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

N87-22617

Rajan Kaul
Avionics Engineering Center
Department of Electrical and Computer Engineering
Ohio University
Athens, Ohio

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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

$$
\sum_{i=0}^{n} \sum_{j=0}^{i} a_{ij} (\Theta_c)^i (\lambda_c)^j
$$

- \(a_{ij}\) - co-efficients
- \(\Theta_c\) - normalized latitude
  - \(\Theta - 52\)
- \(\lambda_c\) - 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 coef-
ficients 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 com-
puted 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 magne-
tic 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 secu-
lar 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 satisfac-
tory. 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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the National Aeronautics and Space Administration at Langley Research
Center under grant number NGR 36-009-017. It was performed at Ohio
University's Avionics Engineering Center.

*National Geophysical Data Center, Boulder, Colorado.
The author would like to acknowledge the help of Dr. Robert Lilley, Associate Director and Mr. James Nickum, project engineer at Avionics Engineering center, whose suggestions proved invaluable in all stages of this research. Special thanks is also due to Dr. Hugh Bloemer, Department of Geography, whose advice was indispensable.

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.
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_{11} )</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_{20} )</td>
<td>-0.14935E+01</td>
<td>-0.11933E+01</td>
<td>-0.75577E+00</td>
<td>0.19160E+01</td>
</tr>
<tr>
<td>( a_{21} )</td>
<td>0.73049E+00</td>
<td>0.19648E+00</td>
<td>-0.99456E+00</td>
<td>-0.17215E+01</td>
</tr>
<tr>
<td>( a_{22} )</td>
<td>0.28976E+00</td>
<td>0.64498E+00</td>
<td>0.57882E+00</td>
<td>0.14505E+03</td>
</tr>
<tr>
<td>( a_{30} )</td>
<td>0.46111E+00</td>
<td>0.10931E+00</td>
<td>0.58517E+00</td>
<td>0.12940E+02</td>
</tr>
<tr>
<td>( a_{31} )</td>
<td>-0.15079E+00</td>
<td>-0.16286E+00</td>
<td>0.70147E+00</td>
<td>0.33821E+03</td>
</tr>
<tr>
<td>( a_{32} )</td>
<td>0.12562E+00</td>
<td>-0.10931E+00</td>
<td>-0.98517E+00</td>
<td>-0.12940E+02</td>
</tr>
<tr>
<td>( a_{40} )</td>
<td>0.25361E+01</td>
<td>0.31737E+00</td>
<td>0.54348E+00</td>
<td>0.13665E+04</td>
</tr>
<tr>
<td>( a_{41} )</td>
<td>-0.29623E+00</td>
<td>0.46667E+00</td>
<td>0.10017E+04</td>
<td>-0.63934E+05</td>
</tr>
<tr>
<td>( a_{42} )</td>
<td>-0.18112E+00</td>
<td>-0.51048E+00</td>
<td>0.77275E+04</td>
<td>0.10816E+03</td>
</tr>
<tr>
<td>( a_{50} )</td>
<td>0.55077E+00</td>
<td>-0.72203E+00</td>
<td>0.14306E+03</td>
<td>-0.50373E+04</td>
</tr>
<tr>
<td>( a_{51} )</td>
<td>0.62795E+00</td>
<td>-0.60910E+00</td>
<td>0.55063E+04</td>
<td>0.31817E+04</td>
</tr>
<tr>
<td>( a_{52} )</td>
<td>-0.15270E+00</td>
<td>-0.19467E+00</td>
<td>-0.40952E+05</td>
<td>-0.82114E+06</td>
</tr>
<tr>
<td>( a_{53} )</td>
<td>0.14304E+00</td>
<td>0.59918E+00</td>
<td>-0.88037E+05</td>
<td>0.89843E+03</td>
</tr>
<tr>
<td>( a_{54} )</td>
<td>0.55360E+00</td>
<td>0.38753E+00</td>
<td>-0.14001E+04</td>
<td>0.58428E+05</td>
</tr>
<tr>
<td>( a_{55} )</td>
<td>-0.76365E+00</td>
<td>-0.10931E+00</td>
<td>0.77275E+04</td>
<td>0.10816E+03</td>
</tr>
<tr>
<td>( a_{60} )</td>
<td>-0.62672E+00</td>
<td>-0.76459E+00</td>
<td>-0.12253E+06</td>
<td>-0.20612E+07</td>
</tr>
<tr>
<td>( a_{61} )</td>
<td>0.79694E+00</td>
<td>-0.62486E+00</td>
<td>0.17499E+07</td>
<td>0.41744E+09</td>
</tr>
<tr>
<td>( a_{62} )</td>
<td>0.15540E+00</td>
<td>0.17782E+00</td>
<td>0.39251E+07</td>
<td>0.10090E+06</td>
</tr>
<tr>
<td>( a_{63} )</td>
<td>0.97851E+00</td>
<td>-0.30012E+00</td>
<td>-0.27612E+07</td>
<td>0.57044E+07</td>
</tr>
<tr>
<td>( a_{64} )</td>
<td>0.11596E+00</td>
<td>0.24909E+00</td>
<td>0.15699E+06</td>
<td>-0.84960E+06</td>
</tr>
<tr>
<td>( a_{65} )</td>
<td>-0.76126E+00</td>
<td>0.74355E+00</td>
<td>-0.18538E+06</td>
<td>0.62532E+06</td>
</tr>
<tr>
<td>( a_{66} )</td>
<td>0.23144E+00</td>
<td>0.48778E+00</td>
<td>-0.38992E+06</td>
<td>-0.45290E+07</td>
</tr>
<tr>
<td>( a_{70} )</td>
<td>-0.16860E+00</td>
<td>0.24723E+00</td>
<td>0.84712E+08</td>
<td>0.10184E+08</td>
</tr>
<tr>
<td>( a_{71} )</td>
<td>0.43030E+00</td>
<td>-0.38370E+00</td>
<td>0.44108E+08</td>
<td>0.11497E+07</td>
</tr>
<tr>
<td>( a_{72} )</td>
<td>-0.69117E+00</td>
<td>0.19785E+07</td>
<td>0.77909E+08</td>
<td>0.16786E+07</td>
</tr>
<tr>
<td>( a_{73} )</td>
<td>0.33027E+00</td>
<td>-0.76731E+00</td>
<td>-0.37480E+09</td>
<td>0.64112E+09</td>
</tr>
<tr>
<td>( a_{74} )</td>
<td>0.93928E+00</td>
<td>-0.40025E+00</td>
<td>0.88535E+07</td>
<td>0.27692E+07</td>
</tr>
<tr>
<td>( a_{75} )</td>
<td>0.96128E+00</td>
<td>0.52668E+00</td>
<td>0.12561E+06</td>
<td>-0.93332E+07</td>
</tr>
<tr>
<td>( a_{76} )</td>
<td>0.22806E+00</td>
<td>-0.21183E+00</td>
<td>0.14212E+06</td>
<td>0.52297E+08</td>
</tr>
<tr>
<td>( a_{77} )</td>
<td>0.56746E+00</td>
<td>-0.29999E+00</td>
<td>-0.15083E+07</td>
<td>-0.54997E+07</td>
</tr>
</tbody>
</table>
Appendix A Concluded.

The coefficients \((a_{ij})\) for the secular change in the \(cot48\) region.

|   | \(a_{00}\) | \(a_{10}\) | \(a_{11}\) | \(a_{20}\) | \(a_{21}\) | \(a_{22}\) | \(a_{30}\) | \(a_{31}\) | \(a_{32}\) | \(a_{33}\) | \(a_{40}\) | \(a_{41}\) | \(a_{42}\) | \(a_{43}\) | \(a_{44}\) | \(a_{50}\) | \(a_{51}\) | \(a_{52}\) | \(a_{53}\) | \(a_{54}\) | \(a_{55}\) | \(a_{60}\) | \(a_{61}\) | \(a_{62}\) | \(a_{63}\) | \(a_{64}\) | \(a_{65}\) | \(a_{66}\) |
|   | \(-0.95533E\ -01\) | \(0.11582E\ -00\) | \(-0.93474E\ -01\) | \(0.13750E\ -01\) | \(-0.22416E\ -01\) | \(0.12437E\ -01\) | \(0.27558E\ -05\) | \(0.53560E\ -03\) | \(-0.70816E\ -03\) | \(0.32333E\ -03\) | \(-0.49965E\ -04\) | \(0.18579E\ -04\) | \(0.38544E\ -05\) | \(0.11451E\ -04\) | \(-0.63005E\ -05\) | \(-0.23992E\ -06\) | \(0.35195E\ -06\) | \(-0.26724E\ -06\) | \(-0.53815E\ -06\) | \(0.44979E\ -06\) | \(-0.12145E\ -06\) | \(0.85465E\ -07\) | \(-0.70500E\ -07\) | \(0.26013E\ -07\) | \(0.30705E\ -09\) | \(-0.12121E\ -07\) | \(-0.15529E\ -08\) | \(0.23462E\ -08\) |
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)
9 FORMAT(1X,'TYPE LAT. AND LONG. AS NNN.NN NNN.NN (F6.2,1X,F6.2)')
READ(7,8) ALAT, ALON
8 FORMAT(F6.2,1X,F6.2)

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
7 FORMAT(F6.2)
DO 5 NN=1,8
DO 6 I=1,NN
READ(K,3,END=13) A(NN,I)
6 CONTINUE
5 CONTINUE

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)**KK)**JJ)
1 CONTINUE
2 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)
15 CONTINUE
16 CONTINUE

101
Appendix B Concluded.

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

REAL) 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.LE.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
### Appendix C. Instruction Set for the AM9511

**Command Summary**

<table>
<thead>
<tr>
<th>Command Code</th>
<th>Command</th>
<th>Command Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 6 5 4 3 2 1 0</td>
<td><strong>7</strong></td>
<td><strong>6</strong></td>
</tr>
<tr>
<td>1 1 0 1 1 0 0 0</td>
<td>SAUX</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>1 1 0 1 1 0 1 1</td>
<td>SSAU</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>1 1 0 1 1 1 1 1</td>
<td>SADU</td>
<td>Add TOS to NOS. Upper half of result to NOS. Pop Stack</td>
</tr>
<tr>
<td>1 1 0 1 1 1 1 0</td>
<td>SSAU</td>
<td>Subtract TOS from NOS. Upper half of result to NOS. Pop Stack</td>
</tr>
<tr>
<td>1 1 0 1 1 0 1 1</td>
<td>SGIV</td>
<td>Divide NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
</tbody>
</table>

**FIXED-POINT 16-BIT**

<table>
<thead>
<tr>
<th>Command Code</th>
<th>Command</th>
<th>Command Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 1 0 1 1 0 0 0</td>
<td>DADD</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 1 0 1 1 0 1 1</td>
<td>DSB</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 1 0 1 1 1 1 1</td>
<td>DMUL</td>
<td>Multiply NOS by TOS. Lower half of result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 1 0 1 1 1 1 0</td>
<td>DMUL</td>
<td>Multiply NOS by TOS. Upper half of result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 1 0 1 1 1 1 0</td>
<td>DOVL</td>
<td>Divide NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
</tbody>
</table>

**FLOATING-POINT 32-BIT**

<table>
<thead>
<tr>
<th>Command Code</th>
<th>Command</th>
<th>Command Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0 0 0 0 0</td>
<td>FADD</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 0 1 0 1</td>
<td>FSUB</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 0 1 0 0</td>
<td>FMUL</td>
<td>Multiply NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 0</td>
<td>FADD</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 0 0 0 1</td>
<td>FSUB</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 0 1 0 0</td>
<td>FMUL</td>
<td>Multiply NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 0 1 0 1</td>
<td>FADD</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 0 1 1 0</td>
<td>FSUB</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 1 0 0 0</td>
<td>FMUL</td>
<td>Multiply NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 1 0 0 1</td>
<td>FADD</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 1 1 0 0</td>
<td>FSUB</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>0 0 0 0 1 1 0 1</td>
<td>FMUL</td>
<td>Multiply NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
</tbody>
</table>

**DERIVED FLOATING-POINT FUNCTIONS**

<table>
<thead>
<tr>
<th>Command Code</th>
<th>Command</th>
<th>Command Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0 0 0 0 1</td>
<td>SQRT</td>
<td>Square root of TOS. Result in TOS</td>
</tr>
<tr>
<td>0 0 0 0 0 0 1 0</td>
<td>SIN</td>
<td>Sine of TOS. Result in TOS</td>
</tr>
<tr>
<td>0 0 0 0 0 0 1 1</td>
<td>COS</td>
<td>Cosine of TOS. Result in TOS</td>
</tr>
<tr>
<td>0 0 0 0 0 1 0 0</td>
<td>ATN</td>
<td>Arc tangent of TOS. Result in TOS</td>
</tr>
<tr>
<td>0 0 0 0 1 0 0 0</td>
<td>LOG</td>
<td>Logarithm of TOS. Result in TOS</td>
</tr>
<tr>
<td>0 0 0 0 1 0 0 1</td>
<td>N</td>
<td>Natural logarithm of TOS. Result in TOS</td>
</tr>
<tr>
<td>0 0 0 0 1 1 0 0</td>
<td>EXP</td>
<td>Exponential (s) of TOS. Result in TOS</td>
</tr>
<tr>
<td>0 0 0 1 0 0 0 1</td>
<td>PWI</td>
<td>NOS raised to the power in TOS. Result in NOS. Pop Stack</td>
</tr>
</tbody>
</table>

**DATA MANIPULATION COMMANDS**

<table>
<thead>
<tr>
<th>Command Code</th>
<th>Command</th>
<th>Command Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0 0 0 0 0</td>
<td>NOP</td>
<td>No Operation</td>
</tr>
<tr>
<td>0 0 0 0 1 1 1 1</td>
<td>FIXS</td>
<td>Convert TOS from floating point to 16-bit fixed point format</td>
</tr>
<tr>
<td>0 0 0 0 0 1 1 1</td>
<td>FIXD</td>
<td>Convert TOS from fixed point to 32-bit fixed point format</td>
</tr>
<tr>
<td>0 0 0 0 1 1 0 1</td>
<td>FLT</td>
<td>Convert TOS from 16-bit fixed point to floating point format</td>
</tr>
<tr>
<td>0 0 0 0 0 1 1 0</td>
<td>FLD</td>
<td>Convert TOS from 32-bit fixed point to floating point format</td>
</tr>
<tr>
<td>0 0 0 1 0 1 0 0</td>
<td>CHSS</td>
<td>Change sign of 16-bit fixed point operand on TOS</td>
</tr>
<tr>
<td>0 0 0 1 0 1 1 0</td>
<td>CHSF</td>
<td>Change sign of 32-bit fixed point operand on TOS</td>
</tr>
<tr>
<td>0 0 0 1 1 0 0 1</td>
<td>CHDS</td>
<td>Change sign of floating point operand on TOS</td>
</tr>
<tr>
<td>0 0 0 1 1 1 0 0</td>
<td>CHDF</td>
<td>Change sign of floating point operand on TOS</td>
</tr>
<tr>
<td>0 0 1 0 0 0 1 1</td>
<td>PTOS</td>
<td>Push 32-bit fixed point onto TOS to NOS (Copy)</td>
</tr>
<tr>
<td>0 0 1 0 1 0 0 1</td>
<td>POPM</td>
<td>Pop 16-bit fixed point operand from TOS to NOS</td>
</tr>
<tr>
<td>0 0 1 1 0 0 0 0</td>
<td>POPH</td>
<td>Pop 32-bit fixed point operand from NOS to NOS</td>
</tr>
<tr>
<td>0 0 1 1 0 0 0 1</td>
<td>POPF</td>
<td>Pop 16-bit fixed point operand from NOS to NOS</td>
</tr>
<tr>
<td>0 0 1 1 0 0 1 1</td>
<td>XCHS</td>
<td>Exchange 16-bit fixed point operands TOS and NOS</td>
</tr>
<tr>
<td>0 0 1 1 0 1 0 0</td>
<td>XCHF</td>
<td>Exchange 32-bit fixed point operands TOS and NOS</td>
</tr>
<tr>
<td>0 0 1 1 1 0 0 1</td>
<td>XCHS</td>
<td>Exchange 16-bit floating point operands TOS and NOS</td>
</tr>
<tr>
<td>0 0 1 1 1 0 1 1</td>
<td>XCHF</td>
<td>Exchange 32-bit floating point operands TOS and NOS</td>
</tr>
</tbody>
</table>

**NOTES**

1. TOS means Top of Stack. NOS means Nest on Stack.
2. AMD Application Note "Algorithm Details for the AMD9112A" provides additional descriptions of each command function, including data ranges, accuracies, stack configurations, etc.
3. Many commands destroy one stack location (bottom of stack) during development of the result. The derived functions may destroy several stack locations. See Application Note for details.

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
CTR1 BSS 1
COFCTR BSS 1

* USED IN LEAST SQUARES ALGORITHM

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
CMND EQU $290C SUBROUTINE TO ISSUE COMMAND TO 9511 TO PERFORM OPERATION

* EQUATES TO VARIABLE ADDRESSES USED IN RNAV

PHGS EQU $EO LATITUDE OF RECEIVER
THGS EQU $DC LONGITUDE OF RECEIVER
P 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
FSQRT EQU $13
CHSF EQU $15

* CONSTANTS AND VARIABLES
BAND EQU $0 ADDR FOR NORMALIZED LONGITUDE FOR PARTICULAR BAND FOLLOWED BY 36 CO-EFFICIENTS FOR EACH BAND AT LOCATION $C800 TO $C3FF - 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
MFIVE EQU MFIVE+4 -5.0
MSIX EQU MSIX+4 -6.0
MSEVEN EQU MSEVEN+4 -7.0

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

A78 EQU MSEVEN+4
A90 EQU A78+4
A100 EQU A90+4
A114 EQU A100+4
AS241 EQU AS241+4
A5201 EQU A114+4
AF80 EQU A5201+4
ADP EQU A5201+4

* NORMALIZED LATITUDE = 52.01*PI/180 RADIANS

ATEMP EQU AF80+4 TEMPORARY LOCATION USED WHILE DETERMINING THE PA
NDL EQU ATEMP+4 MDLO-NORMALIZED LONGITUDE FOR PARTICULAR BAND.
MMDA EQU NDL+4 MDLA-NORMALIZED LATITUDE USED WHILE DETERMINING THE PA
MDL0 EQU MDL0+4 MDL0-NORMALIZED LATITUDE USED WHILE DETERMINING THE PA
MDL0A4 EQU MDL0+4 MDL0A4-NORMALIZED LATITUDE USED WHILE DETERMINING THE PA
MAGVAR EQU MDL0A4+4 CUMULATIVE MAGNETIC VARIATION
RTEMP EQU MAGVAR+4 TEMPORARY LOCATION
MAGVOD EQU RTEMP+4 MAGNETIC VARIATION

ORG $C000

104
* * MOVE CONSTANT NUMBER TABLE IN SCRATCH SPACE

LDA =1
STA BASE+1 BASE = $0100
LDA =0
LDY =0
MOV 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 BASE = $0200
LDY =PHGS
JSR PUSH
LDA =FSUB
JSR CMND
INC BASE+1 BASE = $0300
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 BASE = $0200
LDY =THGS
JSR PUSH
LDA =FSUB
JSR CMND
INC BASE+1 BASE = $0300
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
MT
M2
INC BASE+1 BASE = $0200
LDY = THGS
JSR PUSH
DEC BASE+1 BASE = $0100
LDY = RLTEMP
JSR POP
PUT THGS IN RLTEMP FOR COMPARISON 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
  LDY = A90
  JSR PUSH
  LDY = RLTEMP
  JSR PUSH
  LDA = FSUB
  JSR CMND
  LDY = ATEMP
  JSR POP
  LDA (BASE), Y
  BPL M2
  LDY = A102
  JSR PUSH
  LDY = RLTEMP
  JSR PUSH
  LDA = FSUB
  JSR CMND
  LDY = ATEMP
  JSR POP
  LDA (BASE), Y
  BPL M3
  LDY = A114
  JSR PUSH
  LDY = RLTEMP
  JSR PUSH
  LDA = FSUB
  JSR CMND
  LDY = ATEMP
  JSR POP
  LDA (BASE), Y
  BPL M4
  JMP M5
  IF ATEMP IS +VE -- BAND 1, IF NOT TRY FOR BAND 2
  ATEMP = 78 * PI/180 - THGS

  IF ATEMP IS +VE -- BAND 2, IF NOT TRY FOR BAND 3
  ATEMP = 90 * PI/180 - THGS

  IF ATEMP IS +VE -- BAND 3, IF NOT TRY BAND 4
  ATEMP = 102 * PI/180 - THGS

  IF ATEMP IS +VE -- BAND 4
  ATEMP = 114 * PI/180 - THGS

  MUST BE BAND 5

  SET CO-EFFICIENT TABLE ADDRESS TO CORRESPOND WITH PARTICULAR BAND

  LDY = M£LO
  STA BASE+1
  STA COFTAB+1
  BAND 1

  LDY = M£LO
  STA BASE+1
  BAND 2

  LDY = M£LO
  STA Base
  BAND 3

  LDY = M£LO
  STA Base
  BAND 4

  LDY = M£LO
  STA Base
  BAND 5
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

M6  LDA =0
STA COFTAB
LDY =BAND
JSR PUSH
LDA =$FSUB
JSR CMND
LDA =1
STA BASE+1
LDY =NDL
JSR POP
LDA =4
STA COFCTR
CLC
LDA CTRN
LOAD OUTER LOOP COUNTER
ROL A
ROL A
STA MTEMP
LDY MTEMP
JSR PUSH
LDA CTRI
LOAD INNER LOOP COUNTER
ROL A
ROL A
STA MTEMP
LDY MTEMP
JSR PUSH
LDA =$FSUB
JSR CMND
N-1
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

C9  LDY =RLTEMP
JSR PUSH
LDA =$PWR
JSR CMND
MDLA52**(N-1)
CLC
LDA CTRN
SBC CTRI
AND =1  EXPONENT EVEN?
BNE C4	YES, LOOP OUT
LDA MTEMP1
BEQ C4	NO, IS NEGATIVE FLAG SET?
BNE C5	NO, FLAG NOT SET -- LOOP OUT
LDA =CHSF
JSR CMND	EXPONENT WAS ODD AND NEGATIVE FLAG WAS SET -- THEREFORE CHANGE SIGN AGAIN
C4
LDY =ATEMP
JSR POP
CLC
LDA CTRI
ROL A
STA MTEMP
LDY MTEMP
JSR PUSH
LDY =RLTEMP
JSR POP
LDY =NDL
JSR PUSH
LDY =NDL
LDA (BASE),Y
BPL C7
LDA =0
STA MTEMP1
LDA =CHSF
JSR CMND
JMP C8
C7
LDA =1
STA MTEMP1
C8
LDY =RLTEMP
JSR PUSH
LDA =PWR
JSR CMND

* IN THIS NEXT SEGMENT A TEST IS DONE TO MAKE SURE THE CORRECT SIGN IS ATTACHED WITH THE RESULT AFTER THE EXPONENT CALCULATION.
* LDA CTRI
  AND =1
  BEQ C5
  LDA MTEMP1
  BNE C5
  LDA =CHSF
  JSR CMND
C5
LDY =ATEMP
JSR CMND
LDA =FMUL
JSR CMND
LDA COFTAB+1
STA BASE+1
PUT CO-EFFICIENT TABLE ADDRESS IN BASE
LDA COFCTR
POINT TO CO-EFFICIENT COUNTER
JSR PUSH
LDA =FMUL
JSR CMND
LDA =1
STA BASE+1
BASE = $0100
LDA =MAGVAR
JSR PUSH
LDA =FADD
JSR CMND
ADD TO ACCUMULATE THE VALUE OF MAGVAR
LDA =MAGVAR
JSR CMND
MAGVAR=MAGVAR+A(N,I)*NDL**(I)*MDLA52**(N-I)
LDA =1
INC COFCTR
INC COFCTR
INC COFCTR
INC COFCTR
LDA CTRN
CMP CTRI
BEQ C1
INC CTRI
JMP C2
LDA CTRN
CHECK TO SEE IF OUTER LOOP COMPLETE
CMP =7
BEQ C3
OUTER LOOP ALSO DONE, BRANCH OUT
C3

TABLE 1

BAND1

BAND2

INC CTRN

INCREMENT OUTER LOOP COUNTER

LDA =0

INITIALIZE INNER LOOP COUNTER

JMP C2

START OVER

RTS

RETURN FROM MAGVAR TO MAIN PROGRAM

* TABLE OF CONSTANTS USED BY MAGNETIC VARIATION STORED AT $0100 IN SCRATCHPAD RAM LOCATION.

* STARTING AT $0100 IN SCRATCHPAD RAM LOCATION.

TABLE1 HEX 00,00,00,00 - 0.0 (MZERO)
HEX 01,80,00,00 - 1.0 (MONE)
HEX 02,80,00,00 - 2.0 (MTWO)
HEX 02,00,00,00 - 3.0 (MTHREE)
HEX 03,80,00,00 - 4.0 (MFOUR)
HEX 03,00,00,00 - 5.0 (MFIELD)
HEX 03,00,00,00 - 6.0 (MSIX)
HEX 03,00,00,00 - 7.0 (MSEVEN)
HEX 01,AE,40,F1 - 78*PI/180 (A78)
HEX 03,06,00,00 - 90*PI/180 (A90)
HEX 01,0E,DE,C4 - 102*PI/180 (A102)
HEX 01,DE,AE,AE - 114*PI/180 (A114)
HEX 0A,0B,00,00 - 52.01*PI/180 (A5201)
HEX 7B,8E,FA,35 - PI/180.0 (F180)

* CO-EFFICIENTS FOR THE FIVE BANDS OF THE COT48
THE DATA LABELED BAND(N) IS THE NORMALIZED LONGITUDE FOR EACH BAND. THE CO-EFFICIENTS ARE STORED IN ONE PAGE CHUNKS STARTING AT
*$3800 TO $3CFF.

* ORG $C800

BAND1

HEX 09,90,81,48 - 289.01
HEX 84,09,02,96
HEX 7F,F2,86,07
HEX 80,CA,E9,68
HEX FA,F4,B3,9C
HEX 79,96,AC,C4
HEX 79,EF,5E,07
HEX 75,97,EB,10
HEX 75,F1,09,9A
HEX F7,C5,A5,66
HEX 77,02,06,A6
HEX 71,DC,E9,7F
HEX F1,F8,7E,1B
HEX F1,97,FO,15
HEX 72,77,02,28
HEX 73,83,B0,EB
HEX 6A,F8,66,41
HEX ED,CC,F2,4A
HEX 6D,BF,FC,83
HEX EF,B2,50,90
HEX 6F,89,C1,F7
HEX F0,80,1E,7A
HEX 89,B6,96,3E
HEX 69,AB,24,13
HEX 6A,6D,00,20
HEX 69,02,22,6E
HEX 69,48,29,C8
HEX EC,CC,59,1D
HEX 67,C6,00,89
HEX EF,B9,62,17
HEX 61,EC,8F,OF
HEX 63,ED,7C,38
HEX 64,2F,5F,2F
HEX 66,A1,5E,31
HEX 66,9D,6A,60
HEX 67,C3,E7,CE
HEX 55,C2,FA,4F

ORG $C900

BAND2

HEX 09,8A,81,48 - 277.01
HEX 82,AB,39,97
HEX 7F,9C,26,0D
HEX 80,DA,4A,06
BAND4

<table>
<thead>
<tr>
<th>HEX</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>08,FD,02,8F</td>
<td>253.01</td>
</tr>
<tr>
<td>04,00,80,9D</td>
<td></td>
</tr>
<tr>
<td>FF,FF,02,74</td>
<td></td>
</tr>
<tr>
<td>FF,DA,00,C8</td>
<td></td>
</tr>
<tr>
<td>76,0C,64,B4</td>
<td></td>
</tr>
<tr>
<td>7B,9C,F5,DA</td>
<td></td>
</tr>
<tr>
<td>FB,80,07,85</td>
<td></td>
</tr>
<tr>
<td>74,9E,19,1A</td>
<td></td>
</tr>
<tr>
<td>F7,0C,58,C3</td>
<td></td>
</tr>
<tr>
<td>75,06,CE,22</td>
<td></td>
</tr>
<tr>
<td>F7,A3,84,25</td>
<td></td>
</tr>
<tr>
<td>70,64,42,BA</td>
<td></td>
</tr>
<tr>
<td>EF,0E,86,8B</td>
<td></td>
</tr>
<tr>
<td>73,E2,02,E2</td>
<td></td>
</tr>
<tr>
<td>F2,03,47,E8</td>
<td></td>
</tr>
<tr>
<td>72,85,73,91</td>
<td></td>
</tr>
<tr>
<td>EC,DC,6C,A8</td>
<td></td>
</tr>
<tr>
<td>6F,09,0D,4E</td>
<td></td>
</tr>
<tr>
<td>F0,06,8B,67</td>
<td></td>
</tr>
<tr>
<td>6F,DA,9C,74</td>
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</tr>
<tr>
<td>6F,04,00,19</td>
<td></td>
</tr>
<tr>
<td>71,A2,4F,72</td>
<td></td>
</tr>
<tr>
<td>E7,B1,0E,70</td>
<td></td>
</tr>
<tr>
<td>E1,E5,70,20</td>
<td></td>
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ORG $CC00

BAND5
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