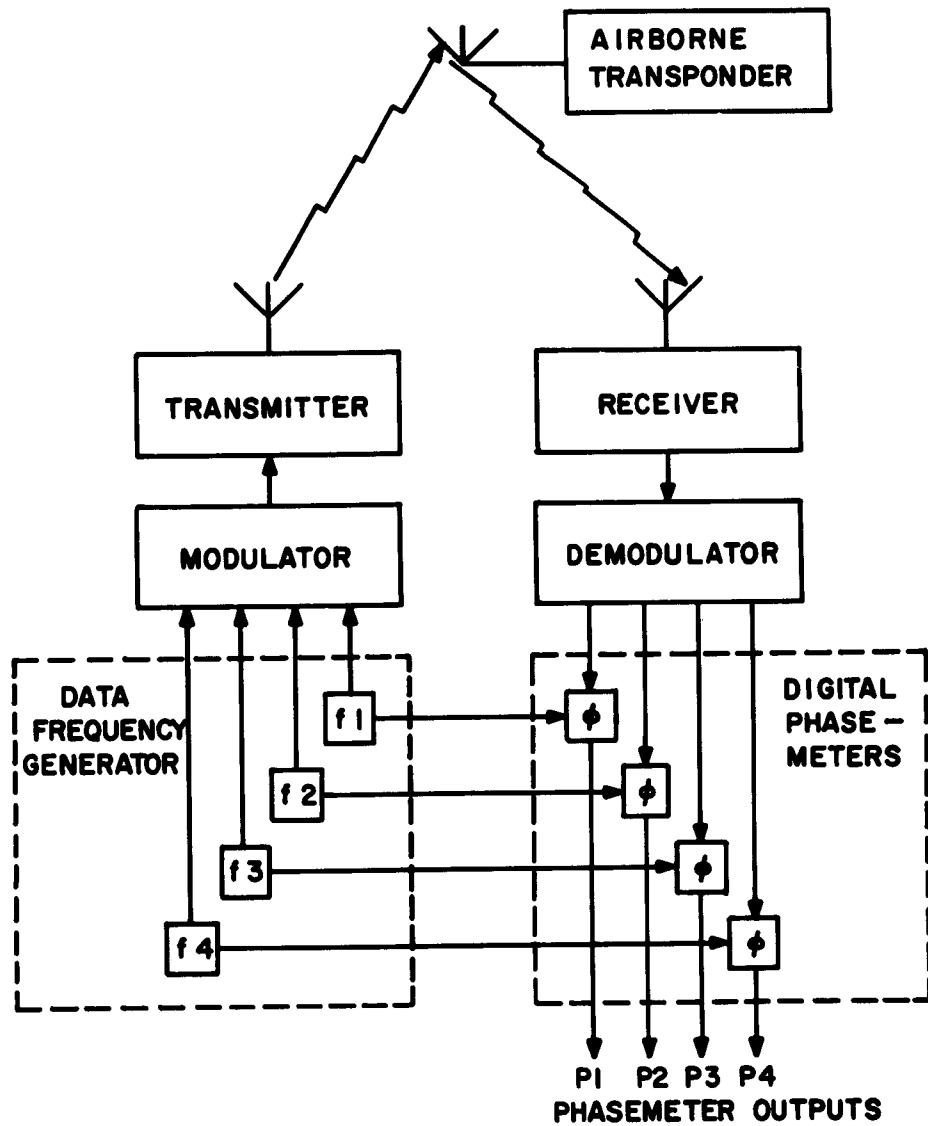


Figure 1

PRINCIPLE OF DME

frequency, $f_1 = VF$, such that 360° loop-range delay (180° one-way delay) corresponds to exactly 1000 feet. Phase angle is measured digitally, with 1000 bits corresponding to 360° loop-range delay. Thus one bit equals one foot one-way distance. In this decimal system, the ranging frequencies become:

$$VF = f_1 ; 360^\circ \text{ loop delay} = 1,000\text{ft one-way distance} \quad (2-1)$$

$$F_n = \frac{1}{10} f_1 ; 360^\circ \text{ loop delay} = 10,000\text{ft one-way distance}$$

$$C_s = \frac{1}{100} f_1 ; 360^\circ \text{ loop delay} = 100,000\text{ft one-way distance}$$

$$V_C = \frac{1}{1000} f_1 ; 360^\circ \text{ loop delay} = 1,000,000\text{ft one-way distance}$$

The actual data frequencies used would be:

$$f_1 = VF \quad (2-2)$$

$$f_2 = \frac{9}{10} f_1 = VF - F_n$$

$$f_3 = \frac{101}{100} f_1 = VF + C_s$$

$$f_4 = \frac{100-10-1}{1000} f_1 = \frac{989}{1000} f_1 = VF - C_s - V_C$$

(The scheme would call for $f_4 = \frac{999}{1000} f_1$, but separating f_4 and f_1 would require an extremely sharp filter with undesirable phase characteristics). With all four frequencies derived from a common crystal oscillator, the above frequency relationships are exactly satisfied at all times.

Since phase delay is proportional to frequency, the digital phases corresponding to an actual distance of 1000 feet are as follows:

$$p_1 = 1000 \text{ bits}$$

$$p_2 = 900 \text{ bits}$$

$$p_3 = 1010 \text{ bits}$$

$$p_4 = 989 \text{ bits}$$

Phase repeats itself when exceeding 360 degrees; therefore phase delays larger than 360 degrees cannot be non-ambiguously measured. The same is true for the digital numbers obtained from the DME phasemeters. While the total phase delays, denoted by small p 's, usually amount to several hundred wavelengths, the phasemeters only provide that fraction of a wavelength by which an unknown integral number of wavelengths is exceeded. The DME phasemeters do not accumulate phase, as is done in DOVAP digitizers. In the decimal DME presently under consideration, the total phase delays p are six-digit numbers, while the phasemeter readings P contain only the last three digits of the total phase delay p .

3. AMBIGUITY RESOLUTION WITH PERFECTLY ACCURATE PHASEMETER OUTPUTS

We consider first the ambiguity resolution process for the case in which all phasemeters read absolutely accurate. As an example, we consider the determination of a range of 756,999.000 feet.

$$p_1 = p_1 \quad p_1 = 756,999.000 \quad (3-1)$$

$$p_2 = \frac{9}{10} p_1 \quad \begin{array}{r} 756,999.000 \\ 75,699.900- \\ \hline p_2 = 681,299.100 \end{array} \quad (3-2)$$

$$p_3 = \frac{101}{100} p_1 \quad \begin{array}{r} 756,999.000 \\ 7,569.990+ \\ \hline p_3 = 764,568.990 \end{array} \quad (3-3)$$

$$p_4 = \frac{989}{1000} p_1 \quad \begin{array}{r} 756,999.000 \\ 7,569.990- \\ 756.999- \\ \hline p_4 = 748,672.011 \end{array} \quad (3-4)$$

The above total phase delays are exact mathematical relationships with respect to p_1 . The digitized phasemeter reading include neither the first three digits, which correspond to multiples of whole wavelengths, nor the digits following the decimal point, which are beyond the resolution of the digital system. Numbering the digits by their power of ten, the phasemeters only provide digits 2, 1, 0 of the total phase delay. To avoid round-off errors, we carry the (unavailable) digits following the decimal point along by the following notation:

$$\begin{array}{ll} p_1 = P_1 & P_1 = p_1 \\ p_2 = P_2 + Q_2 & P_2 = p_2 - Q_2 \\ p_3 = P_3 + Q_3 & P_3 = p_3 - Q_3 \\ p_4 = P_4 + Q_4 & P_4 = p_4 - Q_4 \end{array} \quad (3-5)$$

In these equations, P_1 is assumed accurate, and the Q 's are smaller than one bit. Also, these equations ignore the first three digits of the p 's. In our example:

$$\begin{array}{lll} p_1 = 756,999.000 & P_1 = 999 & Q_1 = 0 \\ p_2 = 681,299.100 & P_2 = 299 & Q_2 = .100 \\ p_3 = 764,568.990 & P_3 = 568 & Q_3 = .990 \\ p_4 = 748,672.011 & P_4 = 672 & Q_4 = .011 \end{array} \quad (3-6)$$

The problem is to resolve the ambiguous phase information, i.e. compute a nonambiguous range from the four phasemeter readings. The range ambiguities are resolved in three consecutive steps.

Under the assumption that all readings are accurate, $P1 = 999$ implies that digits 0, 1, 2 of the range are 999. This portion of the range we call $S1$. By itself, $S1$ is ambiguous because the actual range may be 999; 1,999; 2,999;...; 998,999; 999,999 feet. In fact, there are exactly one-thousand possibilities differing from the correct range by multiples of 1000 feet. These possible values are called fine ambiguities because they could be resolved by a phase measurement of the fine ranging frequency (F_n). Nine hundred of the thousand fine ambiguities are eliminated in the first step:

$$\frac{1}{10} S2 = P1 - P2 = P1 - \frac{9}{10} P1 = \frac{1}{10} P1 \quad (3-7)$$

$$S2 = P1$$

This equation appears as a mere identity when operating with the exact p 's. However, when operating with the three-digit numbers

$$\frac{1}{10} S2 = P1 - P2 = P1 - (P2 - Q2) = P1 - \left(\frac{9}{10} P1 - Q2\right) = \frac{1}{10} P1 + Q2 \quad (3-8)$$

$$S2 = P1 + 10Q2 \quad (3-9)$$

$$S2C = S2 - 10Q2 = P1 \quad (3-10)$$

the difference $\frac{1}{10} S2$ is again a three-digit number so that $S2$ becomes a four-digit number whose last digit is zero. If such a four-digit number is to equal $P1$, we infer that it equals digits 3, 2, 1 of $P1$. In numbers,

$$\begin{array}{r} P1 \quad 999 \\ P2 \quad 299- \\ \hline \frac{1}{10} S2 \quad 700 \end{array} \quad (3-11)$$

$$S2 = 7000 \text{ ft } (=F_n/U)$$

$$S2C = 7000 - 1 = 6999 \text{ ft } (=F_n/C)$$

we see first that $S2$ differs by one bit from the digits 3, 2, 1, 0 of $P1$. This difference is not an equipment error, but a consequence of the quantity $Q2$ which is below the resolution of the phasemeters. The small zero in $S2$ is an insignificant digit which is always zero due to the multiplication by ten. The correct value for $S2$, which we call $S2C$, is to equal $P1$ in the last three digits and is hence $S2C = 6999$. The technique of obtaining $S2C$ from $S2$ will be described when discussing ambiguity resolution with non-ideal phasemeters (Section 4).

The DME manufacturer, Cubic Corporation, denotes the quantities $S2$ and $S2C$ by F_n/U and F_n/C , which stands for "fine uncorrected" and "fine corrected". These symbols refer to the ranging frequencies defined in Equations 3: We would have measured a nonambiguous phase F_n/C , had

we actually used the "fine" ranging frequency. Since sums and differences of the ranging frequencies are used rather than the ranging frequencies themselves, Cubic's notation appears little helpful for someone who has no experience with Cubic's previous DME system which did actually use the ranging frequencies. Therefore, we will use S-symbols for distance-like quantities, but we will mention Cubic's notation to provide a background for understanding Cubic's literature. In the first step we obtained digit 3 of p1, or the range R, respectively. We have just removed nine hundred of the possible one-thousand values for the range R, leaving 6,999; 16,999; ...986,999 996,999 feet. From these one-hundred possibilities, called coarse ambiguities because they appear as multiples of 10,000 feet, ninety are removed by the second step:

$$\frac{1}{100} S3 = P3 - P1 = (p3 - Q3) - p1 = \left(\frac{101}{100} p1 - Q3\right) - p1 = \frac{1}{100} p1 - Q3 \quad (3-12)$$

$$S3 = p1 - 100Q3 \quad (3-13)$$

$$S3C = S3 + 100Q3 = p1 \quad (3-14)$$

Again $\frac{1}{100} S3$ is a three-digit quantity so that S3 becomes a five-digit quantity with two insignificant zeros at the end. The first digit of S3 is to provide digit 4 of the range R. In our example,

$$\begin{array}{r} P3 \ 568 \\ P1 \ 999- \\ \hline \frac{1}{100} S3 \ 569 \end{array} \quad (3-15)$$

$$S3 = 56900 \text{ ft } (=C_s/U)$$

$$S3C = 56900 + 99 = 56999 \text{ ft } (=C_s/C)$$

At this stage there are only ten possibilities left, namely 56,999, 156,999; ...; 856,999; 956,999. These are called very-coarse ambiguities because they appear in multiples of 100,000 feet. The last step singles out the actual range by

$$\begin{aligned} \frac{1}{1000} S4 &= P1 - P4 - \frac{1}{100} S3 \\ &= p1 - (p4 - Q4) - \frac{1}{100} (p1 - 100Q3) \\ &= p1 - \left(\frac{989}{1000} p1 - Q4\right) - \frac{1}{100} p1 + Q3 \\ &= \frac{1}{1000} p1 + Q4 + Q3 \end{aligned} \quad (3-16)$$

$$S4 = p1 + 1000(Q4 + Q3) \quad (=VC/U) \quad (3-17)$$

$$S4C = S4 - 1000(Q4 + Q3) = R1 \quad (=VC/C) \quad (3-18)$$

In our example:

$$\begin{array}{rcl}
 P1 & 999 & \\
 P4 & 672- & \\
 \hline
 \frac{1}{100} & S3 & 569- \\
 \hline
 \frac{1}{1000} & S4 & 758
 \end{array}
 \tag{3-19}$$

$$\begin{array}{rcl}
 S4 & 758,000 & \\
 1000 & Q4 & 11- \\
 1000 & Q3 & 990- \\
 \hline
 S4C & 756,999 &
 \end{array}
 \tag{3-20}$$

$$S4C = 756,999 \text{ feet} = R = (VC/C)$$

Thus we have singled out the actual range R in the following sequence:

$$\begin{array}{ll}
 P1 = 999 & S1 = 999 \text{ ft } (=VF) \\
 S2 = 7,000 (=Fn/U) & S2C = 6,999 \text{ ft } (=Fn/C) \\
 S3 = 56,900 (=Cs/U) & S3C = 56,999 \text{ ft } (=Cs/C) \\
 S4 = 758,000 (=VC/U) & S4C = 756,999 \text{ ft } (=VC/C)
 \end{array}
 \tag{3-21}$$

Note however, that we did not show how to obtain the Q's. Thus the use of equations (3-10), (3-14), and (3-18) is premature at this stage.

4. FINE-AMBIGUITY RESOLUTION WITH PROVISION FOR PHASEMETER ERRORS

While the previous section dealt with ideal phasemeters, for which the errors Q were below the resolution, this section discusses ambiguity resolution with phasemeters having outputs with errors larger than their resolution.

The fine-ambiguity resolution problem is graphically displayed in Figure 2. Three of the one-thousand fine ambiguities namely 5,999; 6,999; 7,999 feet are shown. If S2 comes close to 6,999 feet, for instance 6800 or 7000 feet, as shown as Cases 3 and 4, then 6,999 is clearly established as the correct value for S2, called S2C (correct).

In general, the correct value of the one thousand possible ones is likely to be the one to which S2 comes closest. To establish $S2C = 6,999$ on this basis, S2 would need to lie between 6,500 (499 feet low) and 7,490 (491 feet high), as indicated as Cases 1 and 2. Since $S2 = 10(P1 - P2)$ and P1 is considered an accurate reference at this time, P2 may be inconsistent with regard to P1 by ± 49 units. Writing $P2 = p2 - Q2$, as we did before, Q2 may now be a substantial error ranging from -49 to +49 units to which fractional quantities like those in Equation 3-6 may be added. Note, however, that the likelihood of selecting a wrong S2C increases with

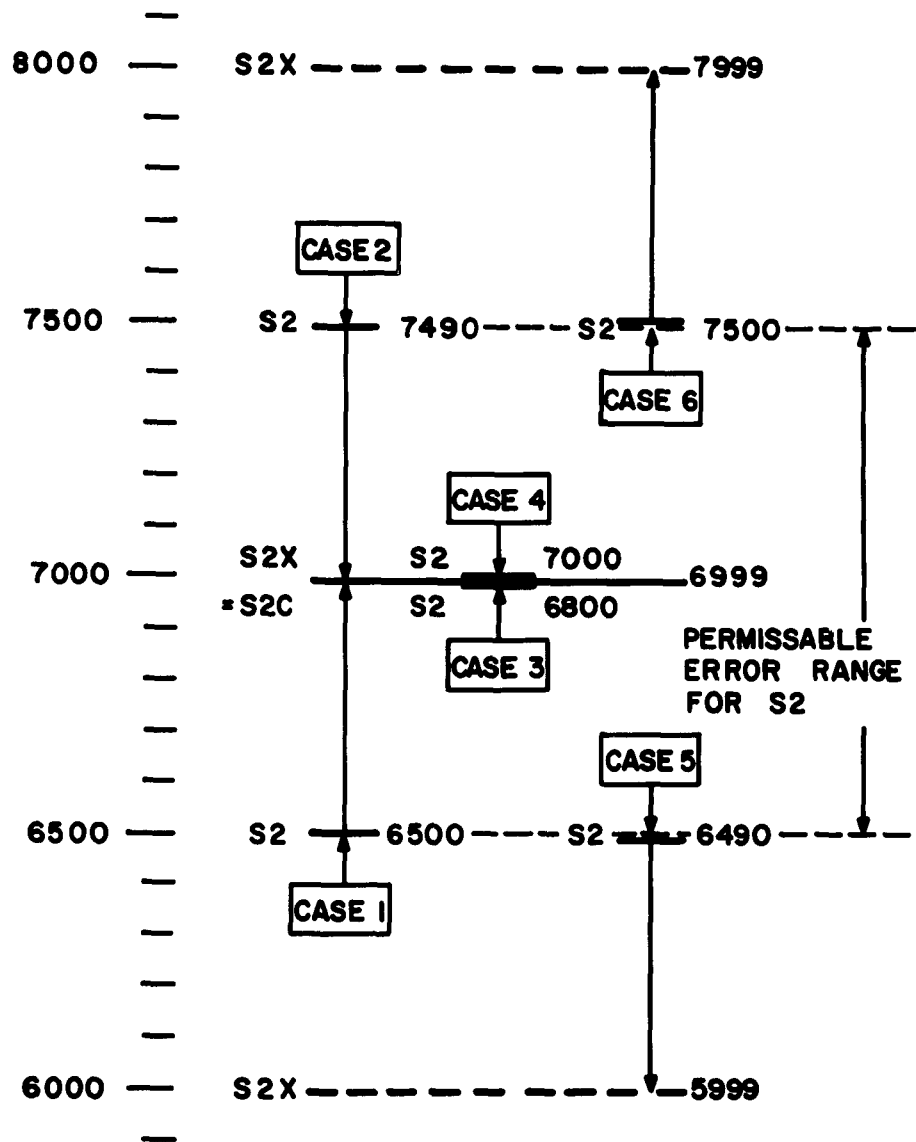


Figure 2

RESOLUTION OF FINE AMBIGUITIES

increasing Q2 and approaches 50% when Q2 approaches +49. The arrows in Figure 2 indicate corrections by which S2 is made to conform with S2C. If S2 differs from S2C by more than +500 feet, as displayed in Figure 2 as Cases 5 and 6, then a so-called ambiguity error is introduced in that the system selects a wrong S2C differing from the correct one by multiples of 1000 feet.

We consider now Cases 1 and 2 of Figure 2.

Case 1

S2 489 ft low
P2 49 units high
Q2 = -49 plus a fraction

P1 = 999
P2 = 299+49 = 348

Case 2

S2 491 ft high
P2 49 units low
Q2 = 49 plus a fraction

P1 = 999
P2 = 299-49 = 250

First, we obtain S2 from (3-7)

$$\begin{array}{r} P1 \ 999 \\ P2 \ 348- \\ \hline 651 \end{array}$$

S2 651o

$$\begin{array}{r} P1 \ 999 \\ P2 \ 250- \\ \hline 749 \end{array} \quad (4-1)$$

S2 749o

Second, we establish the error Q2 according (3-10) as:

$$10Q2 = S2 - S2C \quad (4-2)$$

However, at this point, S2C is not known. We know only that the last three digits (digits 2, 1, 0) of S2C are to equal P1 (or S1). We express our ignorance of digit 3 by writing S2X instead of S2C.

$$10Q2X = S2 - S2X \quad (4-3)$$

Numerically, for the Cases 1 and 2, this amounts to:

$$\begin{array}{r} S2 \ 651o \\ S2X \ X999- \\ \hline 10Q2X \ X511 \end{array}$$

$$\begin{array}{r} S2 \ 749o \\ S2X \ X999 \\ \hline 10Q2X \ X491 \end{array} \quad (4-4)$$

Note that no mathematical operations are performed with an X-digit.

In Case 2 the possible errors (see Figure 3) are 491; 1491;... if S2C was lower than S2, and -509; -1509;... if S2C was above S2. Since we presupposed that the S2C is the S2X coming closest to S2, we need to look for the minimum 10Q2X, which is clearly 10Q2 = 491. The error term Q2 is opposite to the required correction of S2.

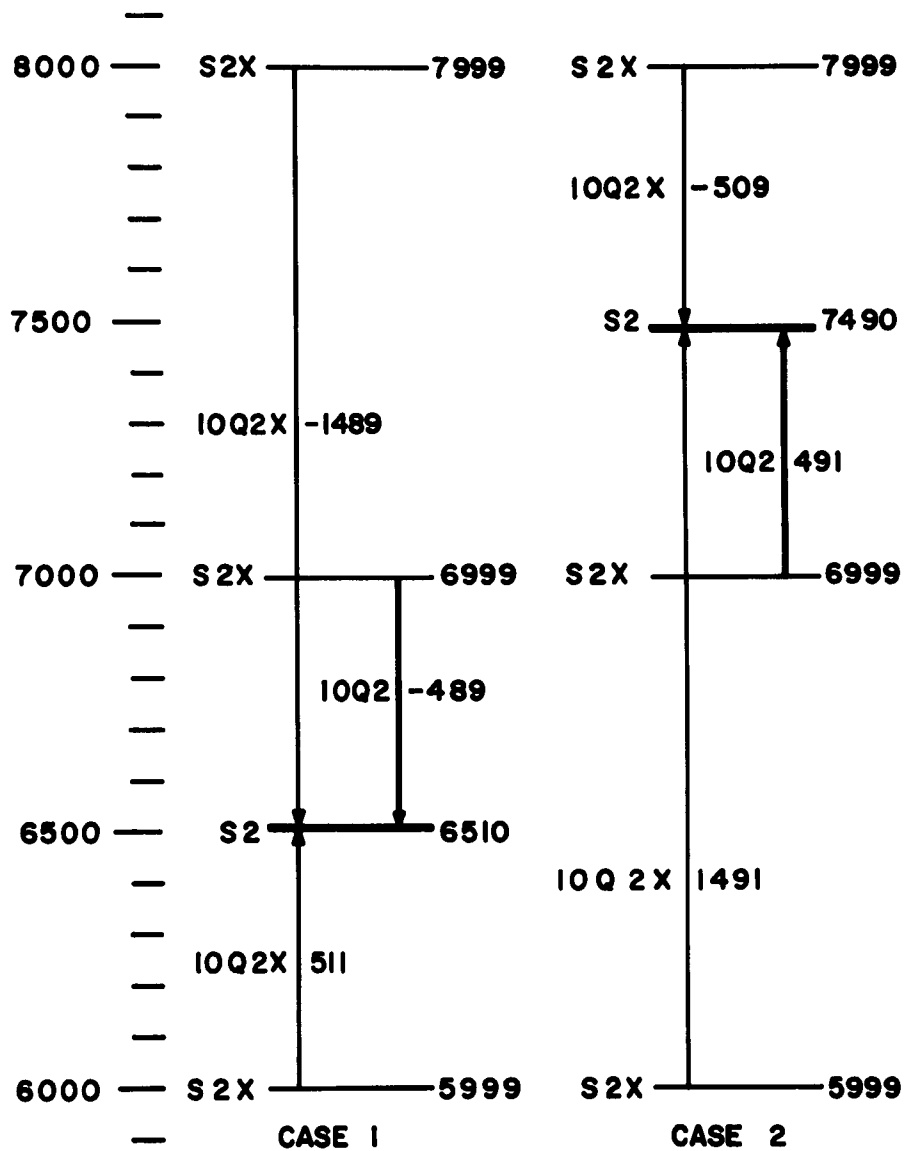


Figure 3

DETERMINATION OF ERROR Q2

In Case 1 the possible errors are 511; 1511;... if S2C was below S2, and -489; -1489;... if S2C was above S2. Here the minimum 10Q2X is 10Q2 = -489.

Note from the examples that 10Q2 is simply determined by:

$$\begin{aligned} 10Q2 &= 10Q2X & 000 \leq 10Q2X \leq 499 & (4-5) \\ 10Q2 &= -\text{complement } 10Q2X & 501 \leq 10Q2X \leq 999 \end{aligned}$$

If we arbitrarily define

$$10Q2 = -\text{complement } 10Q2X \quad 10Q2X = 500 \quad (4-6)$$

then

$$\begin{aligned} 10Q2 &= 10Q2X \text{ if first digit is 0 to 4} \\ 10Q2 &= \text{minus 1000 complement of } 10Q2X \text{ if first digit is 5 to 9.} \end{aligned}$$

Having obtained 10Q2, we obtain S2C from equation (3-10)

$$S2C = S2 - 10Q2 = p1 \quad (4-7)$$

which amounts in the given examples to

$$\begin{array}{rcl} S2 & 6510 & S2 \quad 7490 \\ \underline{10Q2 \quad -489-} & & \underline{10Q2 \quad 491-} \\ S2C & 6999 & S2C \quad 6999 \end{array} \quad (4-8)$$

Note that Q2 does not only determine the error in S2, but also the inconsistency of P2 with respect to P1. If we assume P1 and P2 equally good measurements, we can increase the accuracy by forming an average. However, at this point we assume P1 as an accurate reference, which we will correct after all ambiguities are resolved.

5. COARSE-AMBIGUITY RESOLUTION WITH PROVISION FOR PHASEMETER ERRORS

After resolving the fine ambiguities, we have now one hundred possible range values left, all of them ending in S2C = 6,999. These possible range values we call S3X. Three of these possible values, namely S3X = 46,999; 56,999; 66,999 are shown in Figure 4. To establish S3C = 56,999 feet, S3 should not differ more than ± 4900 feet from S3C. Let us again consider two cases:

Case 1	Case 2
S3 4900 feet low	S3 4900 feet high
P3 49 units low	P3 49 units high
Q3 = +49 plus a fraction	Q3 = -49 plus a fraction

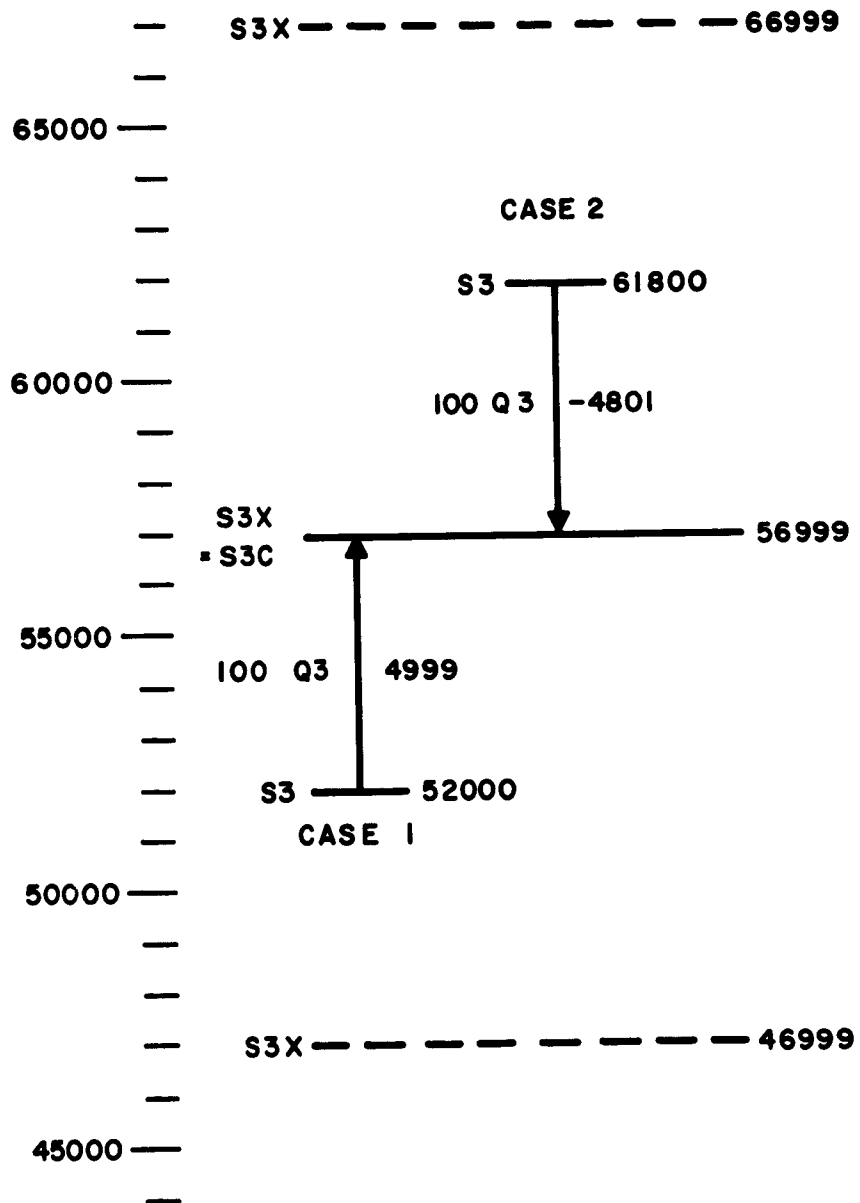


Figure 4

COARSE AMBIGUITY RESOLUTION

$$\begin{aligned} P1 &= 999 \\ P3 &= 568-49 = 519 \end{aligned}$$

$$\begin{aligned} P1 &= 999 \\ P3 &= 568+49 = 617 \end{aligned}$$

First, we obtain S3 from Equation 3-12

$$\begin{array}{r} P3 \quad 519 \\ P1 \quad 999- \\ \hline \frac{1}{100} S3 \quad 520 \end{array}$$

$$S3 \quad 52000$$

$$\begin{array}{r} P3 \quad 617 \\ P1 \quad 999 \\ \hline \frac{1}{100} S3 \quad 618 \end{array}$$

$$S3 \quad 61800$$

(5-1)

Second, we establish Q3X according to Equation 3-14

$$100Q3X = S3X - S3 \quad (5-2)$$

where S3X = S2C augmented by an X as digit 4

$$\begin{array}{r} S3X \quad X6999 \\ S3 \quad 52000- \\ \hline 100Q3X \quad X4999 \end{array}$$

$$\begin{array}{r} S3X \quad X6999 \\ S3 \quad 61800- \\ \hline 100Q3X \quad X5199 \end{array}$$

(5-3)

and obtain 100Q3 by taking the negative 10,000 complement if the first digit of 100Q3X is 5 or more.

$$100Q3 \quad 4999$$

$$100Q3 \quad -4801$$

Finally we obtain S3C from Equation 3-14.

$$S3C = S3 + 100Q3 = p1 \quad (5-4)$$

$$\begin{array}{r} S3 \quad 52000 \\ 100Q3 \quad 4999+ \\ \hline S3C \quad 56999 \end{array}$$

$$\begin{array}{r} S3 \quad 61800 \\ 100Q3 \quad -4801+ \\ \hline S3C \quad 56999 \end{array}$$

6. VERY-COARSE-AMBIGUITY RESOLUTION WITH PROVISION FOR PHASEMETER ERRORS

We are now left with ten possible range values, which are 56,999; 156,999;...; 856,999; 956,999 feet. The last five digits of all of them equal S3C. At this stage, a graphical representation of S4 is not as illuminating as the representations of S2 and S3, because S4 depends on P4 and S3, and therefore on both P3 and P4, as shown in Equations 3-12 and 3-16. In order to clearly demonstrate the method, we carry out as examples the four limiting cases of extreme Q3 and Q4. The extremes for Q3 are taken from the previous section.

	EX. 1	EX. 2	EX. 3	EX. 4
	P4 49 units high		P4 49 units low	
P4	672+49 = 721		672-49 = 623	
Q4	-49 plus a fraction		49 plus a fraction	
Q3	-48.01 49.99		-48.01 49.99	
$\frac{1}{100}$ S3	618 520		618 520	

Applying Equation 3-16

P1	999	999	999	999 (6-1)
P4	721-	721-	623-	623-
$\frac{1}{100}$ S3	<u>618-</u>	<u>520-</u>	<u>618-</u>	<u>520-</u>
$\frac{1}{1000}$ S4	660	758	758	856
S4	660000	758000	758000	856000

Then, from 3-18, with S4X equaling S3C except for the unknown first digit,

$$1000(Q4X+Q3) = S4 - S4X \quad (6-2)$$

from which we compute 1000Q4X by subtracting 1000Q3.

S4	660000	758000	758000	856000
S4X	<u>X56999-</u>	<u>X56999-</u>	<u>X56999-</u>	<u>X56999-</u>
1000(Q4X+Q3)	X03001	X01001	X01001	X99001
<u>1000Q3</u>	<u>-48010-</u>	<u>49990-</u>	<u>-48010-</u>	<u>49990-</u>
1000Q4X	X51011	X51011	X49011	X49011

Note that the last subtraction is performed without carry into the X-digit. As was done before, the negative complement is taken when the first digit is 5 or more, hence

1000Q4	-48989	-48989	49011	49011
--------	--------	--------	-------	-------

We can now obtain the final range R from (3-18)

$$S4C = R = S4 - 1000Q4 - 1000Q3$$

S4	660000	758000	758000	856000 (6-3)
1000Q4	-48989-	-48989-	49011-	49011-
<u>1000Q3</u>	<u>-48010-</u>	<u>49990-</u>	<u>-48010-</u>	<u>49990-</u>
S4C	756999	756999	756999	756999

If we do not care to obtain S4 explicitly, we can combine the operations of (6-1) and (6-2) by using S3C instead of S3.

$$\begin{aligned}
\frac{1}{1000} S40 &= P1 - P4 - \frac{1}{100} S3C & (6-4) \\
&= p1 - \left(\frac{989}{1000} p1 - Q4\right) - \frac{1}{100} p1 \\
&= \frac{1}{1000} p1 + Q4
\end{aligned}$$

$$S40 = p1 + 1000Q4 \quad (6-5)$$

$$S4C = S40 - 1000Q4 \quad (6-6)$$

Examples 1,2

```

1000P1 999000
1000P4 721000-
10S3C 569990-
  S40 708010
  S4X X56999-
1000Q4X X51011

```

```

1000Q4 -48989

```

```

  S40 708010
1000Q4 -48989-
  S4C 756999

```

Examples 3,4

```

1000P1 999000
1000P4 623000-
10 S3C 569990-
  S40 806010
  S4X X56999-
1000Q4X X49011

```

```

1000Q4 49011

```

```

  S40 806010
1000Q4 49011-
  S4C 756999

```

7. ACCURACY IMPROVEMENT BY AVERAGING

For the purpose of ambiguity resolution we assumed P1 as an absolutely accurate reference and associated the Q-errors with the remaining P's. However, since the electronics for the four data frequencies is basically identical, the four phasemeter outputs can be expected to be equally precise. With the ambiguities resolved, the four phasemeter outputs are independent range measurements over which an average may be taken. The four independent range measurements are:

$$R1 = P1 = p1 \quad (7-1)$$

$$R2 = \frac{10}{9} P2 = \frac{10}{9} (p2 - Q2) = p1 - \frac{10}{9} Q2$$

$$R3 = \frac{100}{101} P3 = \frac{100}{101} (p3 - Q3) = p1 - \frac{100}{101} Q3$$

$$R4 = \frac{1000}{989} P4 = \frac{1000}{989} (p4 - Q4) = p1 - \frac{1000}{989} Q4$$

If we give the Q's equal weight in distance, the range average becomes

$$RA = R1 - \frac{1}{9} \left(\frac{10}{9} Q2 + \frac{100}{101} Q3 + \frac{1000}{989} Q4 \right) \quad (7-2)$$

But the Q's may just as well be weighted equally in phase, then

$$RA = R1 - \frac{1}{4}(Q2+Q3+Q4) \quad (7-3)$$

Different weighting factors may be chosen according to the actual noise level of each particular phasemeter.

8. AN IMPROVED METHOD OF AMBIGUITY RESOLUTION

In Sections 4 to 6 we assumed an absolutely accurate P1 and found that the remaining P's may be inconsistent with regard to P1 by plus or minus 49 bits. The assumption of an accurate reference was made merely for mathematical convenience in the ambiguity-resolution process. In Section 7, after supposing that we had properly resolved the ambiguities, we admitted an error in P1 and corrected for it on the basis of an average over the four phasemeter readings.

An error in P1 reduces the 49-bit error margins of the other P's in one direction by the amount of the error in P1. The ideal approach would use the correct average, rather than P1, as the reference for ambiguity resolution. But the average is unavailable until the ambiguity resolution has been performed and is less likely to be correct the larger the error in P1. There appear to be two practical approaches to obtaining the largest error margin for correct ambiguity resolution: one would perform averages after each ambiguity-resolution step, the other would check for correct resolution after the final range word has been obtained. In this report only the step-wise averaging method will be discussed.

We now assume p1 and P1 to be correct only for the resolution of the fine ambiguities. Then we define

$$P2 = \frac{9}{10}p1 - Q2 \quad (8-1)$$

and perform the fine-ambiguity resolution as described in Section 4. In this first step we will not gain anything over the method used in Section 3. Having obtained S3C, we average on the basis of equal phase accuracy of P1 and P2 to obtain a corrected P1 as

$$R2C = S2C - \frac{1}{2}Q2 = p1C \quad (8-2)$$

For the resolution of the coarse ambiguities we assume p1C and P1C (digits 2, 1, 0, -1 of R2C) to be correct. We define then

$$P3 = \frac{101}{100}p1C - U3 \quad (8-3)$$

and proceed as in Section 5, but using P1C instead of P1:

$$\frac{1}{100}S3A = P3 - P1C = \left(\frac{101}{100}p1C - U3\right) - p1C \quad (8-4)$$

$$S3A = p1C - 100U3 \quad (8-5)$$

$$100U3X = S3X - S3A \quad (8-6)$$

where S3X equals R2C augmented by an X in digit 5. With U3 obtained by complementing U3X if its first digit is 5 or more, we compute

$$S3C = S3A + 100U3 \quad (8-7)$$

and perform another average

$$R3C = S3C - \frac{1}{3}U3 = p1CC \quad (8-8)$$

taking into account (by the factor $\frac{1}{3}$) that S3C is an average of two phasemeter readings.

In this way, we have obtained a doubly corrected P1 which we use as reference for the resolution of the very-course ambiguities. We now assume p1CC and P1CC (digits 2, 1, 0, -1, ... of R3C) to be correct. We define then

$$P4 = p1CC - U4 \quad (8-9)$$

We follow now the routine of Section 6 but use P1CC and R3C instead of P1 and S3C, respectively.

$$\frac{1}{1000}S4A = P1CC - P4 - \frac{1}{100}R3C \quad (8-10)$$

$$= p1CC - \left(\frac{989}{1000}p1CC - U4\right) - \frac{1}{100}p1CC$$

$$S4A = p1CC + 1000U4$$

$$1000U4X = S4A - S4X \quad (8-11)$$

where S4X equals R3C augmented by an X as digit 6. After obtaining U4 by the usual complementation,

$$S4C = S4A - 1000U4 \quad (8-12)$$

we compute the final range RA as

$$R4C = S4C - \frac{1}{3}U4 = RA \quad (8-13)$$

taking into account that S4C is an average of three phasemeter readings.

The routine described in this section increases the likelihood for correct resolution of coarse and very-coarse ambiguities.

With correct ambiguity resolution, Equations 8-13 and 7-3 lead to nearly the same average range RA. Equation 8-13 can be written in the form:

$$\begin{aligned} RA &= p1CC - \frac{1}{3}U4 \\ &= p1C - \frac{1}{3}U3 - \frac{1}{3}U4 \\ &= p1 - \frac{1}{3}Q2 - \frac{1}{3}U3 - \frac{1}{3}U4 \end{aligned} \quad (8-14)$$

while Equation 7-3 can be expressed

$$RA = p1 - \frac{1}{3}Q2 - \frac{1}{3}Q3 - \frac{1}{3}Q4 \quad (8-15)$$

The U's can be expressed in terms of the Q's as follows:

$$U3 = (101/100)p1C - P3 = (101/100)(p1 - \frac{1}{3}Q2) - P3 \quad (8-16)$$

$$U3 + (101/100)\frac{1}{3}Q2 = (101/100)p1 - P3 = Q3 \quad (8-17)$$

$$U3 = Q3 - (101/100)\frac{1}{3}Q2 \quad (8-18)$$

$$\begin{aligned} U4 &= (989/1000)p1CC - P4 = (989/1000)(p1C - \frac{1}{3}U3) - P4 \\ &= (989/1000)(p1 - \frac{1}{3}Q2 - \frac{1}{3}U3) - P4 \end{aligned} \quad (8-19)$$

$$= (989/1000) \left[p1 - \frac{1}{3}Q2 - \frac{1}{3}Q3 + \frac{1}{3}(101/100)\frac{1}{3}Q2 \right] - P4$$

$$U4 + (989/1000)\frac{1}{3} \left[1 - \frac{1}{3}(101/100) \right] Q2 + (989/1000)\frac{1}{3}Q3 = \quad (8-20)$$

$$= \left[(989/1000)p1 - P4 \right] = Q4$$

$$U4 = Q4 - (989/1000)\frac{1}{3}Q3 - (989/1000)\frac{1}{3} \left[1 - (101/100)\frac{1}{3} \right] Q2 \quad (8-21)$$

Using now 8-18 and 8-21 in Equation 8-14:

$$RA = p1 - \frac{1}{3} \left[1 - \frac{1}{3}(101/100) - \frac{1}{3}(989/1000) \left(1 - (101/100)\frac{1}{3} \right) \right] Q2 \quad (8-22)$$

$$- \frac{1}{3} \left[1 - \frac{1}{3}(989/1000) \right] Q3 - \frac{1}{3}Q4$$

$$= p1 - \frac{1}{3} \left[1 - (811/600,000) \right] Q2 - \frac{1}{3} \left[1 + (11/3,000) \right] Q3 - \frac{1}{3}Q4$$

where the last line very nearly equals Equation 8-15.

9. THE BINARY DME

After discussing a comparatively simpler decimal system, we now return to the actual system, as was described in Section 1. This system differs from the decimal system in two ways: The ranging frequencies are related by 1:16 (as compared to 1:10) and 360° loop-range delay is digitized in $2^{13} = 8,192$ bits. The very-fine data frequency, f_1 , is chosen such that 360° loop-range delay equal 2^{10} or 1024 feet. Thus one bit of P_1 equals $\frac{1}{8}$ foot. As convenient reference, a table of powers of 2 is given below:

2^{21}	2,097,152	2^{10}	1,024
2^{20}	1,048,576	2^9	512
2^{19}	524,288	2^8	256
2^{18}	262,144	2^7	128
2^{17}	131,072	2^6	64
2^{16}	65,536	2^5	32
2^{15}	32,768	2^4	16
2^{14}	16,384	2^3	8
2^{13}	8,192	2^2	4
2^{12}	4,096	2^1	2
2^{11}	2,048	2^0	1

With respect to p_1 , the phase delays for the other data frequencies are then:

$$p_2 = \frac{2^4-1}{2^4} p_1 = \frac{15}{16} p_1 \quad (9-1)$$

$$p_3 = \frac{2^8+1}{2^8} p_1 = \frac{257}{256} p_1$$

$$p_4 = \frac{2^{12}-2^4-1}{2^{12}} = \frac{4079}{4096} p_1$$

The binary routine equivalent to the decimal one described in Sections 4, 5, and 6 is displayed in Figure 5. To minimize the number of shifting operations, the 13-bit phasemeter words are to extend from position 23 to 11. Thus the unit, equal to $\frac{1}{8}$ foot, is located in position 11. All decimal numbers of this section refer to a unit in position 11.

We define all quantities with respect to p1 as

$$P1 = p1 \quad (9-2)$$

$$P2 = p2 - Q2 = \frac{15}{16}p1 - Q2$$

$$P3 = p3 - Q3 = \frac{257}{256}p1 - Q3$$

$$P4 = p4 - Q4 = \frac{4079}{4096}p1 - Q4$$

where the P's are the 13-bit binary phasemeter outputs which would exist at the time of the zero crossing of a reference phase (REF) generated within the DME. Since the read command, which is derived from range timing, is generally not coincident with the zero crossing of the reference phase, the actual phasemeter outputs, denoted by D's, equal the correspondent P's increased by the instantaneous reference phase at the time of reading. The reference phase is recorded as a positive 13-bit number compatible with the phasemeter outputs. Thus the P's are obtained from the D's as

$$P1 = D1 - REF \quad (9-3)$$

$$P2 = D2 - REF$$

$$P3 = D3 - REF$$

$$P4 = D4 - REF$$

Note that all quantities of Equation 9-3 are to appear as positive 13-bit numbers. Therefore, there should be no carry into the 14th bit. We now resolve the fine ambiguities;

$$S2 = 16P1 - 16P2 = 16p1 - 16\left(\frac{15}{16}p1 - Q2\right) \quad (9-4)$$

$$= p1 + 16Q2$$

Note that multiplication by powers of 2 may be programmed as shifting operations. S2 is a 17-bit binary number with four insignificant zeros as the last four bits. S2X equals P1 augmented by four binary X-bits at the beginning. The distinction between S2X and P1 is made, and the X-bits are shown in Figure 5, for the sole purpose of emphasizing that no operations are to be performed on these X digits. Yet, we refer to S2X as a 13-bit number, not counting the X-bits.

$$16Q2X = S2 - S2X \quad (9-5)$$

16Q2X is also a 13-bit number augmented by four X-bits. In accordance with Section 4, the negative complement to 8192 is to be taken when 16Q2X exceeds half its range. In the decimal system, 10Q2X ranged from 0 to 999 and was to be complemented when exceeding 499. The binary 16Q2X ranges from 0 to 8191, or 0 to 1 111 111 111 111, and is to be complemented when exceeding 4095 or 0 111 111 111 111. Therefore complementation depends only on the first bit (position 23): if it is a one, then 16Q2 is the negative complement to 8192 of 16Q2X. Otherwise 16Q2 = 16Q2X.

For proper ambiguity resolution, the decimal 10Q2 may range from -500 to +499. Similarly, proper ambiguity resolution with the binary system will be obtained with 16Q2 between -4096 and +4095 or Q2 between -256 and +255. Having computed Q2,

$$S2C = S2 - 16Q2 \quad (9-6)$$

The coarse-ambiguity resolution follows closely Section 5.

$$\begin{aligned} S3 &= 256 P3 - 256 P1 = 256 \left(\frac{257}{256} p1 - Q3 \right) - 256 p1 \\ &= p1 - 256 Q3 \end{aligned} \quad (9-7)$$

$$256Q3X = S3X - S3 \quad (9-8)$$

$$S3C = S3 + 256Q3 \quad (9-9)$$

S3 is a 21-bit number with eight insignificant zeros at the end. S3X, as shown in Figure 5, equals S2C augmented by four X-bits at the beginning. Again, the X-bits are to emphasize that no operations are to be performed on them. 256Q3X ranges from zero to 131071 just as the decimal equivalent 10Q3X ranged from zero to 9999. If it exceeds half its range, i.e. 65 535, the negative complement to 131072 is to be taken. Since numbers larger than 65 535 are identified by a one in position 27, negative complementation is to be performed when bit 27 is a one. For proper ambiguity resolution, 256Q3 may range from -65536 to +65535 or Q3 from -256 to +255.

The resolution of the very-coarse ambiguities follows Section 6. Since at this time, there is no particular use of obtaining S4 explicitly, we start with computing S40.

$$S40 = 4096 P1 - 4096 P4 - 16 S3C \quad (9-10)$$

$$\begin{aligned} &= 4096 p1 - 4096 \left(\frac{4079}{4096} p1 - Q4 \right) - \frac{16}{4096} p1 \\ &= p1 + 4096 Q4 \end{aligned}$$

$$4096Q4X = S40 - S4X \quad (9-11)$$

$$S4C = S40 - 4096Q4 \quad (9-12)$$

Since S3C is a 21-bit number, so is S40. S4X equals S3C augmented by four X-bits at the beginning, as shown in Figure 5. Again, the sole purpose of showing these X-bits is to indicate that no operations are to be performed on them. 4096Q4X appears as a number of 21 significant bits, and ranges from zero to 2 097 151. The negative complement to 2 097 152 will be taken when 4096Q4X exceeds half its range, i.e. 1 048 575, which is indicated by a one in position 31. For correct ambiguity resolution, 4096Q4 may range from -1048576 to +1048575 or Q4 from -256 to +255.

In the final averaging process

$$RA = S4C - \frac{1}{2}Q2 - \frac{1}{2}Q3 - \frac{1}{2}Q4 \quad (9-13)$$

where the last three bits of Q4 are omitted to avoid exceeding a word length of 36 bits. Probably more than just those 3 bits could be omitted from both Q3 and Q4, but the time saving does not appear significant and using the complete Q's eliminates round-off errors.

10. THE IMPROVED METHOD OF AMBIGUITY RESOLUTION IN BINARY FORM

This routine is explained in detail for a decimal system in Section 8. See Figure 6 for a graphical aid. The resolution of the fine ambiguities is identical to that of Section 9:

$$S2 = 16P1 - 16P2 \quad (10-1)$$

$$16Q2X = S2 - S2X \quad (10-2)$$

$$S2C = S2 - 16Q2 \quad (10-3)$$

Now S2C is corrected by half the inconsistency of P1 and P2 as

$$R2C = S2C - \frac{1}{2}Q2 \quad (10-4)$$

R2C is a 22-bit binary number. Its last 18 bits, called P1C, are used as an improved reference for the resolution of the coarse ambiguities. We define now P3 with regard to this new reference as

$$P3 = \frac{257}{256}P1 - U3 \quad (10-5)$$

Then the coarse ambiguities are resolved as

$$S3A = 256P3 - 256P1C = 256\left(\frac{257}{256}p1C - U3\right) - 256p1C \quad (10-6)$$

$$= p1C - 256 U3$$

$$256U3X = S3X - S3A \quad (10-7)$$

where S3X equals R2C with four X-bits added at the beginning. The negative complement is taken, as usual, when bit 27 is a one. Otherwise $U3 = U3X$.

$$S3C = S3A + 256 U3 \quad (10-8)$$

Then we perform a second average

$$R3C = S3C - \frac{1}{3}U3 \quad (10-9)$$

We use the last 24 bits of R3C, called P1CC, as a reference for the resolution of the very-coarse ambiguities. Defining P4 with regard to this new reference

$$P4 = \frac{4079}{4096}p1CC - U4 \quad (10-10)$$

we compute S4A, U4, and S4C as

$$\begin{aligned} S4A &= 4096P1CC - 4096P4 - 16R3C \\ &= 4096p1CC - 4096\left(\frac{4079}{4096}p1CC - U4\right) - \frac{16}{4096}p1CC \end{aligned} \quad (10-11)$$

$$= p1CC + 4096U4$$

$$4096U4 = S4A - S4X \quad (10-12)$$

where S4X equals R3C with four X-bits added at the beginning. After taking the negative complement of 4096U4X when bit 31 is a one,

$$S4C = S4A - 4096U4 \quad (10-13)$$

Finally, the average range is

$$RA = S4C - \frac{1}{2}U4 \quad (10-14)$$

Figure 6 shows that the last bits of Q3 and Q4 are omitted when making the range corrections.

11. SMOOTHING

Smoothing, or time-averaging, may be applied to either the phasemeter outputs P or to the final averaged range RA. The same precision will be attained in either case as long as the phasemeter noise is small enough as to not introduce ambiguities. For the case of large phasemeter noise, smoothing the raw phasemeter data would enhance the ambiguity resolution capability. Consideration of the merits of various smoothing techniques should be made after actual DME noise characteristics have been studied.

12. DME TAPE FORMAT

DME data are recorded on standard low-density IBM tape in blocks of 120 36-bit words. One sample point, or sample, comprises 12 words, thus one block contains ten samples. The format of one sample is shown in Figure 7. Usually one 36-bit word contains two phasemeter words. Bits are numbered 0 to 35 according to the computer bit-weighting 2^0 to 2^{35} . Word 9 identifies tape location with computer bit weighting in full. All numbers are positive, therefore no position is reserved for identifying a sign. Word sequence for one sample is as follows:

Word 1	bits 19 - 0	G-2 timing
Word 2	bits 35 - 18	reserved for identification code
	bits 17 - 5	DME phase-reference word
Word 3	bits 35 - 23	D1 phasemeter output, Target 1
	bit 22	reserved for additional quality indication
	bit 21	D1 phasemeter lock-on indication
	bit 17 - 5	D2 phasemeter output, Target 1
	bit 4	reserved for additional quality indication
	bit 3	D2 phasemeter lock-on indication
Word 4	bit 35 - 23	D3 phasemeter output, Target 1
	bit 22	reserved for additional quality indication
	bit 21	D3 phasemeter lock-on indication
	bit 17 - 5	D4 phasemeter output, Target 1
	bit 4	reserved for additional quality indication
	bit 3	D4 phasemeter lock-on indication
Word 5	Target 2, otherwise as Word 3	
Word 6	Target 2, otherwise as Word 4	
Word 7	Target 3, otherwise as Word 3	
Word 8	Target 3, otherwise as Word 4	
Word 9 - 12	Spare, reserved for Doppler data.	

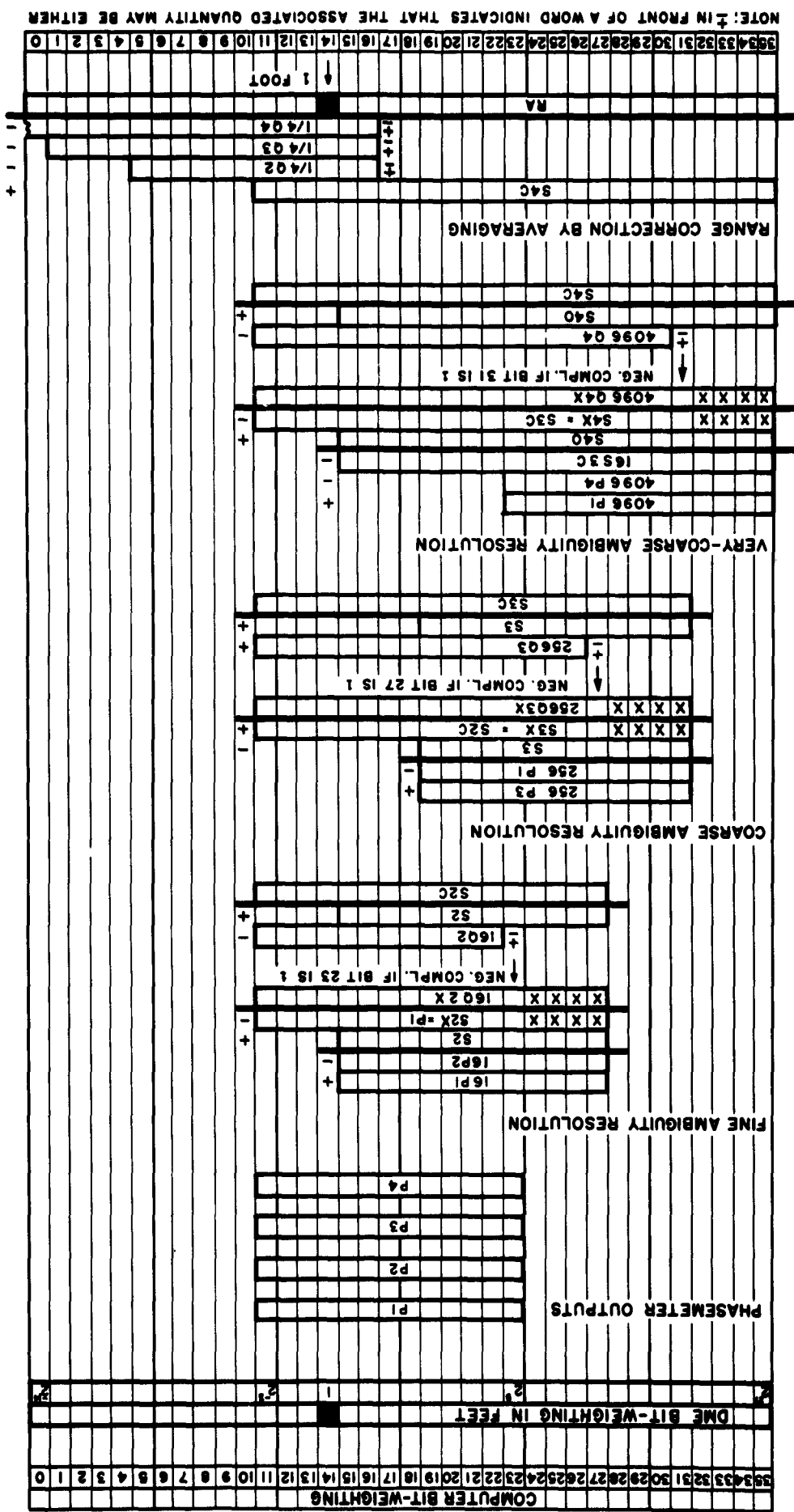


Figure 5 DME AMBIGUITY RESOLUTION WITH FOLLOWING RANGE CORRECTION

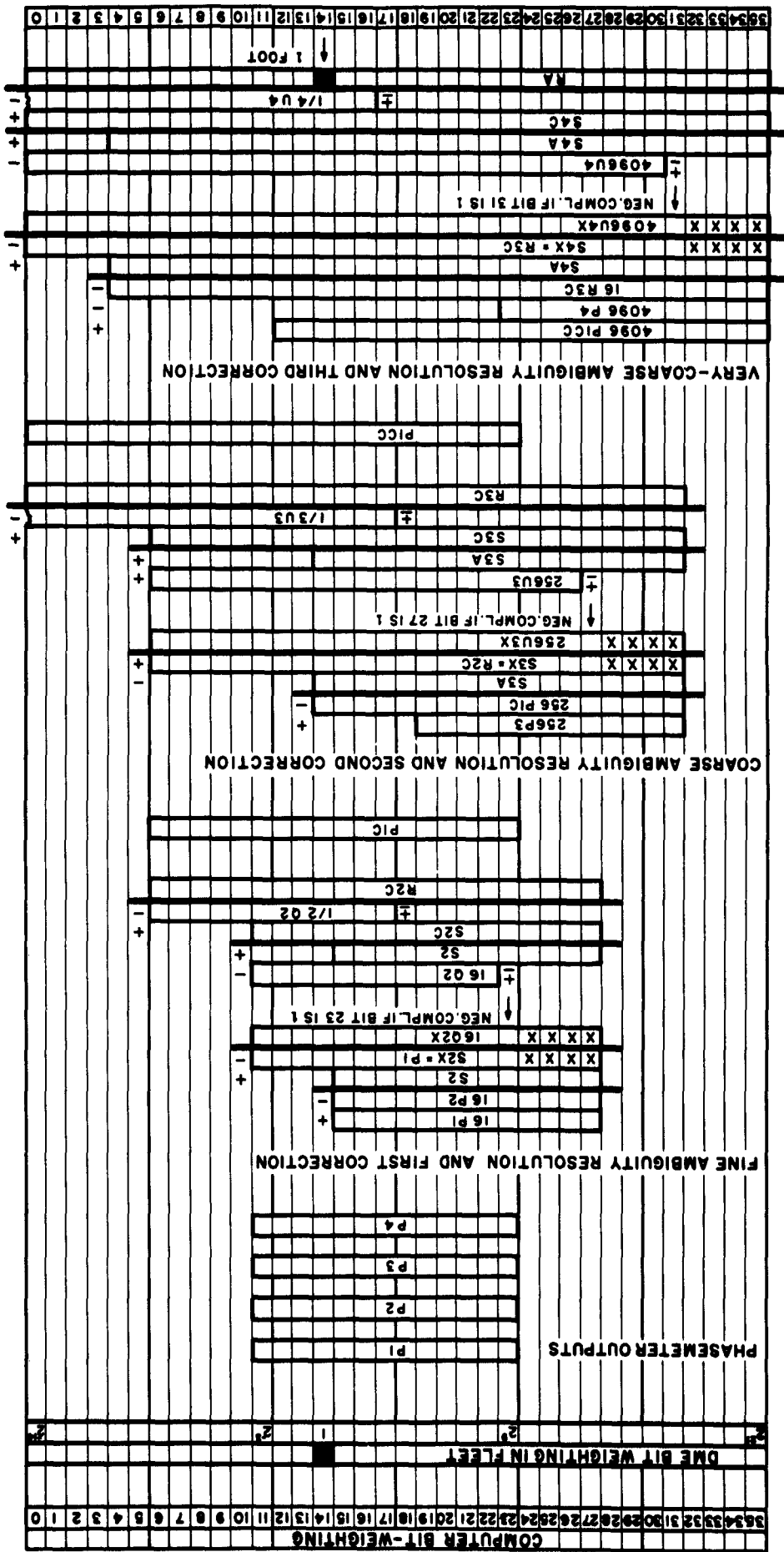


Figure 6 IMPROVED DME AMBIGUITY RESOLUTION WITH STEP-BY-STEP AVERAGING

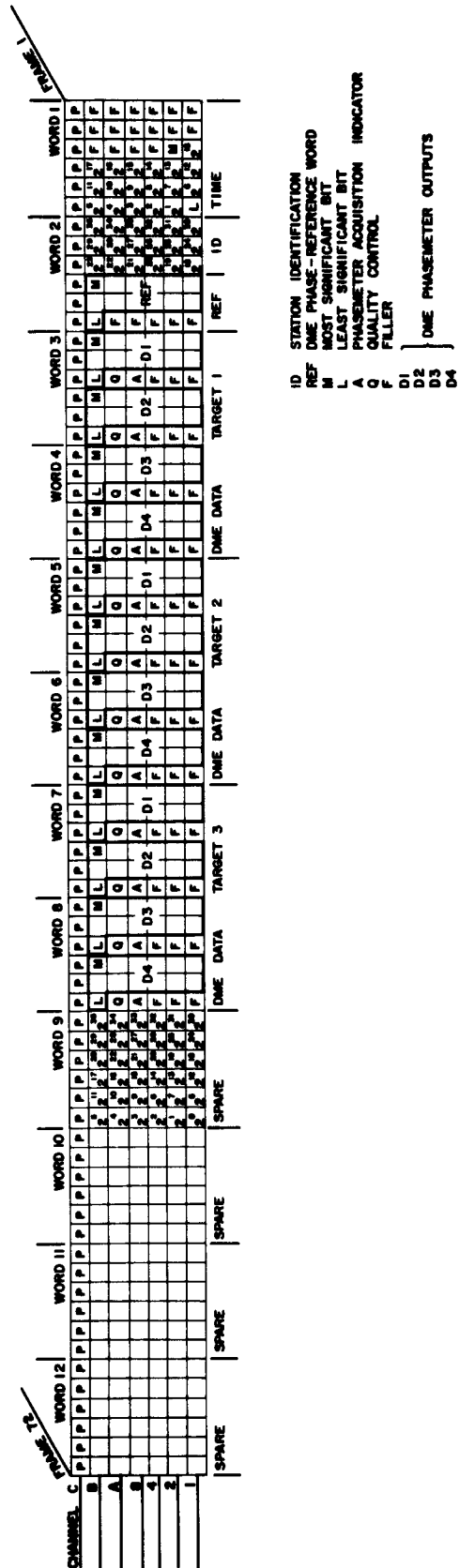


Figure 7 DME TAPE FORMAT

HEADQUARTERS
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AD Instrumentation Department, U. S. Army Electronics Research and Development Activity, White Sands Missile Range, New Mexico DME DATA REDUCTION, By D. F. Holberg, USA-ERDA-1, 29 pp incl illus, January 1963 UNCLASSIFIED Report The ambiguity-resolution problem for a Distance Measuring Equipment (DME), using four independent modulation frequencies in the 500-kc region, is described in mathematical terms. The method is developed for a DME model with decimal modulation-frequency relationships and then applied to the actual system whose modulation frequencies are related by binary numbers. Finally, two digital-computer routines providing for both ambiguity resolution and accuracy increase by averaging over the four phase measurements are developed.	UNCLASSIFIED 1. Data Format 2. Data Reduction 3. Ambiguity Resolution 4. Mathematical Analysis Copies of this document may be obtained upon request from: Armed Services Technical Information Agency Arlington Hall Station Attn: TIPCR Arlington 12, Virginia	AD Instrumentation Department, U. S. Army Electronics Research and Development Activity, White Sands Missile Range, New Mexico DME DATA REDUCTION, By D. F. Holberg, USA-ERDA-1, 29 pp incl illus, January 1963 UNCLASSIFIED Report The ambiguity-resolution problem for a Distance Measuring Equipment (DME), using four independent modulation frequencies in the 500-kc region, is described in mathematical terms. The method is developed for a DME model with decimal modulation-frequency relationships and then applied to the actual system whose modulation frequencies are related by binary numbers. Finally, two digital-computer routines providing for both ambiguity resolution and accuracy increase by averaging over the four phase measurements are developed.	UNCLASSIFIED 1. Data Format 2. Data Reduction 3. Ambiguity Resolution 4. Mathematical Analysis Copies of this document may be obtained upon request from: Armed Services Technical Information Agency Arlington Hall Station Attn: TIPCR Arlington 12, Virginia
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