A MICRO-COMPUTER-BASED SYSTEM
TO COMPUTE MAGNETIC VARIATION*

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A micro-computer-based implementation of a magnetic variation model for the continental United States is presented. The implementation computes magnetic variation as a function of latitude and longitude for general aviation receivers such as Loran-C.

I. INTRODUCTION

A mathematical model of magnetic variation in the continental United States (COT48) has been implemented in the Ohio University Loran-C receiver. The model is based on a least squares fit of a polynomial function. The implementation on the micro-processor based Loran-C receiver is possible with the help of an Am 9511 math chip, manufactured by Advanced Micro Devices, which performs 32 bit floating point mathematical operations. A Peripheral Interface Adapter (M6520) is used to communicate between the 6502 based micro-computer and the 9511 math chip. The implementation provides magnetic variation data to the pilot as a function of latitude and longitude. This report briefly describes the model and the real time implementation in the receiver.

II. THE MATHEMATICAL MODEL

The model was developed at the United States Geological Survey (USGS) by Fabiano et al. [1], by performing least squares analysis on more than 34,000 data measurements taken between 1900 and 1974. The analysis provides an analytical model of the magnetic field which is used to compute the magnetic variation.

For the actual magnetic variation calculation the COT48 region is partitioned into five, 12 degree longitudinal bands from 66 degrees West to 126 degrees West. A set of coefficients for each of the five bands is determined by the analytical model. A seventh order polynomial function of the analytical model is applied to compute the magnetic variation. The secular change is calculated in a similar way, the only difference being that a sixth order polynomial function is used. Also, the secular change case is not partitioned into bands and therefore the same set of coefficients is used for the entire COT48 region.

The polynomial function adapted for the procedure is

\[ \sum_{i=0}^{n} \sum_{j=0}^{l} a_{ij} (\theta_c)^{i-j} (\lambda_c)^j \]

- \( a_{ij} \) - co-efficients
- \( \theta_c \) - normalized latitude
  \[ = \theta - 52^\circ \]
- \( \lambda_c \) - normalized longitude
  \[ \lambda - \gamma \]
- \( \gamma \) - Table 1 - east longitude normalizing factor
- \( \theta \) - co-latitude = 90°-latitude
- \( \lambda \) - east longitude = 360°-longitude

The limits on each band and other constants are specified in Table 1 [2].
For the magnetic variation calculation \(n=7\), and thus 36 coefficients are specified for each band in the COT48 region, while in the secular change calculation \(n=6\), therefore only 28 coefficients are required for the whole COT48 region. All the coefficients are given in Appendix A.

The model was simulated in FORTRAN on an IBM 370 computer at Ohio University and a contour plot was made of the magnetic variation in the COT48 region (figure 1). The FORTRAN program listing is included in Appendix B. A copy of an actual magnetic variation chart published by the Defense Mapping Agency (DMA) is shown in figure 2. Comparisons between actual published values of the magnetic variation and values calculated by the model were made and are described later in this report.

III. MICRO-COMPUTER IMPLEMENTATION

The magnetic variation model was implemented on a 6502 based Super-Jolt micro-computer. The 6502 microprocessor has only an 8-bit data bus, so the processor needs a large amount of memory and rapid access. The calculations in the implementation of the model require complex floating point operations of exponents. It is therefore desirable to use an external hardware device to support the microprocessor in these calculations.

The Am9511 was chosen to be implemented with the Super-Jolt system. It is a peripheral math processor which performs the necessary floating point mathematical operations. The Am9511 is designed to be used in conjunction with microprocessor systems that have an 8-bit data bus. The stack oriented processor can handle 16 and 32-bit floating point operands and performs arithmetic and trigonometric functions. An instruction set of the Am9511 is included in Appendix C [3].

Additional hardware is necessary to allow the microprocessor to communicate with the math processor. An M6520 peripheral Interface Adapter (PIA) is used for handshaking with the microcomputer. The PIA consists of two 8-bit ports and several control registers for interface with external support devices. The overall design of the microcomputer, which is a part of the Ohio University Loran-C project is shown in figure 3.

IV. INTERFACING SOFTWARE

Special software is needed to allow the hardware components to interact with one another. The four subroutines 'PINT', 'PUSH', 'POP' and 'CMND' were written by Fischer [4] with this particular goal in mind. 'PINT' initializes the Am9511 and the PIA and, also, the scratchpad RAM locations. 'PUSH' is used to copy a four byte number from RAM to the stack of the Am9511. 'POP' does exactly the opposite by copying a four byte floating point number from the stack of the Am9511 to scratchpad RAM. 'CMND' sends an instruction byte to the Am9511 to perform the desired operation. It also checks the status register of the math processor to determine the outcome of the operation. Flow charts of the above subroutines are given in figure 4.

The actual magnetic variation program 'MAGVAR', occupies about 800 bytes of memory including scratchpad RAM locations. The coefficients 36
for each of the five bands, occupy 900 bytes of memory. Each of the coefficients is converted into a 32-bit floating point format compatible with the Am9511 representing four bytes. The secular variation calculation is not included in the real time implementation for reasons which shall be addressed later in this report. The complete program listing is given in Appendix D at the end of this report. The 'MAGVAR' program takes about 1.5 seconds in execution time. However, since the magnetic variation does not change rapidly in a small geographic region, it does not need to be computed every time navigation position information is updated, when included in the actual navigation receiver such as the Ohio University Loran-C. For example a small change in the software can allow computation of the magnetic variation every 30 miles, or a one degree change in geographic position or any other interval desired.

V. RESULTS AND CONCLUSIONS

Initially, the values for the magnetic variation were computed by the FORTRAN simulation and compared to values published by National Geophysical Data Center.* The results obtained were accurate to a large degree. Table 2 summarizes two points in each band, of which comparisons were made in the COT48 region. The reason for the discrepancy in the values could arise from the differences between the data and the model. Fabiano and others [1] evaluated the model and compared it to surveyed data for 1,450 points. From these measurements an overall root mean squared deviation of 0.5 degrees was found in the magnetic variation in the COT48 region. Also, a probable cause for the larger discrepancy in the region of bands 2 and 3 could indicate magnetic variation anomalies in the Great Lakes region.

In general, the results were found to be satisfactory and the decision was made to implement the model on the Ohio University Loran-C receiver. The results computed by the microcomputer were within 0.1 degrees of the values computed by the FORTRAN simulation. As indicated earlier, the secular change was not implemented on the receiver. The magnetic variation in the COT48 region changes less than 11 minutes of arc annually at its worst case. This translates to a change of less than one degree over a period of five years at its worst case. Since the Ohio University Loran-C receiver is a research tool, not implementing the secular change function would not have a crucial impact on the outcome of future research. The coefficients for the model are derived every five years by the USGS, and can be updated very easily to keep the model current.

The overall performance of the implementation proves to be satisfactory. The major advantages are that the magnetic variation is available all the time to the pilot to allow accurate determination of the compass heading. It is computed automatically and is one less adjustment or source of error during a flight, thus also reducing the chances of pilot error.

VI. ACKNOWLEDGMENTS

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* National Geophysical Data Center, Boulder, Colorado.
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VII. REFERENCES


[2] Ibid., Fabiano, Jones and Peddie.


VIII. APPENDICES

A. Co-efficients for the 5-band and secular change in COT48.

B. FORTRAN Program Listing of "MAGVAR".

C. Instruction Set for the Am9511.

D. 6502 Assembly Language Program Listing of the Magnetic Variation Implementation on the Ohio University Loran-C Receiver.
Table 1. Limits on Five Bands and the East Longitude Normalizing Factor.

<table>
<thead>
<tr>
<th>Band</th>
<th>Partition °W longitude</th>
<th>λ(degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66-77</td>
<td>289</td>
</tr>
<tr>
<td>2</td>
<td>78-89</td>
<td>277</td>
</tr>
<tr>
<td>3</td>
<td>90-101</td>
<td>265</td>
</tr>
<tr>
<td>4</td>
<td>102-113</td>
<td>253</td>
</tr>
<tr>
<td>5</td>
<td>114-125</td>
<td>241</td>
</tr>
</tbody>
</table>
Table 2. Comparisons Between Actual and Computed Values of Magnetic Variation.

<table>
<thead>
<tr>
<th>Band</th>
<th>Latitude Deg. N</th>
<th>Longitude Deg. W</th>
<th>Magnetic Variation Actual</th>
<th>Magnetic Variation Computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 66°W - 78°W</td>
<td>36</td>
<td>77</td>
<td>7.72°W</td>
<td>7.40°W</td>
</tr>
<tr>
<td>2 78°W - 90°W</td>
<td>40</td>
<td>73</td>
<td>13.05°W</td>
<td>12.71°W</td>
</tr>
<tr>
<td>3 90°W - 102°W</td>
<td>34</td>
<td>93</td>
<td>4.37°E</td>
<td>5.90°E</td>
</tr>
<tr>
<td>4 102°W - 114°W</td>
<td>36</td>
<td>103</td>
<td>9.93°E</td>
<td>10.91°E</td>
</tr>
<tr>
<td>5 114°W - 126°W</td>
<td>38</td>
<td>123</td>
<td>16.18°E</td>
<td>16.59°E</td>
</tr>
</tbody>
</table>
Figure 1. Continental U.S. magnetic variation.
Figure 2. Magnetic variation in the United States from world declination chart (source Defense Mapping Agency).
Figure 3. Block diagram for the microcomputer system.
Figure 4. Logic flow diagrams illustrating steps control program executes to communicate with 9511.
CMND

SET PIA SIDE-A TO OUTPUTS

SEND 8-BIT COMMAND TO 9511 VIA PIA SIDE-A

SET C/D HIGH, WR LOW

WAIT FOR END TO COME HIGH

SET PIA SIDE-A TO INPUTS

SET C/D HIGH, RD LOW

WAIT FOR PAUSE TO COME HIGH

GET 8-BIT STATUS FROM 9511 VIA PIA SIDE-A

DISABLE 9511

END

Figure 4. Concluded.
Appendix A. Co-efficients For the 5-band and Secular Change in COT48.

The coefficients \(a_{ij}\) for the magnetic variation in the conterminous United States (5 bands).

<table>
<thead>
<tr>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
<th>Band 4</th>
<th>Band 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_{00})</td>
<td>(-0.12544E \ 02)</td>
<td>(-0.26754E \ 01)</td>
<td>(0.66671E \ 01)</td>
<td>(0.13031E \ 02)</td>
</tr>
<tr>
<td>(a_{10})</td>
<td>(0.47404E \ 00)</td>
<td>(0.30498E \ 00)</td>
<td>(0.73577E \ 00)</td>
<td>(-0.24981E \ 00)</td>
</tr>
<tr>
<td>(a_{20})</td>
<td>(-0.79262E \ 00)</td>
<td>(-0.85269E \ 00)</td>
<td>(-0.62856E \ 00)</td>
<td>(-0.36471E \ 00)</td>
</tr>
<tr>
<td>(a_{30})</td>
<td>(-0.19389E \ 00)</td>
<td>(-0.11933E \ 01)</td>
<td>(0.75537E \ 00)</td>
<td>(-0.24981E \ 00)</td>
</tr>
<tr>
<td>(a_{40})</td>
<td>(-0.35571E \ 00)</td>
<td>(-0.20406E \ 00)</td>
<td>(-0.83811E \ 00)</td>
<td>(-0.20406E \ 00)</td>
</tr>
<tr>
<td>(a_{50})</td>
<td>(-0.39411E \ 00)</td>
<td>(-0.30498E \ 00)</td>
<td>(-0.47404E \ 00)</td>
<td>(-0.24981E \ 00)</td>
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<tr>
<td>(a_{60})</td>
<td>(-0.47404E \ 00)</td>
<td>(-0.30498E \ 00)</td>
<td>(-0.73577E \ 00)</td>
<td>(-0.24981E \ 00)</td>
</tr>
<tr>
<td>(a_{70})</td>
<td>(-0.47404E \ 00)</td>
<td>(-0.30498E \ 00)</td>
<td>(-0.73577E \ 00)</td>
<td>(-0.24981E \ 00)</td>
</tr>
<tr>
<td>(a_{80})</td>
<td>(-0.47404E \ 00)</td>
<td>(-0.30498E \ 00)</td>
<td>(-0.73577E \ 00)</td>
<td>(-0.24981E \ 00)</td>
</tr>
<tr>
<td>(a_{90})</td>
<td>(-0.47404E \ 00)</td>
<td>(-0.30498E \ 00)</td>
<td>(-0.73577E \ 00)</td>
<td>(-0.24981E \ 00)</td>
</tr>
</tbody>
</table>
Appendix A Concluded.

The coefficients \((a_{ij})\) for the secular change in the cor48 region.

\[
\begin{align*}
a_{00} & = -0.95533E \ 01 \\
a_{10} & = 0.11582E \ 00 \\
a_{11} & = -0.93474E \ -01 \\
a_{20} & = 0.12437E \ -01 \\
a_{21} & = -0.22416E \ -01 \\
a_{22} & = 0.27558E \ -05 \\
a_{30} & = 0.27558E \ -05 \\
a_{31} & = 0.53560E \ -03 \\
a_{32} & = -0.70816E \ -03 \\
a_{33} & = 0.32333E \ -03 \\
a_{40} & = -0.49965E \ -04 \\
a_{41} & = 0.18579E \ -04 \\
a_{42} & = -0.38644E \ -05 \\
a_{43} & = 0.11451E \ -04 \\
a_{44} & = -0.63005E \ -05 \\
a_{50} & = -0.23992E \ -06 \\
a_{51} & = 0.35195E \ -06 \\
a_{52} & = -0.26724E \ -06 \\
a_{53} & = -0.53815E \ -06 \\
a_{54} & = 0.44979E \ -06 \\
a_{55} & = -0.12145E \ -06 \\
a_{60} & = 0.85465E \ -07 \\
a_{61} & = -0.70500E \ -07 \\
a_{62} & = 0.26013E \ -07 \\
a_{63} & = 0.30705E \ -09 \\
a_{64} & = -0.12121E \ -07 \\
a_{65} & = -0.15529E \ -08 \\
a_{66} & = 0.23462E \ -08 
\end{align*}
\]
FORTRAN Program Listing of "MAGVAR"

THIS PROGRAM COMPUTES THE MAGNETIC VARIATION AS A
FUNCTION OF LATITUDE AND LONGITUDE. THE SECULAR
CHANGE IS ALSO CALCULATED. IT IS BASED ON THE
USD 80 POLYNOMIAL MODEL DEVELOPED BY FABIANO AND
OTHERS AT THE UNITED STATES GEOLOGICAL SURVEY IN
DENVER CO. PLEASE CONSULT USGS CIRCULAR NO. 810 FOR DETAILS.

RAJAN KAUL - 3/84

THE INPUT VARIABLES ARE ALAT, ALON AND YEAR
REPRESENTING LATITUDE, LONGITUDE AND YEAR.
VARIABLES A AND A1 ARE THE COEFFICIENTS TO BE READ

DIMENSION A(8,8),A1(8,8)
DATA EAST/'EAST'/,WEST/'WEST'/

READ LATITUDE AND LONGITUDE

WRITE(6,9) TYPE LAT. AND LONG. AS NNN.NN NNN.NN (F6.2,1X,F6.2)
READ(7,8) ALAT,ALON

DETERMINE WHICH BAND THE POINT IS IN TO LOAD CORRECT
SET OF COEFFICIENTS CORRESPONDING TO PARTICULAR BAND.

IF(ALON.GE.66.0.AND.ALON.LT.78.0) K=11
IF(ALON.GE.78.0.AND.ALON.LT.90.0) K=12
IF(ALON.GE.90.0.AND.ALON.LT.102.0) K=13
IF(ALON.GE.102.0.AND.ALON.LT.114.0) K=14
IF(ALON.GE.114.0.AND.ALON.LT.126.0) K=15

READ NORMALIZED LONGITUDE FOR PARTICULAR BAND AND THE
COEFFICIENTS.

READ(K,7) DLON

DEFINE COLATITUDE AND NORMALIZED EAST LONGITUDE

DLA=90.0-ALAT
DLO=360.0-ALON

INITIALIZE MAGNETIC VARIATION AND PERFORM CALCULATION

AK=0.0
DO 1 N=1,8
DO 2 I=1,N
KK=IABS(N-I)
JJ=IABS(I-I)
DL=DLO-DLON
IF(DL.EQ.0.0) DL=360.0
AK=AK+(A(N,I)*((DLA-52.01)**KK)*((DL)**JJ))
CONTINUE
CONTINUE

READ COEFFICIENTS FOR SECULAR CHANGE CALCULATION

DO 15 NN=1,7
DO 16 I=1,NN
READ(16,23,END=14) A1(NN,I)
CONTINUE
CONTINUE
DEFINE COLATITUDE AND NORMALIZED EAST LONGITUDE

DLA=90.0-ALAT
DLO=360.0-ALON

INITIALIZE SECULAR CHANGE AND PERFORM CALCULATION

SV=0.0
DO 11 N=1,7
   DO 12 I=1,N
      KK=IABS(N-I)
      JJ=IABS(I-I)
      DL=DLO-DLON
      IF(DL.EQ.0.0) DL=360.0
      SV=SV+(A(N,I)*((DLA-52.01)*KK)*((DL)**JJ))
   CONTINUE
CONTINUE

READ YEAR

WRITE(6,17)
FORMAT(5X,'TYPE YEAR AS NN,N (F4,1) E.G. JUN 84 = 84.5')
READ(7,18) YEAR
FORMAT(F4,1)

COMPUTE SECULAR VARIATION ANNUAL AND TO PRESENT DATE.

ALSO COMPUTE MAGNETIC VARIATION

SECVAR:SV*(YEAR-85.0)/60.0
SS:SV/60.0
VAR=AK+SECVAR
IF(VAR.LT.0.0) DIR=WEST
IF(VAR.GT.0.0) DIR=EAST
V=ABS(VAR)
WRITE(6,4) ALAT,ALON,V,DIR,SS
FORMAT(5X,'LATITUDE = ',F6.2/,5X,'LONGITUDE = ',F6.2/,5X,'MAGNETIC VARIATION = ',F6.2/,5X,'SECULAR CHANGE (ANNUAL) = ',F6.2)
STOP
END
### Command Summary

<table>
<thead>
<tr>
<th>Command Code</th>
<th>Command Mnemonic</th>
<th>Command Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed-Point 16-Bit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01101100</td>
<td>SAADD</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>01101101</td>
<td>SSUB</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>01101110</td>
<td>SMAU</td>
<td>Multiply NOS by TOS. Result stored in NOS. Pop Stack</td>
</tr>
<tr>
<td>01101111</td>
<td>SMUL</td>
<td>Multiply NOS by TOS. Upper half of result to NOS. Pop Stack</td>
</tr>
<tr>
<td>11101111</td>
<td>SGDIV</td>
<td>Divide NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td><strong>Fixed-Point 32-Bit</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00101100</td>
<td>DADD</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>01011010</td>
<td>DSUB</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>01011011</td>
<td>DMUL</td>
<td>Multiply NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>01011111</td>
<td>DMUL</td>
<td>Multiply NOS by TOS. Upper half of result to NOS. Pop Stack</td>
</tr>
<tr>
<td>01110111</td>
<td>DQIV</td>
<td>Divide NOS by TOS. Result to NOS. Pop Stack</td>
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<tr>
<td><strong>Floating-Point 32-Bit</strong></td>
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<td></td>
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<tr>
<td>00010001</td>
<td>FADD</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>00100010</td>
<td>FSUB</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>00100011</td>
<td>FMUL</td>
<td>Multiply NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>00110011</td>
<td>FDIV</td>
<td>Divide NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td><strong>Derived Floating-Point Functions</strong></td>
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<tr>
<td>00000001</td>
<td>SQRT</td>
<td>Square root of TOS. Result in TOS</td>
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<tr>
<td>00000010</td>
<td>SIN</td>
<td>Sine of TOS. Result in TOS</td>
</tr>
<tr>
<td>00000011</td>
<td>COS</td>
<td>Cosine of TOS. Result in TOS</td>
</tr>
<tr>
<td>00000100</td>
<td>ASIN</td>
<td>Inverse Sine of TOS. Result in TOS</td>
</tr>
<tr>
<td>00000101</td>
<td>ACOS</td>
<td>Inverse Cosine of TOS. Result in TOS</td>
</tr>
<tr>
<td>00001011</td>
<td>ATAN</td>
<td>Inverse Tangent of TOS. Result in TOS</td>
</tr>
<tr>
<td>00001100</td>
<td>LOG</td>
<td>Common Logarithm (base 10) of TOS. Result in TOS</td>
</tr>
<tr>
<td>00001101</td>
<td>LN</td>
<td>Natural Logarithm (base e) of TOS. Result in TOS</td>
</tr>
<tr>
<td>00010011</td>
<td>EXP</td>
<td>Exponential (e^) of TOS. Result in TOS</td>
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<tr>
<td><strong>Data Manipulation Commands</strong></td>
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<tr>
<td>00000000</td>
<td>NOP</td>
<td>No Operation</td>
</tr>
<tr>
<td>00001110</td>
<td>FIXS</td>
<td>Convert TOS from 32-bit fixed point format to 16-bit fixed point format</td>
</tr>
<tr>
<td>00011110</td>
<td>FIXD</td>
<td>Convert TOS from 32-bit fixed point format to 32-bit fixed point format</td>
</tr>
<tr>
<td>00101101</td>
<td>FLTS</td>
<td>Convert TOS from 16-bit fixed point format to 32-bit fixed point format</td>
</tr>
<tr>
<td>00111100</td>
<td>FLTD</td>
<td>Convert TOS from 32-bit fixed point format to 16-bit fixed point format</td>
</tr>
<tr>
<td>01011000</td>
<td>CHS</td>
<td>Change sign of 16-bit fixed point operand on TOS</td>
</tr>
<tr>
<td>01101000</td>
<td>CHS</td>
<td>Change sign of 32-bit fixed point operand on TOS</td>
</tr>
<tr>
<td>01101011</td>
<td>CHSF</td>
<td>Change sign of 32-bit fixed point operand on TOS</td>
</tr>
<tr>
<td>01101101</td>
<td>PTOS</td>
<td>Push TOS to stack</td>
</tr>
<tr>
<td>01101111</td>
<td>PTOF</td>
<td>Pop TOS from stack</td>
</tr>
<tr>
<td>01110000</td>
<td>POPM</td>
<td>Pop 16-bit fixed point operand from TOS to NOS. Pop Stack</td>
</tr>
<tr>
<td>01110011</td>
<td>POPF</td>
<td>Pop 32-bit fixed point operand from TOS to NOS. Pop Stack</td>
</tr>
<tr>
<td>01111000</td>
<td>POPM</td>
<td>Pop 16-bit fixed point operand from TOS to NOS. NOS becomes TOS</td>
</tr>
<tr>
<td>01111011</td>
<td>POPF</td>
<td>Pop 32-bit fixed point operand from TOS to NOS. NOS becomes TOS</td>
</tr>
<tr>
<td>01111100</td>
<td>POPM</td>
<td>Pop 16-bit fixed point operand from TOS to NOS. NOS becomes TOS</td>
</tr>
<tr>
<td>01111111</td>
<td>POPF</td>
<td>Pop 32-bit fixed point operand from TOS to NOS. NOS becomes TOS</td>
</tr>
<tr>
<td><strong>NOTES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>TOS means Top of Stack. NOS means Next on Stack.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>APU registers contain descriptions of each command function, including data ranges, accuracies, stack configurations, etc.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Many commands destroy one stack location (bottom of stack) during development of the result. The derived function may destroy several stack locations. See Application Notes for details.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>The Inexact arithmetic functions handle angles in radians, not degrees.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>No remainder is available for the fixed-point divide function.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Results will be undefined for any combination of operands causing bit not specified in this table.</td>
<td></td>
</tr>
</tbody>
</table>

*Original not available at time of publication.*
Appendix D. 6502 Assembly Language Program Listing of the Magnetic Variation Implementation on the Ohio University Loran-C Receiver.

ORG $A8
BASE BSS 2
ORG $55
CTRN BSS 1
CTRI BSS 1
COFCTR BSS 1
COFTAB BSS 2
MTEMP BSS 1
MTEMPI BSS 1

* EQUATES TO SUBROUTINE CALLS

PUSH EQU $28AC SUBROUTINE TO PUSH NUMBER ON TO 9511 STACK
POP EQU $28DC SUBROUTINE TO POP NUMBER FROM 9511 STACK
CMDND EQU $290C SUBROUTINE TO ISSUE COMMAND TO 9511 TO PERFORM OPERATION

* EQUATES TO VARIABLE ADDRESSES USED IN RNAV

PHGS EQU $E0 LATITUDE OF RECEIVER
THGS EQU $DC LONGITUDE OF RECEIVER
PI8 EQU $2C 180.0/PI
PA12 EQU $30 2*PI
F90 EQU $24 PI/2

* AM9511A COMMANDS.

PWR EQU $0B
FADD EQU $10
FSUB EQU $11
FMUL EQU $12
FDIV EQU $13
FADD EQU $14

* CONSTANTS AND VARIABLES

BAND EQU $8 ADDR FOR NORMALIZED LONGITUDE FOR PARTICULAR BAND
* FOLLOWED BY 36 COEFFICIENTS FOR EACH BAND AT LOCATION $C800 TO $CFF - ONE PAGE FOR EACH OF 5 BANDS.

* CONSTANTS FOR DIVISION IN LEAST SQUARES ALGORITHM FOR MAGVAR.

MZERO EQU $0 -0.0
MONE EQU MZERO+4 - 1.0
MTWO EQU MONE+4 -2.0
MTHREE EQU MTWO+4 -3.0
MFOUR EQU MTHREE+4 -4.0
MFIVE EQU MFOUR+4 -5.0
MSIX EQU MFIVE+4 -6.0
MSEVEN EQU MSIX+4 -7.0

* CONSTANTS THAT DEFINE LIMITS IN BANDS OF COT48 TO DETERMINE WHICH SET OF COEFFICIENTS NEED TO BE USED IN THE ALGORITHM TO DETERMINE MAGNETIC VARIATION.

A78 EQU MSEVEN+4
A90 EQU A78+4
A102 EQU A90+4
A114 EQU A102+4
A5201 EQU A114+4
NORMALIZED LATITUDE = 52.01*PI/180 RADIANS
F180 EQU A5201+4
P1/180
ATEMP EQU F180+4 TEMPORARY LOCATION USED WHILE DETERMINING THE PA
NLD EQU ATEMP+4 NLO-NORMALIZED LONGITUDE FOR PARTICULAR BAND.
MDLA EQU NLD+4 PI/2-PHGS (DEGREES)
MDLQ EQU MDLA+4 2*PI/2-PHGS (DEGREES)
MDLA52 EQU MDLQ+4 MDLA-5201
MAGVAR EQU MDLA52+4 CUMULATIVE MAGNETIC VARIATION
RLTEMP EQU MAGVAR+4 TEMPORARY LOCATION
MAGV0 EQU RLTEMP+4 MAGNETIC VARIATION

ORG $C000

104
* * MOVE CONSTANT NUMBER TABLE IN SCRATCH SPACE
* LDA =1
STA BASE+1      BASE = $0100
LDA =0
LDY =0
MO LDA TABLE1,y
STA (BASE)+y
INY
CPY =56
BNE MO

* * MAGNETIC VARIATION CALCULATION
* LDA =0
STA CTRN
STA CTRI INITIALIZE COUNTERS

* CALCULATE MDLA
* INC BASE+1
INC BASE+1      BASE = $0300
LDY =F90
JSR PUSH
DEC BASE+1
LDY =PHGS
JSR PUSH
LDA =FSUB
JSR CMND
INC BASE+1
LDY =P18
JSR PUSH
LDA =FMUL
JSR CMND
DEC BASE+1
DEC BASE+1      BASE = $0100
LDY =MDLA
MDLA = 90-PHGS
JSR POP

* CALCULATE MDLO
* INC BASE+1
INC BASE+1      BASE = $0300
LDY =A12
JSR PUSH
DEC BASE+1
LDY =THGS
JSR PUSH
LDA =FSUB
JSR CMND
INC BASE+1
LDY =P18
JSR PUSH
LDA =FMUL
JSR CMND
DEC BASE+1
DEC BASE+1      BASE = $0100
LDY =MDLO
MDLO = 360-THGS
JSR POP

* CALCULATE MDLA52
* LDY =MDLA
JSR PUSH
LDY =A5201
JSR PUSH
LDA =FSUB
JSR CMND
JSR CMND
LDY =MDLA52
JSR POP
MDLA52 = MDLA-52

105
* INC BASE+1  BASE = $0200
LDY =THGS
JSR PUSH
DEC BASE+1  BASE = $0100
LDY =RLTEMP
JSR POP  PUT THGS IN RLTEMP FOR COMPARISION PURPOSES IN THE NEXT SEGMENT TO DETERMINE WHICH BAND TO USE
* DETERMINE WHICH BAND IT IS TO CALCULATE MAGVAR.
* *
LDY =A78
JSR PUSH
LDY =RLTEMP
JSR PUSH
LDA =FSUB
JSR CMND
LDY =ATEMP
JSR POP
LDA (BASE),Y
BPL M1  IF ATEMP IS +VE -- BAND 1, IF NOT TRY FOR BAND 2
* *
LDY =A90
JSR PUSH
LDY =RLTEMP
JSR PUSH
LDA =FSUB
JSR CMND
LDY =ATEMP
JSR POP
LDA (BASE),Y
BPL M2  IF ATEMP IS +VE -- BAND 2, IF NOT TRY FOR BAND 3
* *
LDY =A102
JSR PUSH
LDY =RLTEMP
JSR PUSH
LDA =FSUB
JSR CMND
LDY =ATEMP
JSR POP
LDA (BASE),Y
BPL M3  IF ATEMP IS +VE -- BAND 3, IF NOT TRY BAND 4
* *
LDY =A114
JSR PUSH
LDY =RLTEMP
JSR PUSH
LDA =FSUB
JSR CMND
LDY =ATEMP
JSR POP
LDA (BASE),Y
BPL M4  IF ATEMP IS +VE -- BAND 4
JMP M5  MUST BE BAND 5
* *
SET COEFFICIENT TABLE ADDRESS TO CORRESPOND WITH PARTICULAR BAND
*
M1
LDY =MDLO
JSR PUSH
LDA =$C8
STA BASE+1
STA COFTAB+1  BAND 1
JMP M6
*
M2
LDY =MDLO
JSR PUSH
LDA =$C9
STA BASE+1
STA COFTAB+1 BAND 2
JMP M6

M3
LDY #MDLO
JSR PUSH
LDA #$CA
STA BASE+1
STA COFTAB+1 BAND 3
JMP M6

M4
LDY #MDLO
JSR PUSH
LDA #$CB
STA BASE+1
STA COFTAB+1 BAND 4
JMP M6

M5
LDY #MDLO
JSR PUSH
LDA #$CC
STA BASE+1
STA COFTAB+1 BAND 5
JMP M6

M6
LDA =0
STA COFTAB
LDY =BAND
JSR PUSH
LDA =$FSUB
JSR CMND
LDA =1
STA BASE+1
LDY =NDL
JSR POP
LDA =$4
STA COFCTR
CLC
LDA CTRN
LOAD OUTER LOOP COUNTER
ROL A
ROL A
POINT TO LOCATION FOR EXPONENTS FOR LEAST SQUARE
STA MTEMP
LDY MTEMP
JSR PUSH
LDA CTRI
LOAD INNER LOOP COUNTER
ROL A
ROL A
POINT TO LOCATION FOR EXPONENTS
STA MTEMP
LDY MTEMP
JSR PUSH
LDA =$FSUB
JSR CMND
N-I
LDY =$RLTEMP
JSR POP
LDY =$MDLA52
JSR PUSH
LDY =$MDLA52
LDA (BASE),Y
BPL C6
LDA =1
STA MTEMP1
LDA =$CHSF
JSR CMND
JMP C9

C6
LDA =0
STA MTEMP1
LDY =$RLTEMP
JSR PUSH
LDA =$PWR
JSR CMND
MDLA52**(N-I)
CLC
LDA CTRN
SBC CTRI
AND =1 EXPONENT EVEN?
BNE C4  YES, LOOP OUT
LDA MTEMP1 NO, IS NEGATIVE FLAG SET ?
BEQ C4  NO, FLAG NOT SET -- LOOP OUT
LDA =CHSF EXPONENT WAS ODD AND NEGATIVE FLAG
JSR CMND WAS SET -- THEREFORE CHANGE SIGN AGAIN
C4  LDY =ATEMP
JSR POP MDAL52**(N-I)
CLC
LDA CTRI LOAD INNER LOOP COUNTER FOR LEAST SQUARES PROCED
ROL A
* POINT TO LOCATION FOR EXPONENTS
ROL A
STA MTEMP
LDY MTEMP
JSR PUSH
LDY =RLTEMP
JSR POP
LDY =NDL
JSR PUSH
LDY =NDL
LDA (BASE),Y
BPL C7
BNE C5
LDA =0 STA MTEMP1
LDA =CHSF
JSR CMND
JMP C8
C7  LDA =1
STA MTEMP1
C8  LDY =RLTEMP
JSR PUSH
LDA =PWR
JSR CMND NDL**1

* IN THIS NEXT SEGMENT A TEST IS DONE TO MAKE SURE THE CORRECT SIGN
* IS ATTACHED WITH THE RESULT AFTER THE EXPONENT CALC'ULATION.

LDA CTRI
AND =1
BEQ C5
LDA MTEMP1
BNE C5
LDA =CHSF
JSR CMND
C5  LDY =ATEMP
JSR PUSH
LDA =FMUL
JSR CMND MDAL52**(N-I)*NDL**1
LDA COFTAB+1 PUT CO-EFFICIENT TABLE ADDRESS IN BASE
LDA COFCTR POINT TO CO-EFFICIENT COUNTER
JSR PUSH
LDA =FMUL
JSR CMND A(N(I)*NDL**(1)*MDAL52**(N-I)
LDA =1
STA BASE+1 BASE = $0100
LDA =MAGVAR
JSR PUSH
LDA =FADD ADD TO ACCUMULATE THE VALUE OF MAGVAR
JSR CMND MAGVAR=MAGVAR+A(N,I)*NDL**1*MDAL52**(N-I)
LDA COFCTR INC COFCTR
INC COFCTR IN(C) N(C)
INC COFCTR POINT TO NEXT SET OF CO-EFFICIENTS
LDA CTRN CMP CTRI
BEQ C1 IF THEY ARE EQUAL INNER LOOP DONE, CHECK IF OUTE
INC CTRI
JMP C2 IF NOT, GO BACK AND COMPLETE OUTER LOOP
C1  LDA CTRN CHECK TO SEE IF OUTER LOOP COMPLETE
CMP =7
BEQ C3 OUTER LOOP ALSO DONE, BRANCH OUT
**Table of Constants Used by Magnetic Variation Stored Starting at $0100 in Scratchpad RAM Location.**

<table>
<thead>
<tr>
<th>Address</th>
<th>Hex Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>00,00,00,00</td>
<td>0.0 (MZERO)</td>
<td></td>
</tr>
<tr>
<td>01,80,00,00</td>
<td>1.0 (MONE)</td>
<td></td>
</tr>
<tr>
<td>02,80,00,00</td>
<td>2.0 (MTWO)</td>
<td></td>
</tr>
<tr>
<td>03,80,00,00</td>
<td>3.0 (MTHREE)</td>
<td></td>
</tr>
<tr>
<td>03,80,00,00</td>
<td>4.0 (MFOUR)</td>
<td></td>
</tr>
<tr>
<td>03,80,00,00</td>
<td>5.0 (MFIVE)</td>
<td></td>
</tr>
<tr>
<td>03,80,00,00</td>
<td>6.0 (MSIX)</td>
<td></td>
</tr>
<tr>
<td>03,80,00,00</td>
<td>7.0 (MSEVEN)</td>
<td></td>
</tr>
<tr>
<td>01,AE,40,F1</td>
<td>78°PI/180 (A78)</td>
<td></td>
</tr>
<tr>
<td>01,09,06,DA</td>
<td>90°PI/180 (A90)</td>
<td></td>
</tr>
<tr>
<td>01,9E,DE,C4</td>
<td>102°PI/180 (A102)</td>
<td></td>
</tr>
<tr>
<td>01,FE,AD,AE</td>
<td>114°PI/180 (A114)</td>
<td></td>
</tr>
<tr>
<td>06,40,0A,30</td>
<td>52.01°PI/180 (A5201)</td>
<td></td>
</tr>
<tr>
<td>79,8E,FA,35</td>
<td>PI/180.0 (F180)</td>
<td></td>
</tr>
</tbody>
</table>

**Coefficients for the Five Bands of the COT48**

The data labeled Band(N) is the normalized longitude for each band. The coefficients are stored in one page chunks starting at $3800 to $3CFF.

**Band 1**

<table>
<thead>
<tr>
<th>Address</th>
<th>Hex Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>09,90,81,48</td>
<td>289.01</td>
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<tr>
<td>84,08,02,96</td>
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<td>7F,F2,86,07</td>
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<td></td>
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<tr>
<td>80,CA,E9,68</td>
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<td></td>
</tr>
<tr>
<td>FA,FA,B3,9C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>79,9B,AC,C4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>79,EF,5E,07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75,97,EB,10</td>
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<td></td>
</tr>
<tr>
<td>75,F1,0C,9A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7F,C5,A5,66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>77,A2,06,A6</td>
<td></td>
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</tr>
<tr>
<td>71,DA,E9,7F</td>
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<tr>
<td>F1,F8,7E,18</td>
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<tr>
<td>F1,97,FO,15</td>
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<tr>
<td>72,EF,02,28</td>
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<td>73,B3,00,EB</td>
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<td>6A,F8,66,41</td>
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<td>ED,CC,F2,4A</td>
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<td>6D,BF,FC,83</td>
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<td>EF,B2,50,90</td>
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<td>6F,99,C1,F7</td>
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<td>F0,80,1E,7A</td>
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</tr>
<tr>
<td>69,8E,96,3E</td>
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<tr>
<td>69,AB,24,13</td>
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<tr>
<td>6A,AE,80,20</td>
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<td></td>
</tr>
<tr>
<td>69,02,22,6E</td>
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<td></td>
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<tr>
<td>69,F8,29,0B</td>
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<td>EC,CC,59,1D</td>
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<td>67,C6,00,89</td>
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<td>60,B9,62,17</td>
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<td>61,EC,8F,0F</td>
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<td>ED,ED,7C,3B</td>
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<tr>
<td>64,CE,5F,2F</td>
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<td>66,A1,5E,31</td>
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<td>69,8E,6A,60</td>
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<tr>
<td>67,C3,7E,CE</td>
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</tr>
<tr>
<td>65,C2,FA,4F</td>
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</table>

**Band 2**

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<th>Description</th>
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<tr>
<td>82,AB,39,97</td>
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<td>7F,9C,26,0D</td>
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</tr>
<tr>
<td>80,DA,4A,06</td>
<td></td>
<td></td>
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</tbody>
</table>
HEX FA, C3, 82, A1
HEX 7B, 96, 1F, 46
HEX 7B, A0, F5, 0D
HEX 76, A9, 00, E8
HEX F6, C0, C6, EB
HEX F7, D5, 7C, 74
HEX F7, BF, 48, 07
HEX 72, 85, 1D, 21
HEX 72, C3, BC, 09
HEX F2, 06, 1C, 5F
HEX F3, 97, 6B, BF
HEX F6, 9F, AC, 25
HEX EE, 82, A3, 89
HEX 6E, 82, 1F, 27
HEX EF, C0, 00, 58
HEX EF, C3, E7, 79
HEX 72, A2, 8A, 81
HEX 72, 89, 90, 7C
HEX E9, A4, 31, 8A
HEX E9, 86, 30, 51
HEX 6A, BE, EF, E4
HEX EB, 80, 6E, 9B
HEX 68, 85, BA, 65
HEX 6C, 87, 98, 91
HEX 6F, A3, AC, 5A
HEX 64, A9, E4, CF
HEX E5, 83, D6, 58
HEX 69, 9A, F4, 1D
HEX 6B, 83, 02, DF
HEX 68, A8, 88, 9B
HEX 6B, E2, 35, A1
HEX EA, 83, 72, 90
HEX EB, A1, 00, C3
ORG $CA00
BAND3
HEX 09, 84, 81, A8 = 265.01
HEX 03, D5, 38, CD
HEX 79, F1, 19, 1D
HEX 80, A0, E9, 70
HEX F9, 87, B4, B1
HEX 79, C1, 81, 09
HEX FA, A2, F3, EB
HEX 76, 97, BB, AF
HEX F5, 9A, D3, 6F
HEX 76, B7, E2, A7
HEX 72, F5, 70, 94
HEX 72, E3, F3, 4B
HEX 70, A0, 0F, 1E
HEX 73, A2, 0E, 7C
HEX 74, 96, D5, 2F
HEX 72, E6, F3, C5
HEX EF, 89, 69, 28
HEX EE, A8, D1, DA
HEX F0, 93, B3, 7A
HEX F0, 89, EE, A9
HEX F0, EA, E5, 6B
HEX EF, 87, 09, C6
HEX EA, B3, 91, 11
HEX 67, 96, 50, EE
HEX 68, A8, 95, 5F
HEX E7, ED, 2E, 80
HEX ED, D2, 95, 5A
HEX ED, F8, 00, 15
HEX EB, D1, 56, 79
HEX 66, 91, 88, 02
HEX 65, 97, 80, FC
HEX 66, 85, 08, 91
HEX E1, CE, 0C, 45
HEX 69, BE, 20, A2
HEX 6A, 86, DF, B0
HEX 6A, 98, 99, 19
HEX E7, 81, BF, 35
ORG $CB00
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<th>Band 4</th>
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<td>04, DD, 80, 90</td>
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<td>75, BB, CE, 22</td>
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<td>F7, A3, B4, 25</td>
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<td>70, E5, 42, 8A</td>
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<td>EF, D6, 86, BB</td>
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<td>73, E2, 02, E2</td>
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<td>F2, D3, 47, EB</td>
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<td>72, 85, 73, 91</td>
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<td>E0, DC, 5C, A8</td>
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<td>6F, C9, DD, 4E</td>
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<td>F0, 9E, BB, 57</td>
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<td>6F, DA, 9C, 74</td>
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<td>6F, C4, 00, 19</td>
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