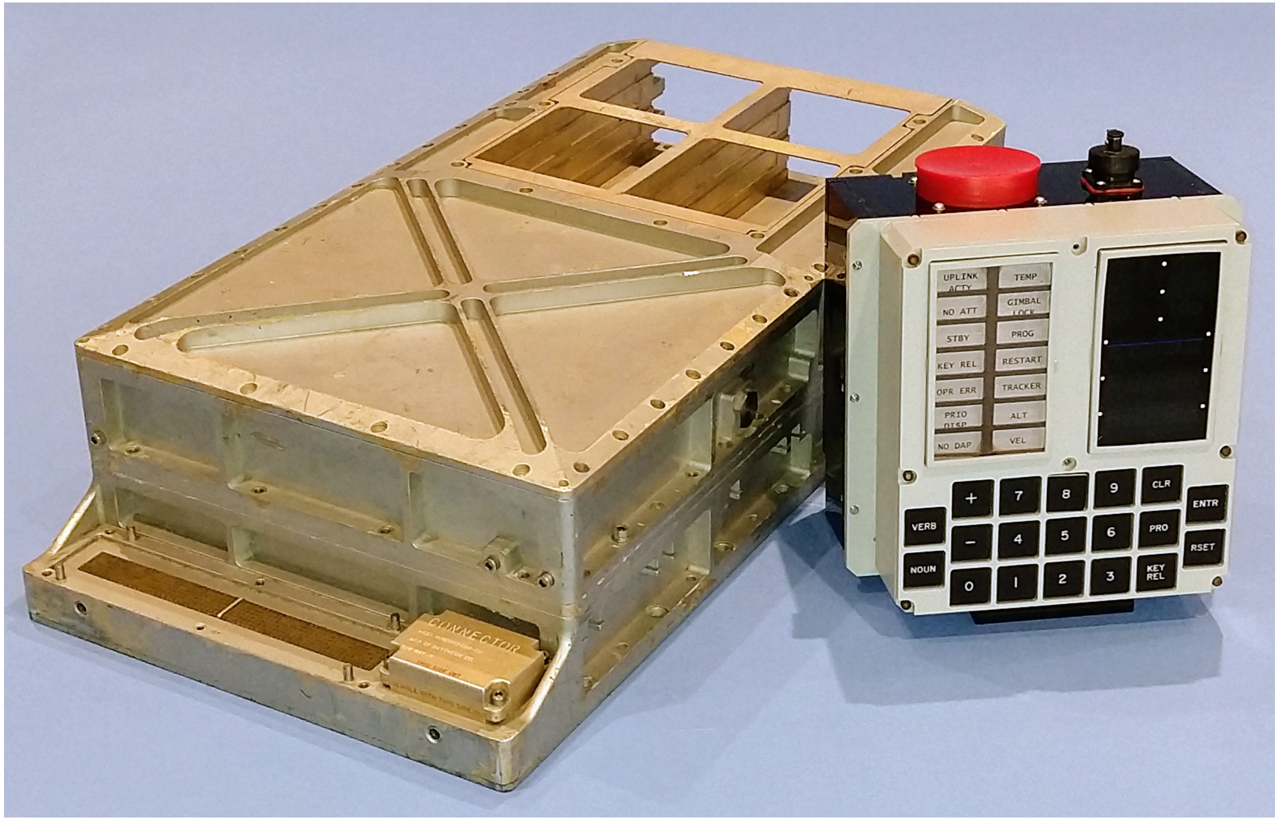
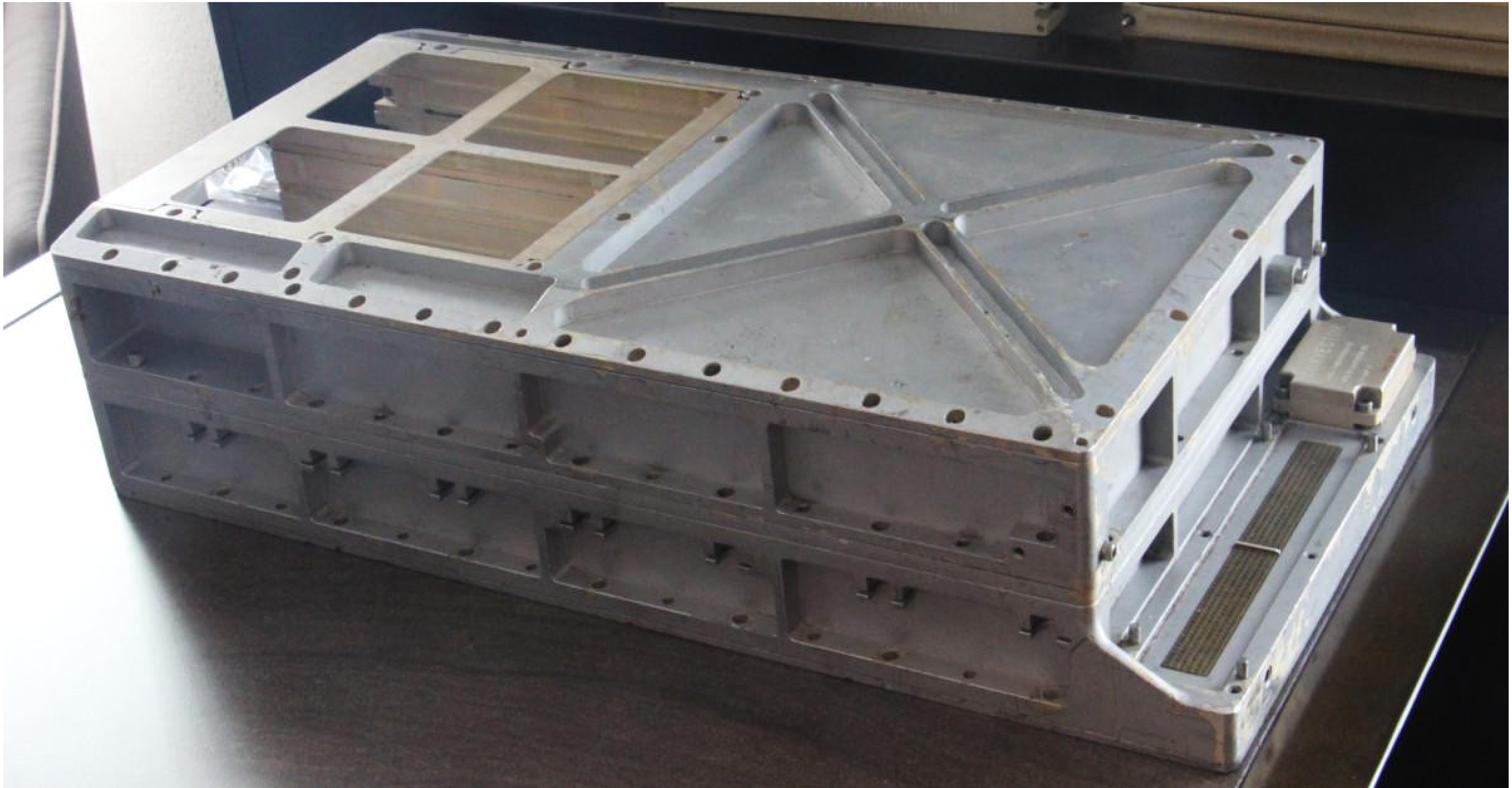
Restoring an Apollo Guidance Computer



Ken Shirriff

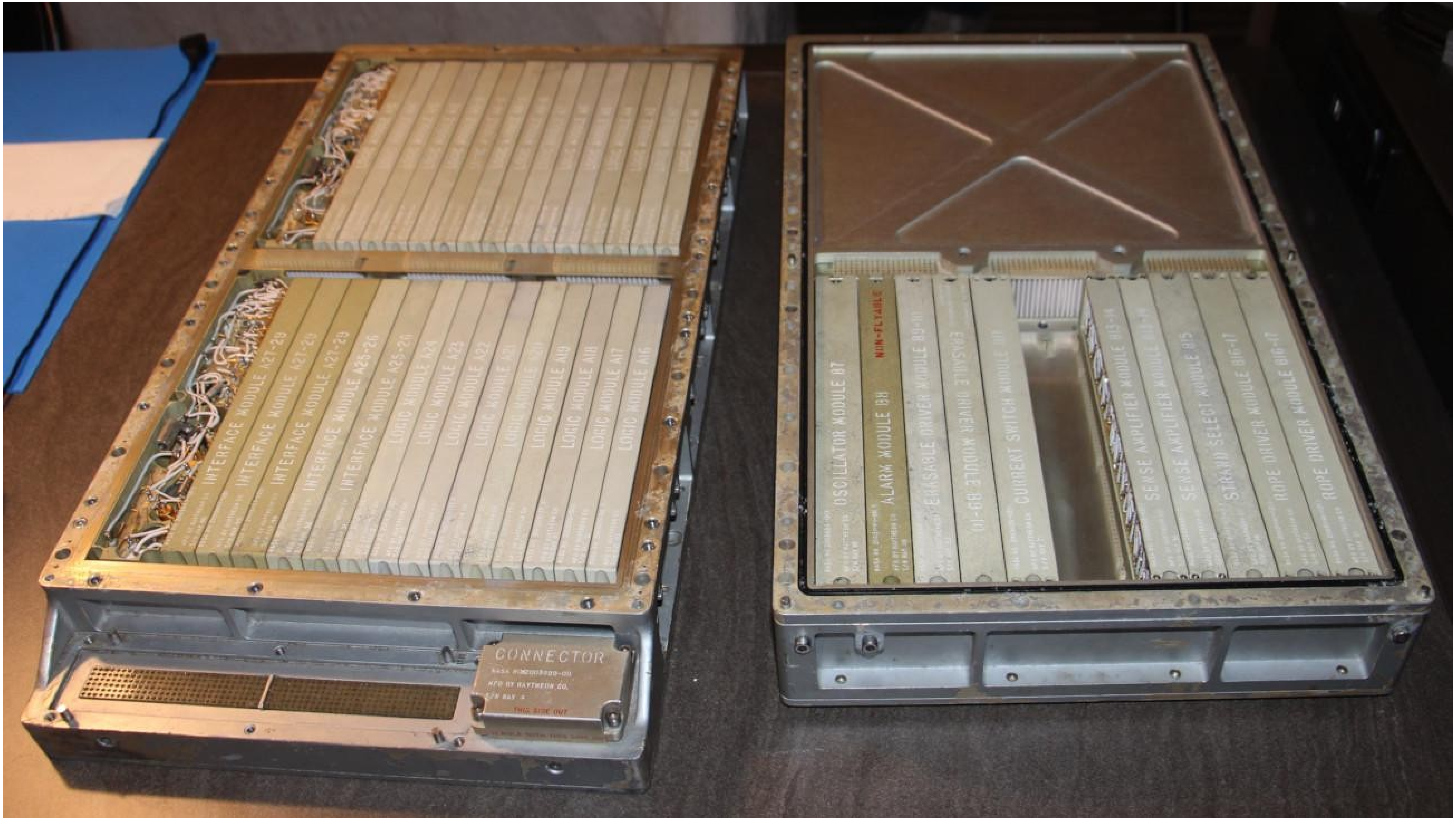
righto.com

The AGC



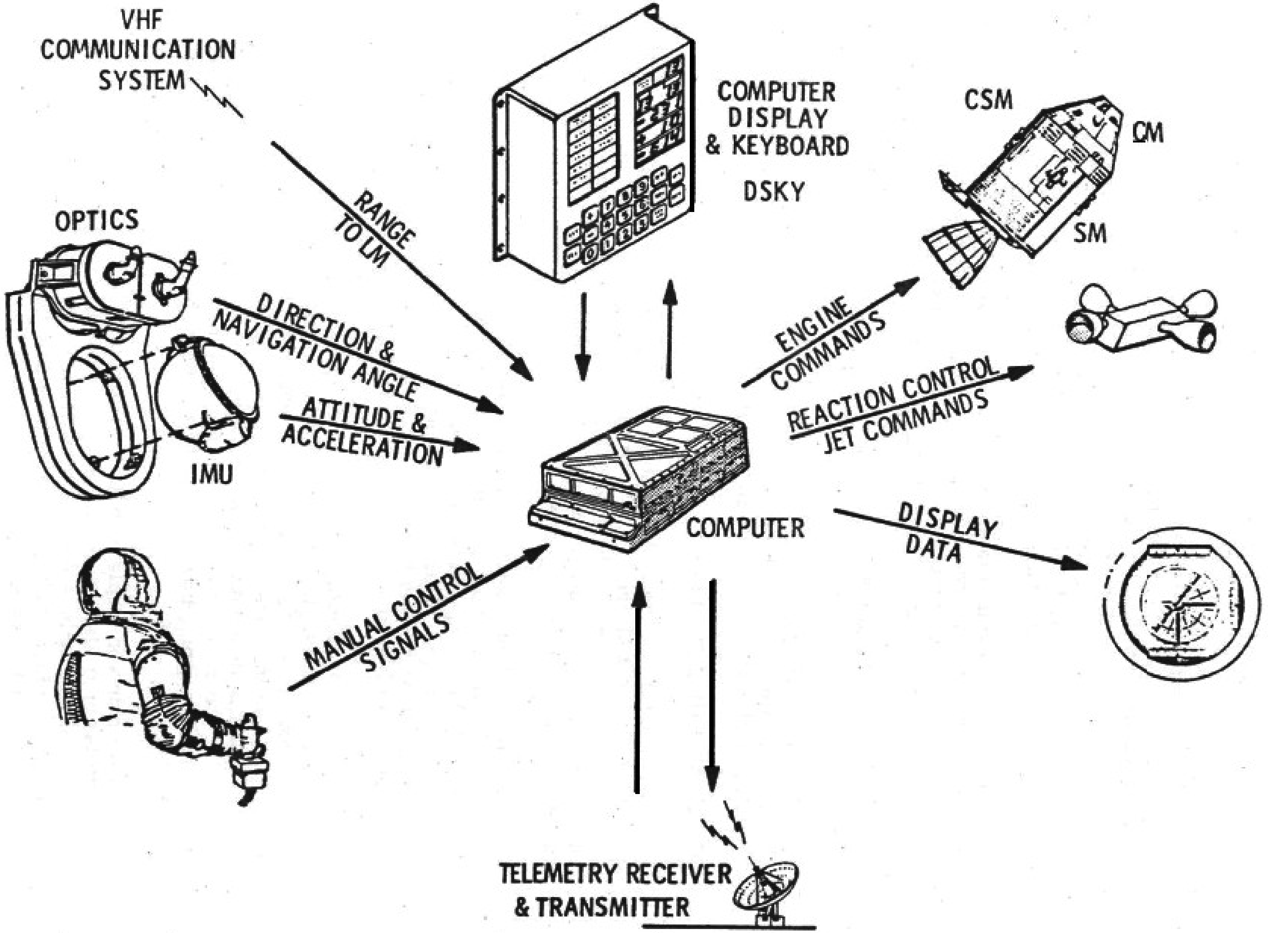
The AGC

- Real-time guidance, navigation, control
- 15-bit computer. 2K words RAM, 36K words ROM
- Under 1 cubic foot, 70 pounds, 55 watts
- First silicon integrated circuit computer
- ~43,000 instructions per second

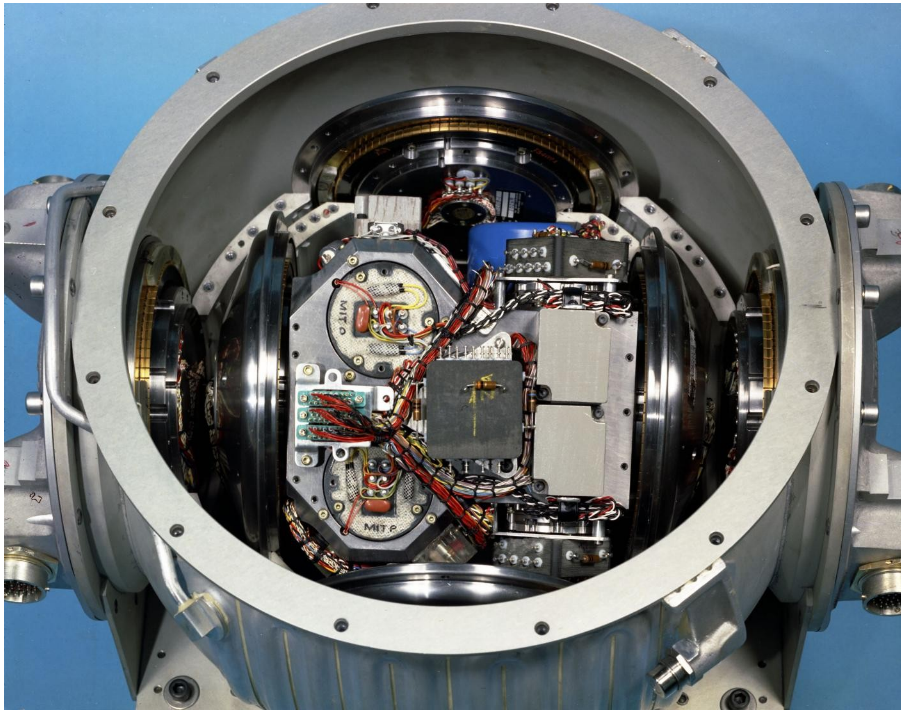

INTERFACE MODULE A27-29
INTERFACE MODULE A27-29
INTERFACE MODULE A27-29
INTERFACE MODULE A25-26
INTERFACE MODULE A25-26
LOGIC MODULE A24
LOGIC MODULE A23
LOGIC MODULE A22
LOGIC MODULE A21
LOGIC MODULE A20
LOGIC MODULE A19
LOGIC MODULE A18
LOGIC MODULE A17
LOGIC MODULE A16
CONNECTOR
MFD BY RAYTHEON CO.
THIS SIDE OUT
OSCILLATOR MODULE B7
NON-FLYABLE
ALARM MODULE B8
ERASABLE DRIVER MODULE B9-10
ERASABLE DRIVER MODULE B9-10
CURRENT SWITCH MODULE B11
SENSE AMPLIFIER MODULE B13-14
SENSE AMPLIFIER MODULE B15
STRAND SELECT MODULE B16-17
ROPE DRIVER MODULE B16-17
ROPE DRIVER MODULE B16-17

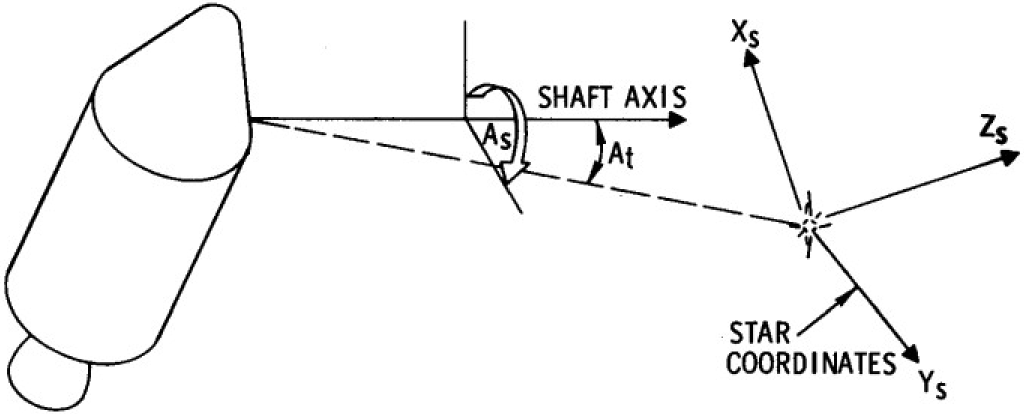
Apollo Guidance Computer

- Brain of the spacecraft
- Descendent of Polaris missile guidance
- Made by MIT (Draper Labs) and Raytheon



Inertial Measurement Unit (IMU)



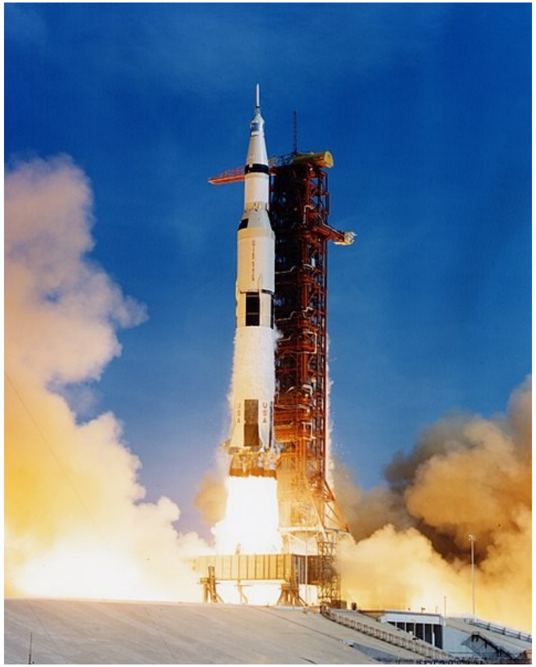


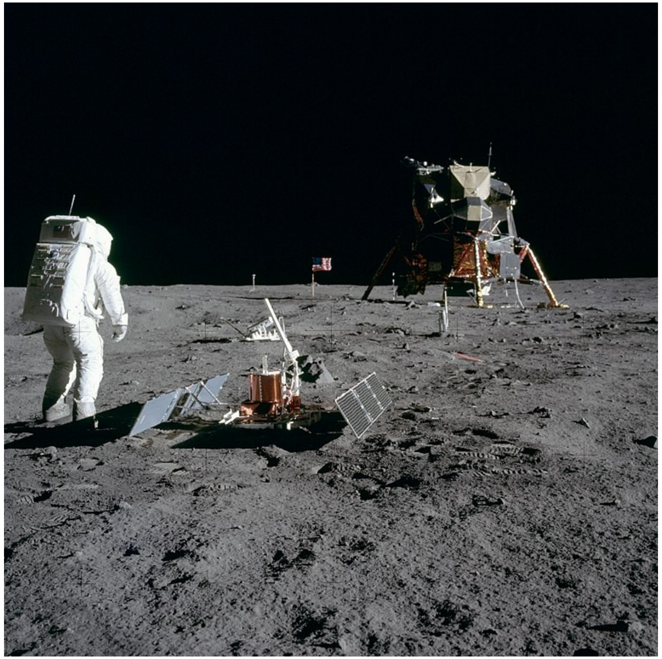
- Key to tracking position in space
- 3-axis gyroscopes and accelerometers
- Periodically aligned to stars
- AGC computes position

Photo: Draper / WeHackTheMoon

Apollo: landing on the Moon

- May 25, 1961: land a man on the Moon before the decade is out
- July 20, 1969: Apollo 11 Moon landing



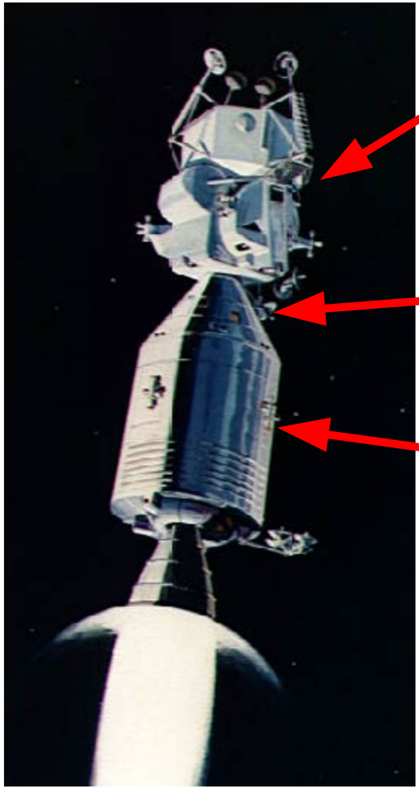


Computers at the time

- Large transistorized computers
  - IBM 7094 (1959): “Hidden Figures”
  - Batch:
    punch cards, tapes
- IC invented in 1958

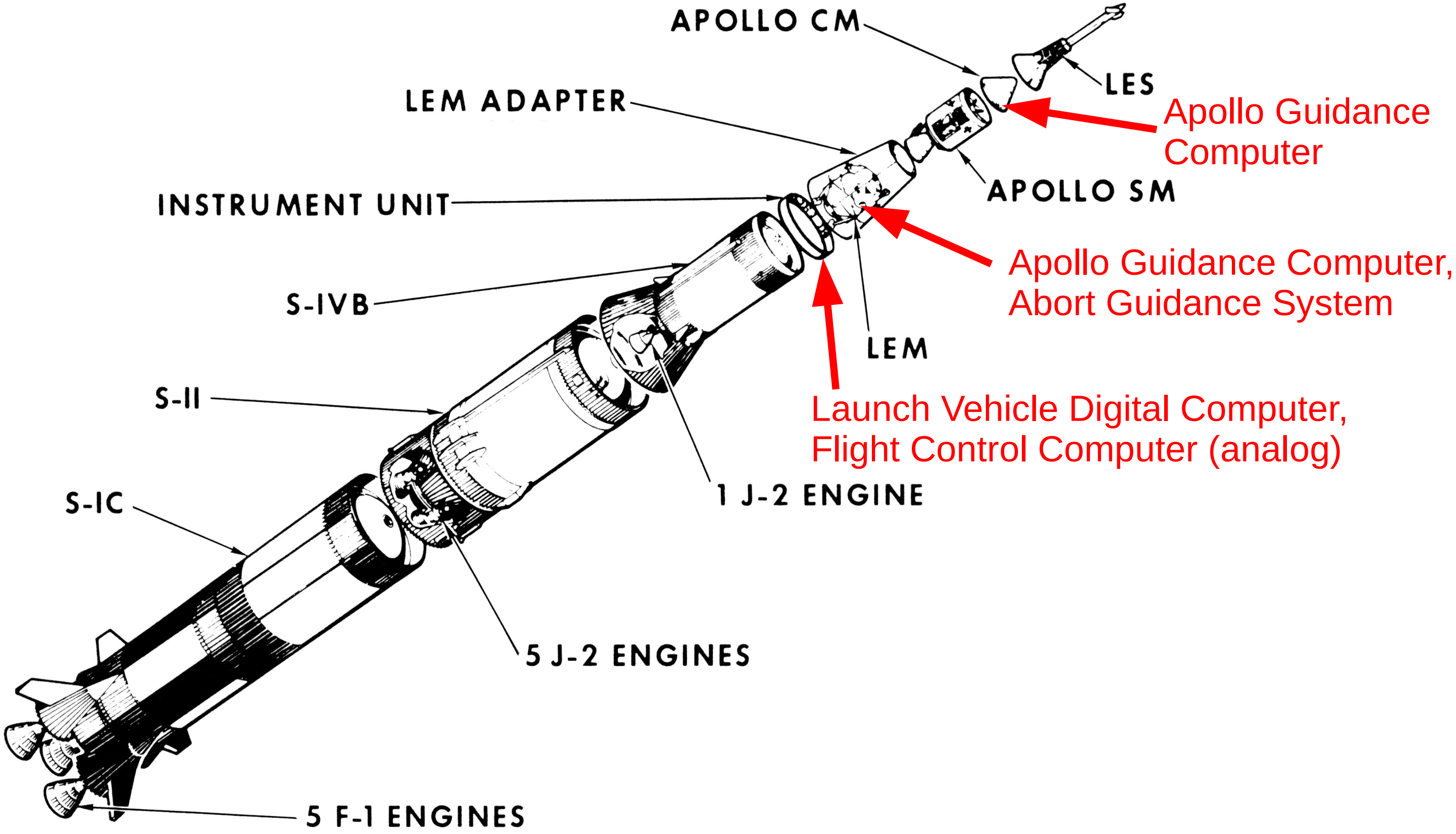
Photo: IBM / Columbia University Computing History

Apollo spacecraft components



- Lunar module
  - Landed on Moon
  - Rendezvous with Command/Service modules
- Command module
  - Held astronauts, only part that returned to Earth
- Service module
  - Rocket to/from Moon orbit
  - Power, oxygen, communication
  - Apollo 13: oxygen tank exploded

Computers in the mission



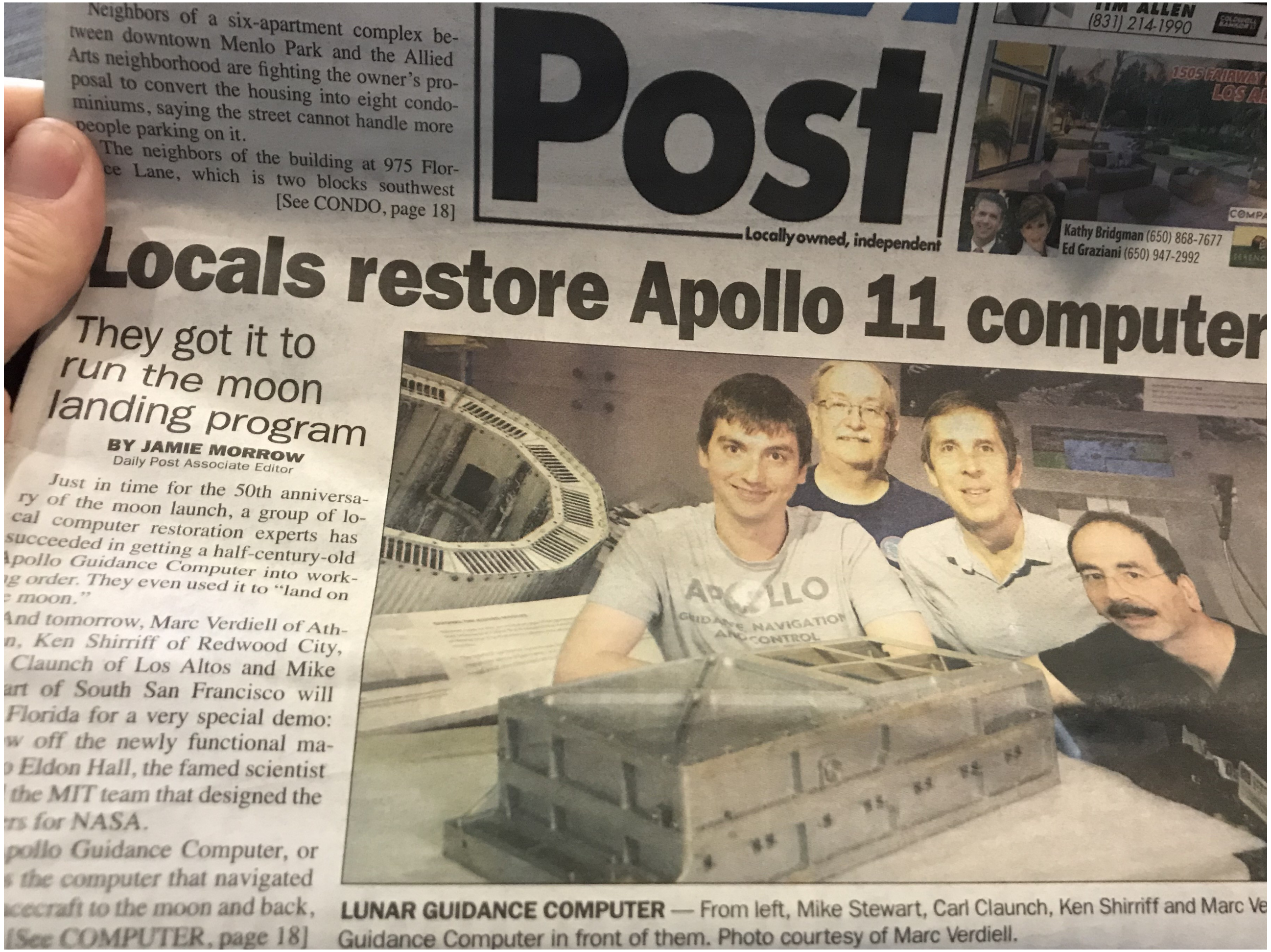
Apollo Guidance Computer

Apollo Guidance Computer, Abort Guidance System

Launch Vehicle Digital Computer, Flight Control Computer (analog)

Restoration team

- Mike Stewart
- Carl Claunch
- Me
- Marc Verdiell



Neighbors of a six-apartment complex between downtown Menlo Park and the Allied Arts neighborhood are fighting the owner's proposal to convert the housing into eight condominiums, saying the street cannot handle more people parking on it.

The neighbors of the building at 975 Flor-ce Lane, which is two blocks southwest

[See CONDO, page 18]

Post
Locally owned, independent

Locals restore Apollo 11 computer

They got it to run the moon landing program

BY JAMIE MORROW
Daily Post Associate Editor

Just in time for the 50th anniversary of the moon launch, a group of local computer restoration experts has succeeded in getting a half-century-old Apollo Guidance Computer into working order. They even used it to "land on e moon."

And tomorrow, Marc Verdiell of Ath-n, Ken Shirriff of Redwood City, Claunch of Los Altos and Mike art of South San Francisco will Florida for a very special demo: w off the newly functional ma-o Eldon Hall, the famed scientist the MIT team that designed the rs for NASA.

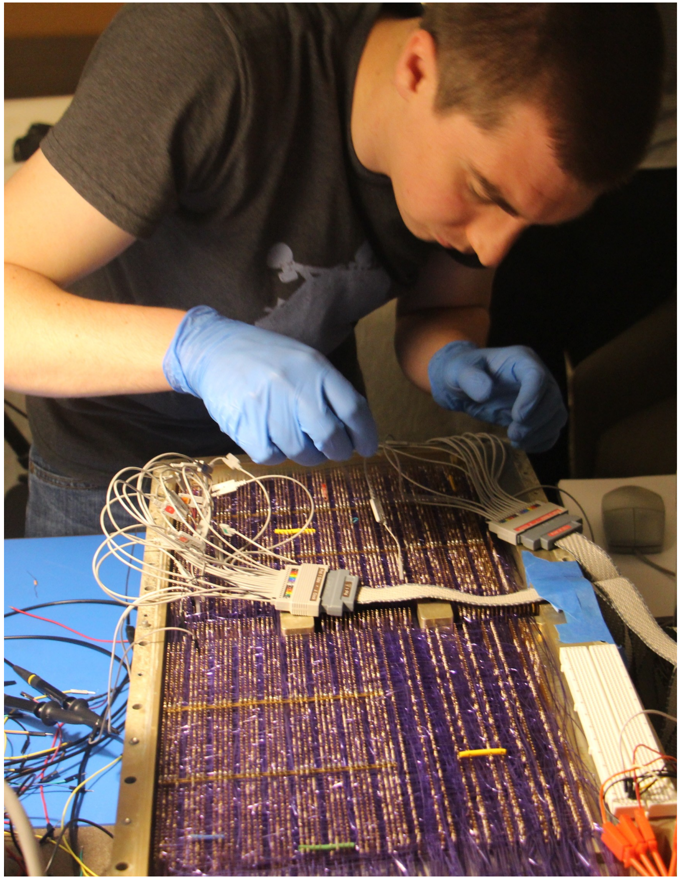
pollo Guidance Computer, or the computer that navigated cecraft to the moon and back,

[See COMPUTER, page 18]

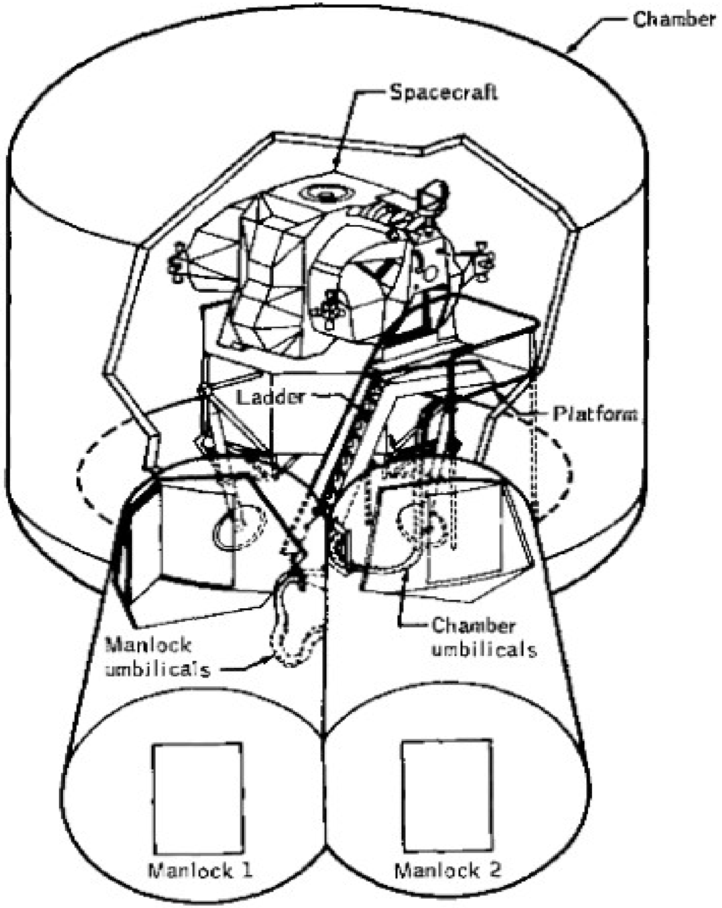
LUNAR GUIDANCE COMPUTER — From left, Mike Stewart, Carl Claunch, Ken Shirriff and Marc Ve Guidance Computer in front of them. Photo courtesy of Marc Verdiell.

Restoration

- Most of the AGC worked perfectly
- Some difficult problems
  - Broken wire in core memory
  - No core ropes (ROM)
  - Failed diodes
  - Obsolete connectors



Lunar Test Article LTA-8



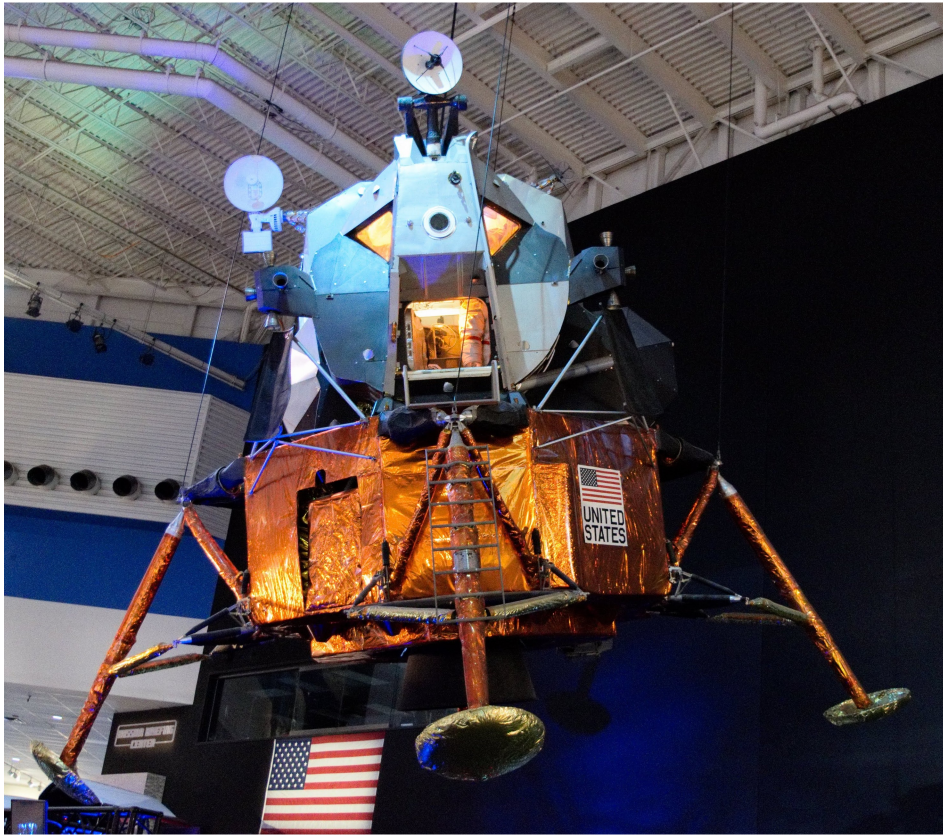


Photo: Mike Stewart

Lunar Test Article LTA-8

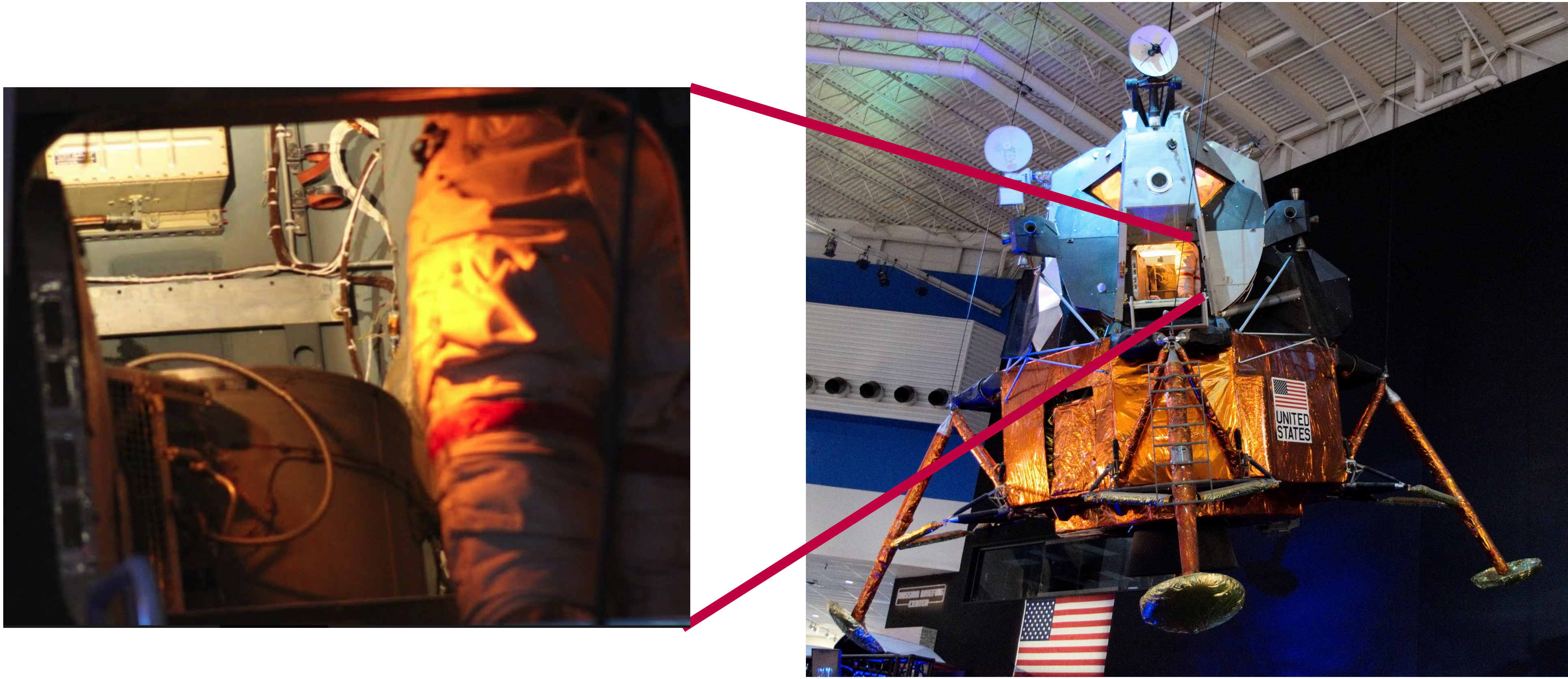
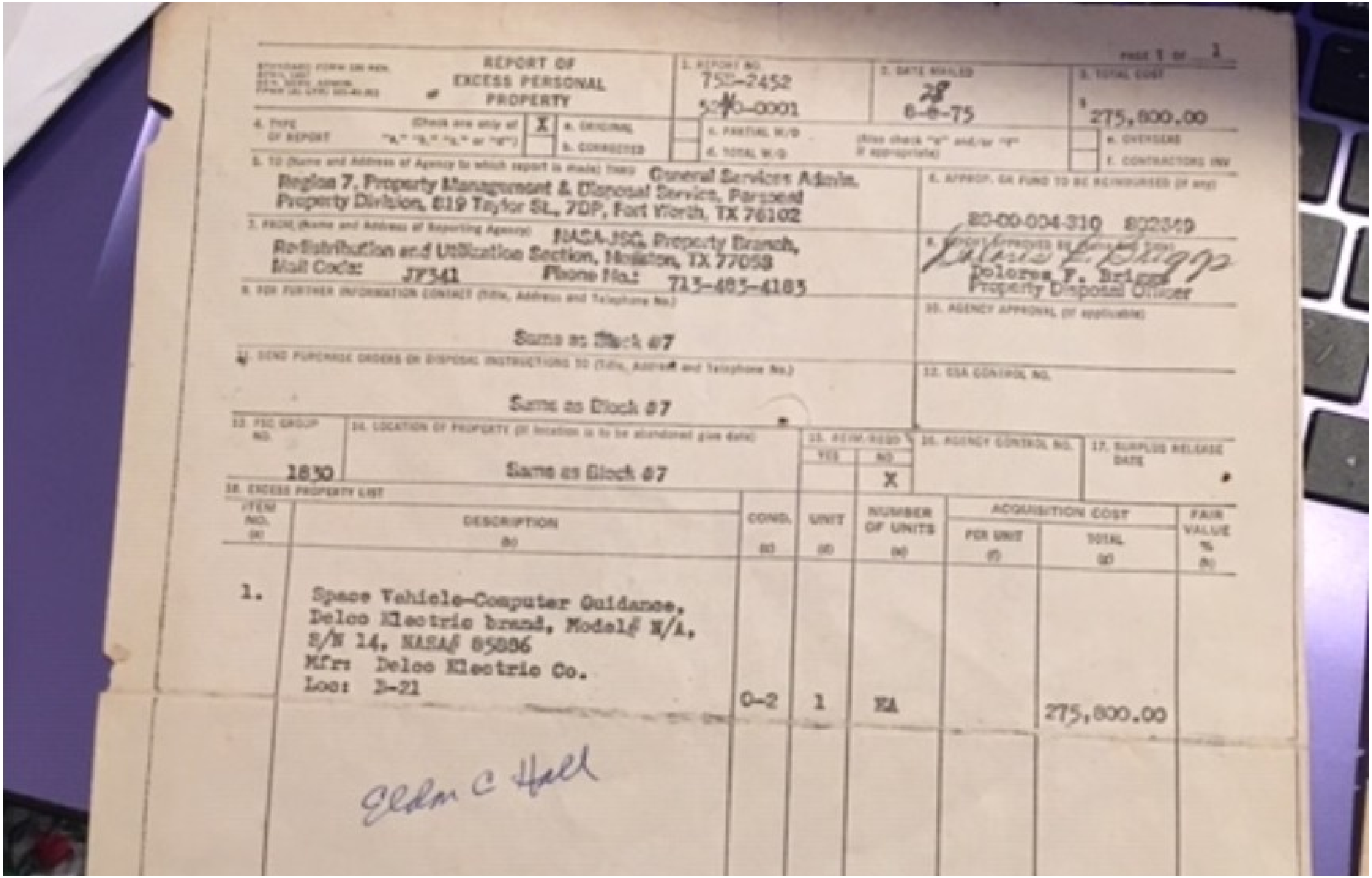


Photo: Mike Stewart

Jimmie Loocke

- Bought 2 tons of space scrap in the 1970s
- Found an AGC in there
- Wanted it restored for 50th anniversary of Moon landing

Photo: Wall Street Journal



PAGE 1 OF 1

[illegible]

REPORT OF EXCESS PERSONAL PROPERTY

1. REPORT NO. 75D-2452 52[illegible]0-0001

2. DATE MAILED 28 6-6-75

3. TOTAL COST $ 275,800.00

4. TYPE OF REPORT (Check one only of "a," "b," "c," or "d") ☒ a. ORIGINAL ☐ b. CORRECTED ☐ c. PARTIAL W/D ☐ d. TOTAL W/D (Also check "e" and/or "f" if appropriate) ☐ e. OVERSEAS ☐ f. CONTRACTORS INV

5. TO (Name and Address of Agency to which report is made) General Services Admin.
Region 7, Property Management & Disposal Service, Personal
Property Division, 819 Taylor St., 7DP, Fort Worth, TX 76102

6. APPROP. OR FUND TO BE REIMBURSED (if any)
80-00-004-310 802349

7. FROM (Name and Address of Reporting Agency) NASA-JSC, Property Branch,
Redistribution and Utilization Section, Houston, TX 77058
Mail Code: JP341 Phone No.: 713-483-4183

8. REPORT APPROVED BY (Signature Title)
Dolores F. Briggs
Property Disposal Officer

9. FOR FURTHER INFORMATION CONTACT (Title, Address and Telephone No.)
Same as Block #7

10. AGENCY APPROVAL (if applicable)

11. SEND PURCHASE ORDERS OR DISPOSAL INSTRUCTIONS TO (Title, Address and Telephone No.)
Same as Block #7

12. GSA CONTROL NO.

13. FSC GROUP NO. 1830

14. LOCATION OF PROPERTY (If location is to be abandoned give date)
Same as Block #7

15. REIM. REQD? YES ☐ NO ☒

16. AGENCY CONTROL NO.

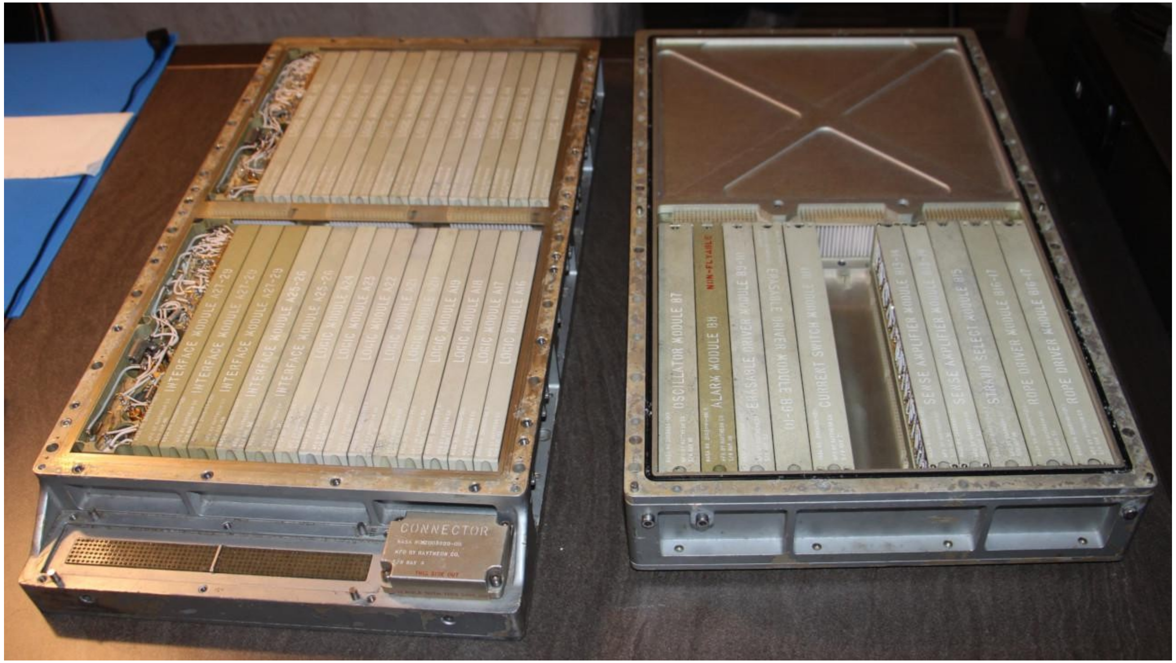
17. SURPLUS RELEASE DATE

18. EXCESS PROPERTY LIST

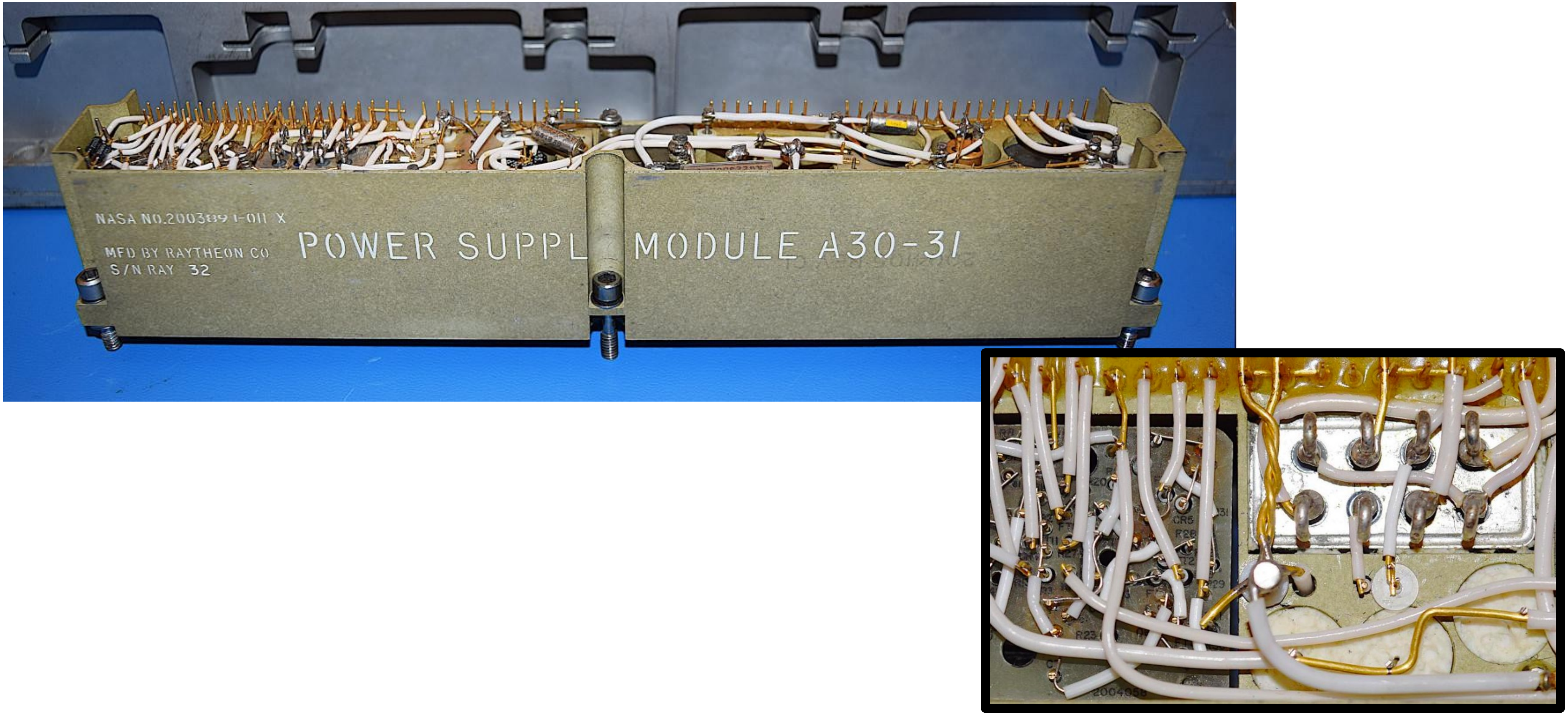
ITEM NO. (a)	DESCRIPTION (b)	COND. (c)	UNIT (d)	NUMBER OF UNITS (e)	ACQUISITION COST PER UNIT (f)	ACQUISITION COST TOTAL (g)	FAIR VALUE % (h)
1.	Space Vehicle-Computer Guidance, Delco Electric brand, Model# N/A, S/N 14, NASA# 85886 Mfr: Delco Electric Co. Loc: B-21	0-2	1	EA		275,800.00	
	Eldon C Hall						

AGC Hardware

- Tray A: mostly logic and interfaces
- Tray B: mostly core memory and support

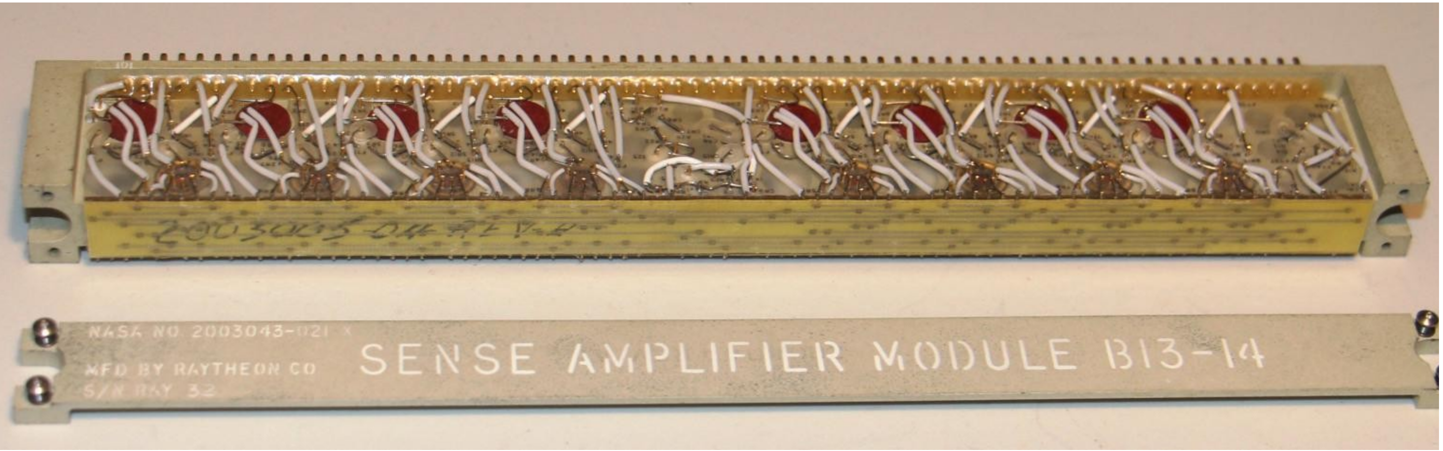


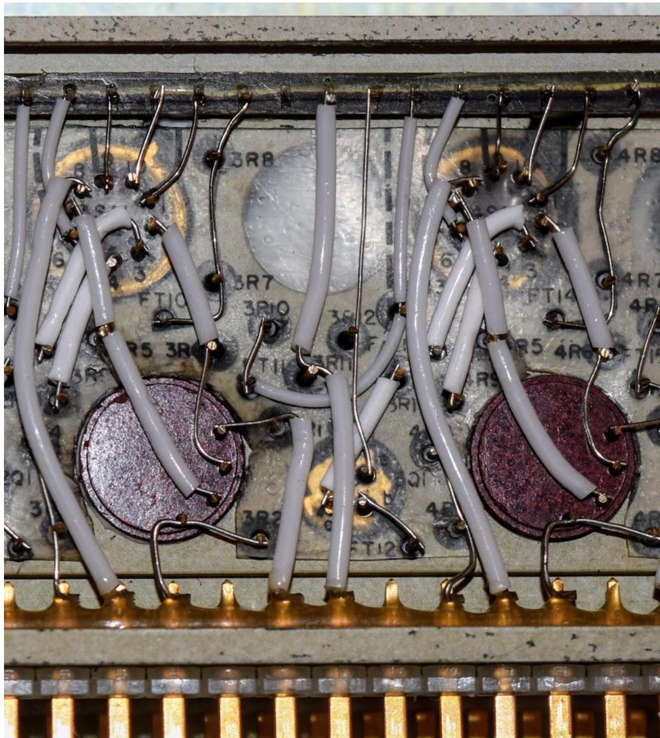
Switching power supplies



Cordwood modules

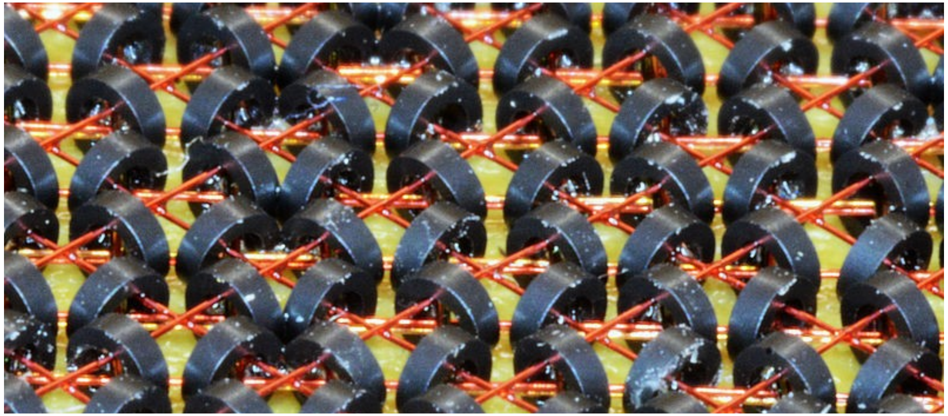
- Cordwood construction in non-logic modules
  - Components perpendicular through module
  - Welded connections, not soldered
  - Encased in epoxy for flight





Erasable memory module: RAM

- 2K words (15 bits + parity): ~4KB
  - Magnetic core memory
  - 32,768 tiny ferrite cores on thin wires
  - Core planes folded, encased in epoxy



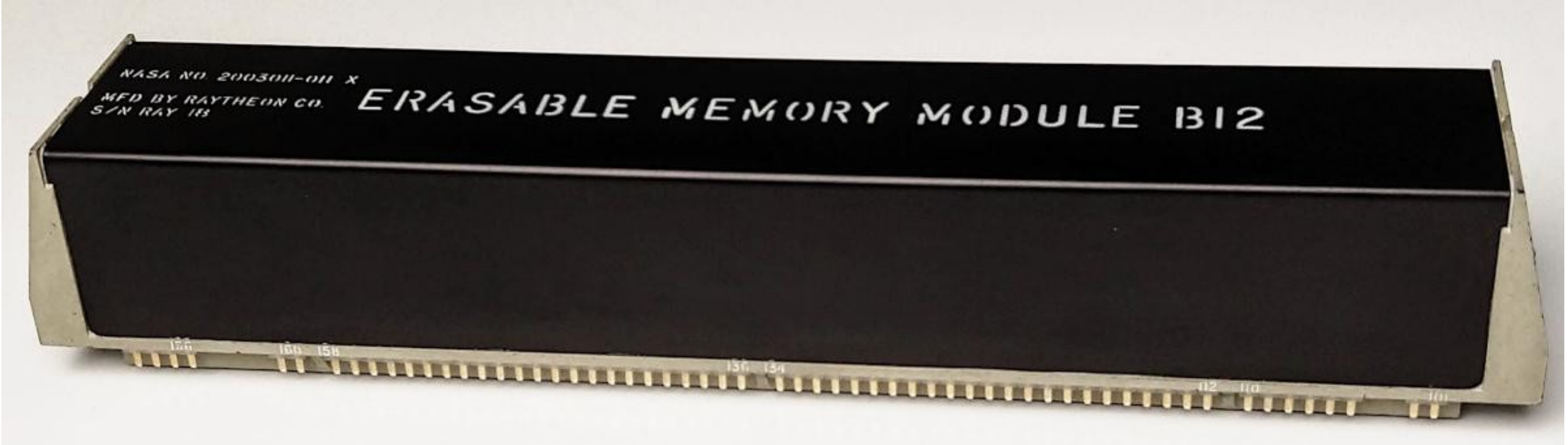
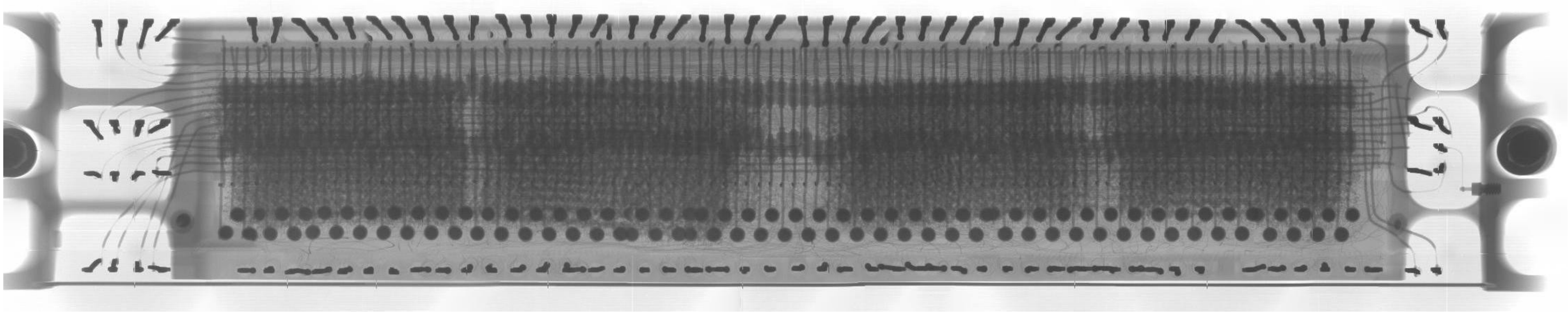


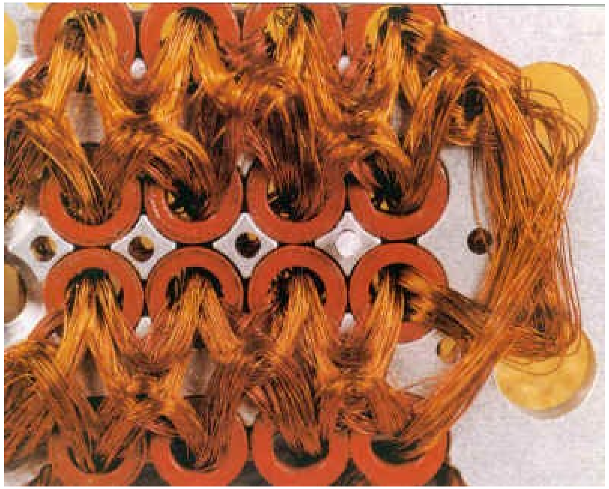
Photo by Jud McCranie (CC BY-SA 4.0).

Broken wire in core module

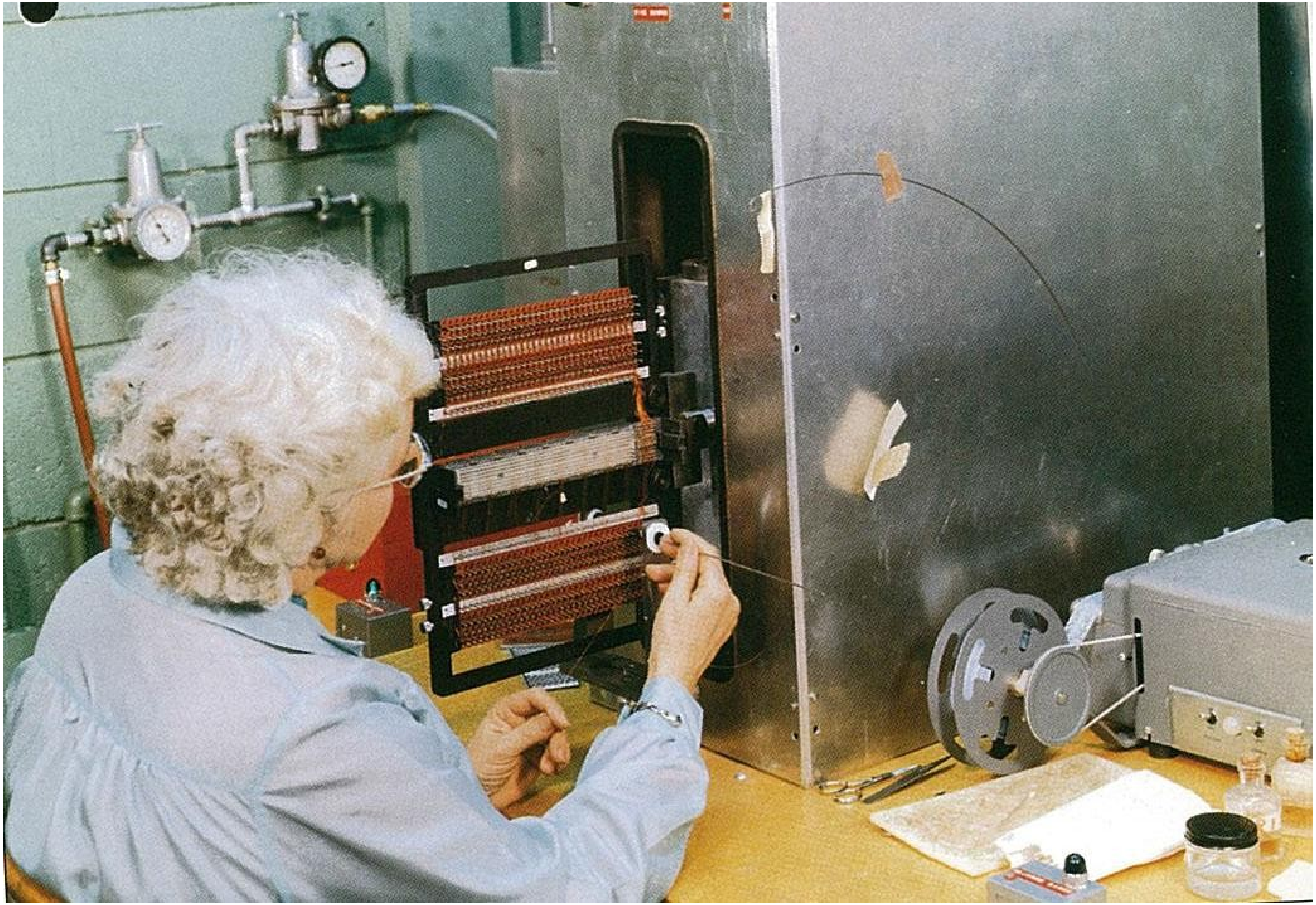


Core rope modules: ROM

- Six modules held 36K words (~72 KB)
  - All software for the mission
- Data woven into the module during construction

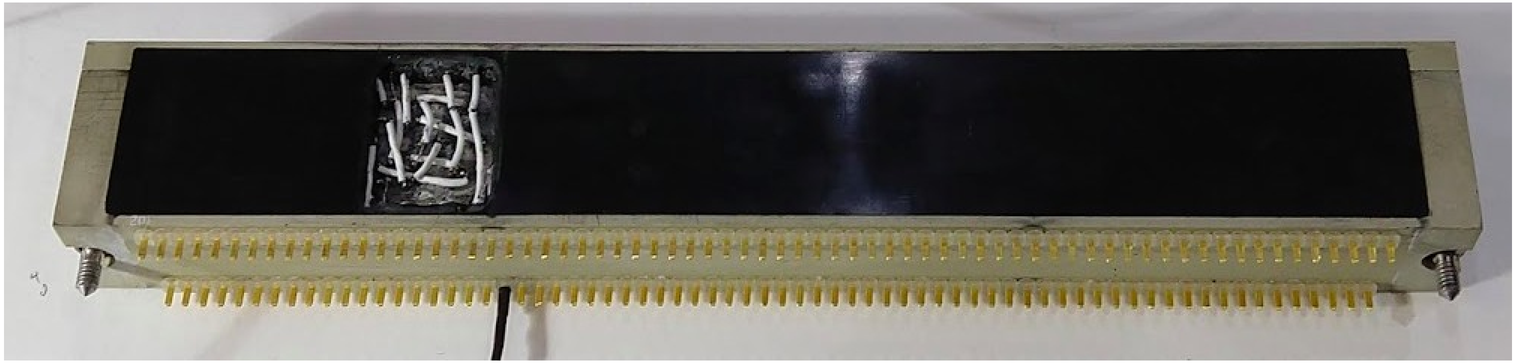


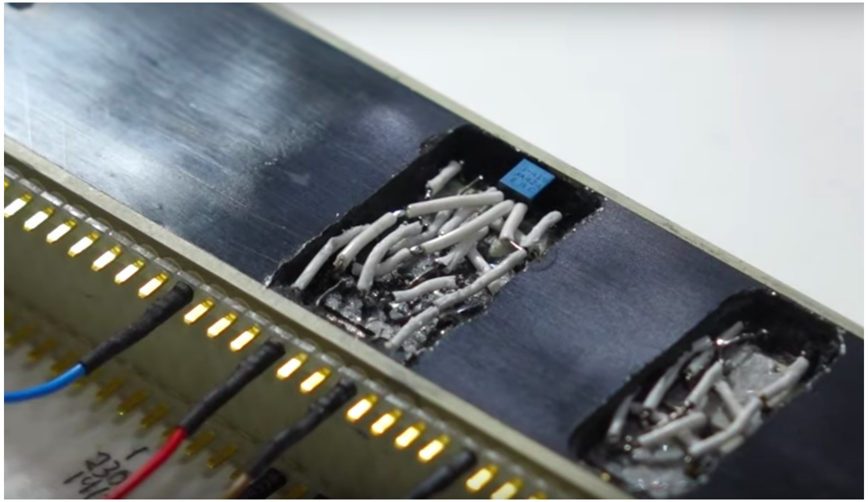
Computers for Apollo



Raytheon / Smithsonian

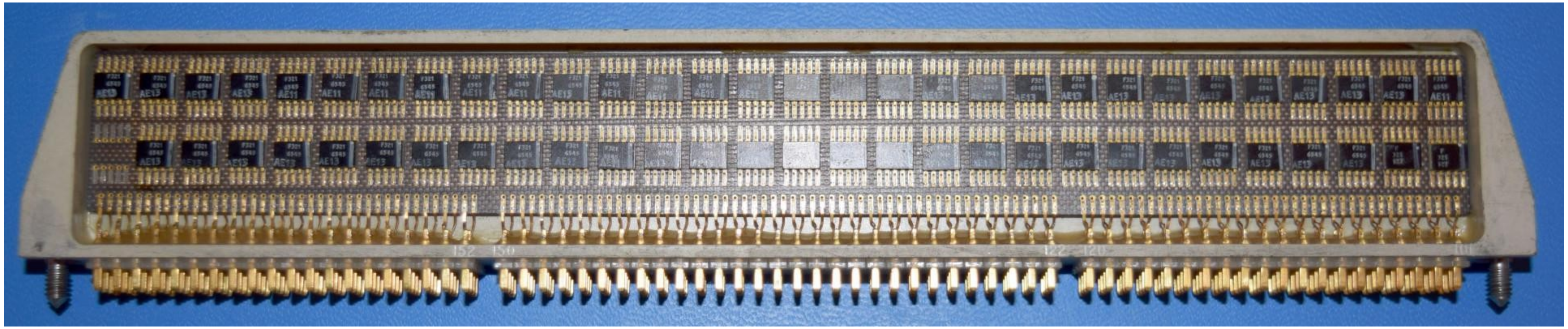
Failures in current switch module



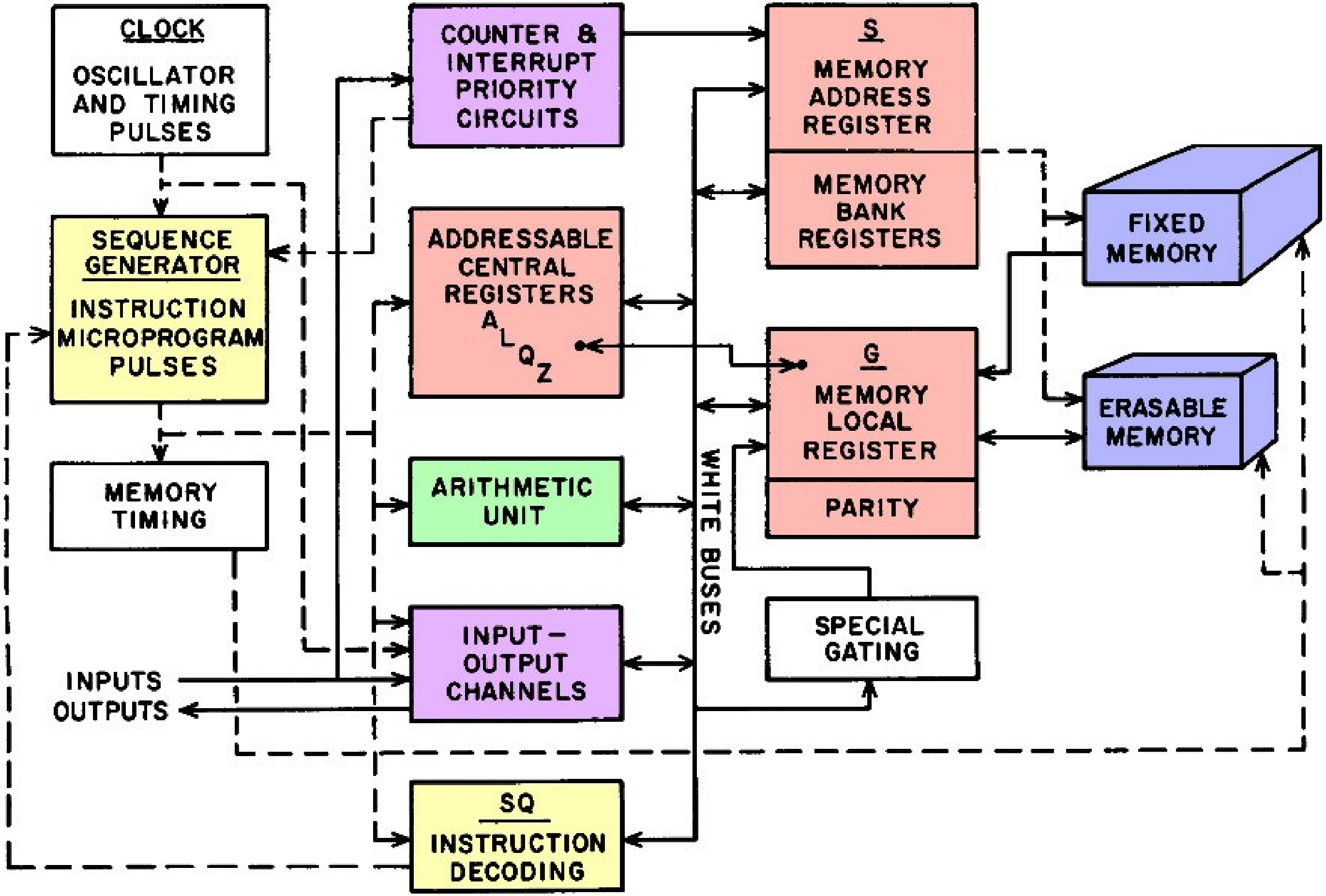


Logic modules

- IC invented 1958. AGC decided on ICs 1962.
- Used two ICs: NOR gate and sense amplifier
  - No microprocessor; processor built from ~5600 simple gates
- 120 ICs (240 gates) per module
- Surface mount, 7-layer PCB: advanced technologies

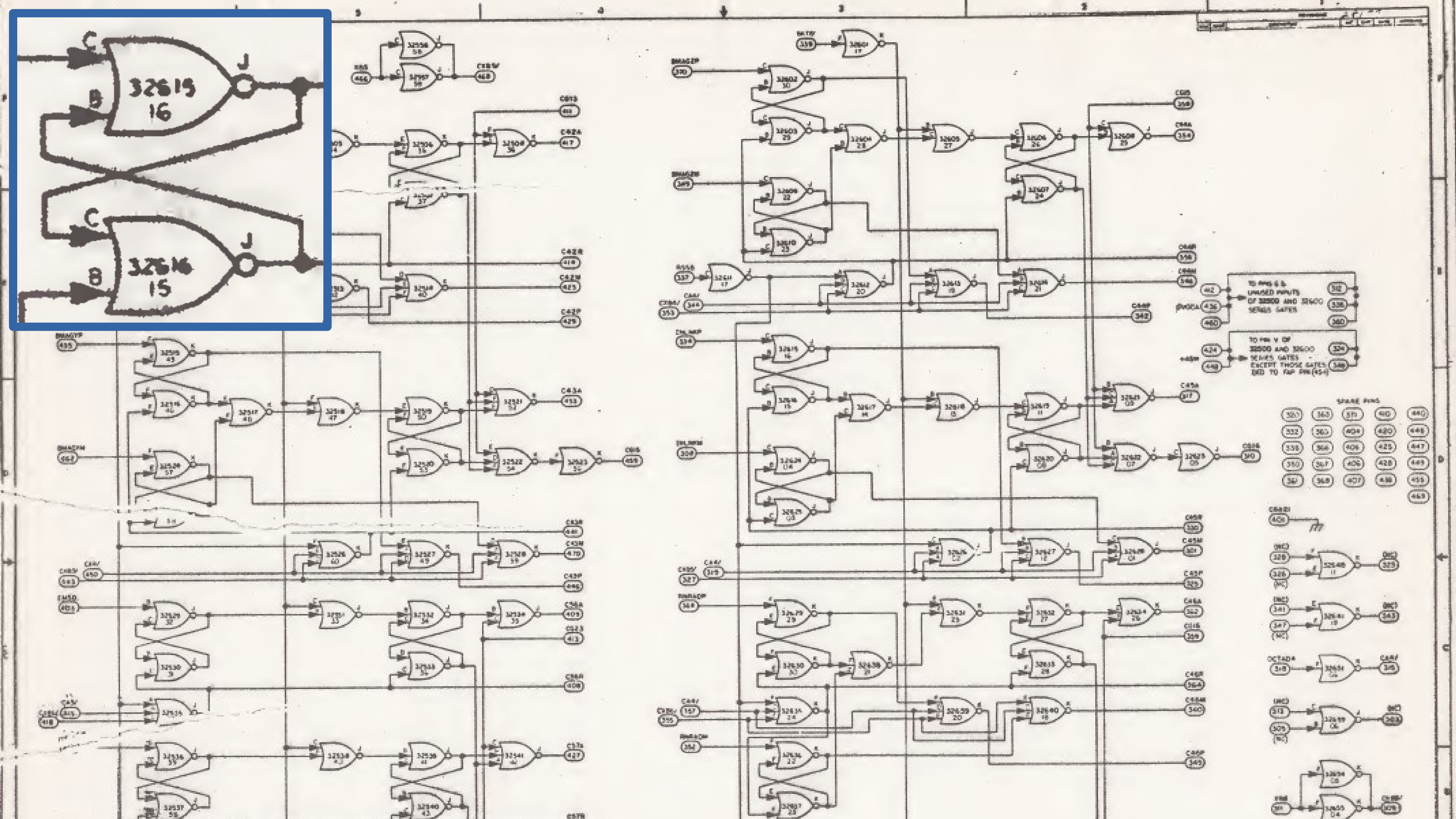


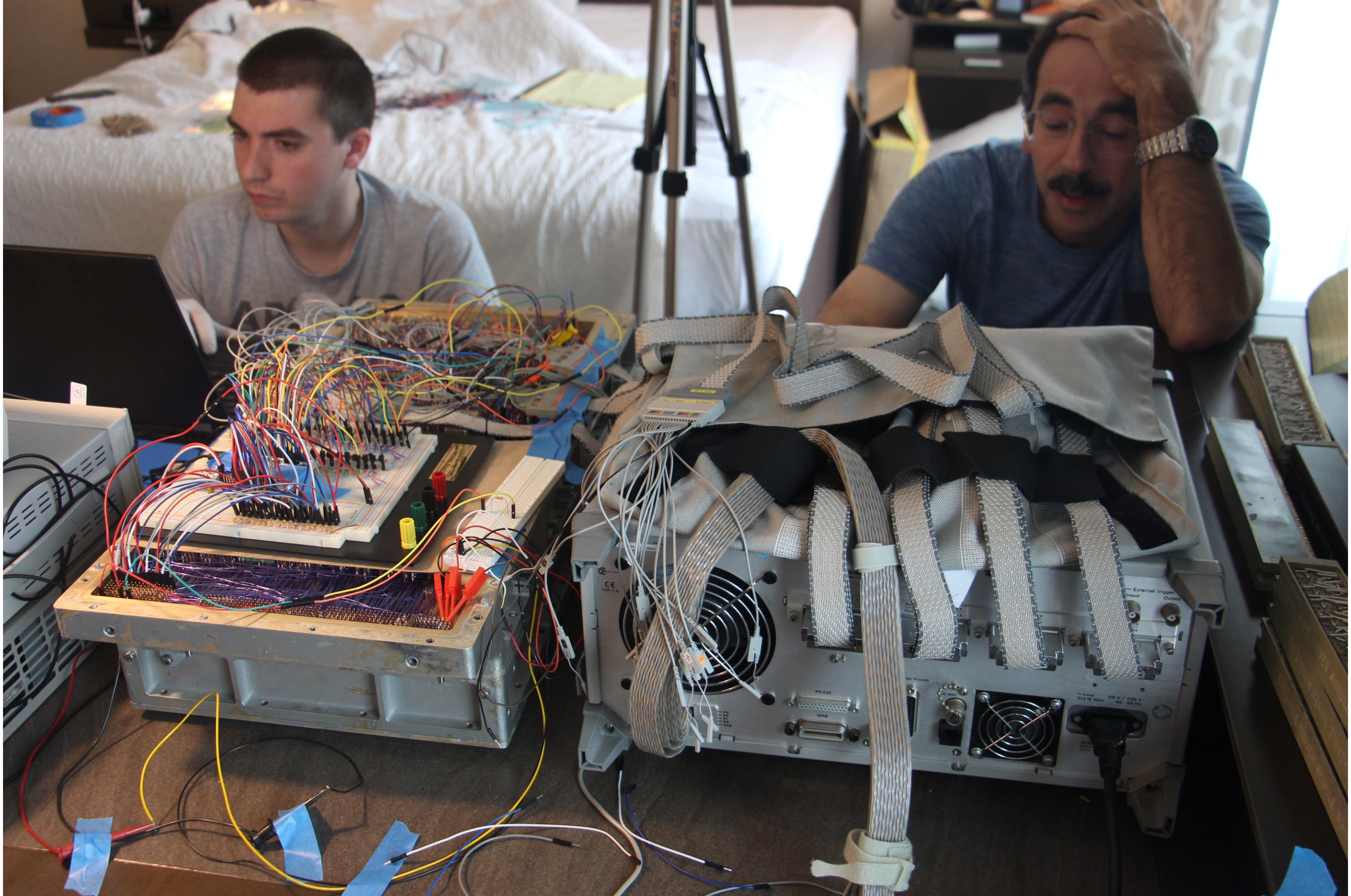
AGC architecture



CPU

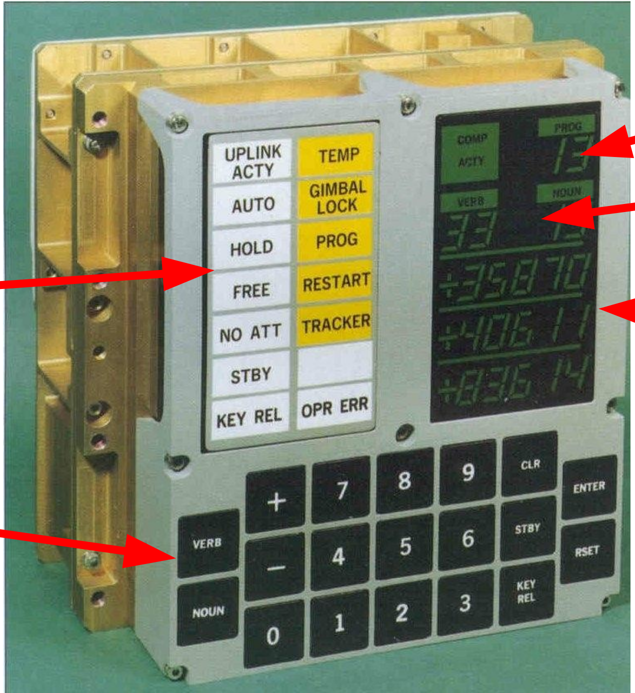
- 15-bit processor built from NOR gates
- Lots of I/O, background counter updates
- Error checking, alarms
- 1’s complement (mostly): +0 and -0


C
B
32615
16
J
C
B
32616
15
J
BMAGYP
BMAGXM
BMAGZP
BMAGZM
RSSB
CHINC
CA9/
PINC
CDU
C
C42A
C42B
C42M
C42P
C43A
C43M
C43P
C43R
C
C45A
C45M
C45P
C45R
C46A
C46M
C46P
C46R
CGIS
CGSB
TO PINS 6 &
UNUSED INPUTS
OF 32500 AND 32600
SERIES GATES
TO PIN V OF
32500 AND 32600
SERIES GATES
EXCEPT THOSE GATES
TIED TO FAP PIN (454)
SPARE PINS
(NC)
OCTAD4
CA8/



DSKY: Display & Keyboard

- Primary human interface to AGC
  - Simple Verb + Noun commands
  - Carl built a replica DSKY



Program

Verb and noun

3 data lines

Error and status lights

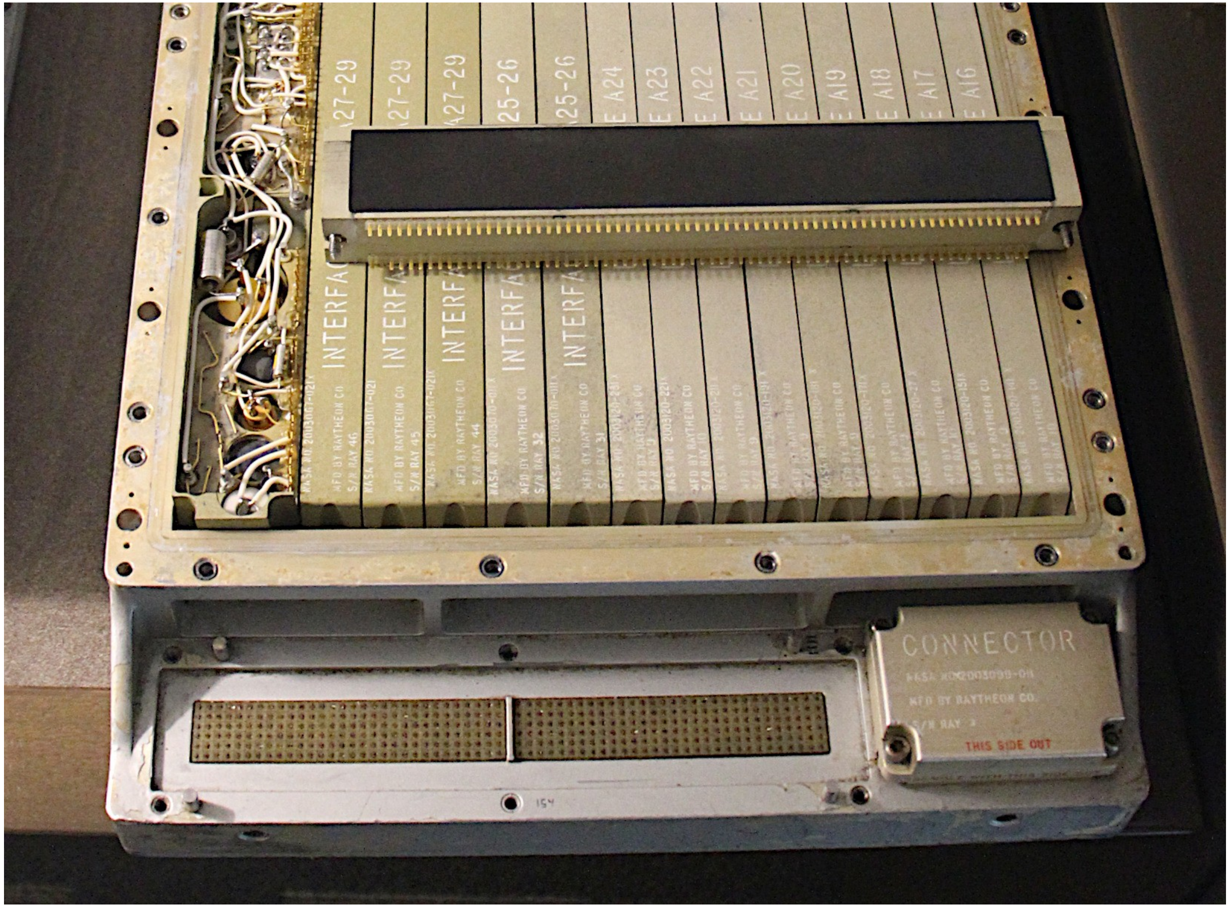
Keypad, usable with gloves on

Electroluminescent, not LED

Verbs and nouns

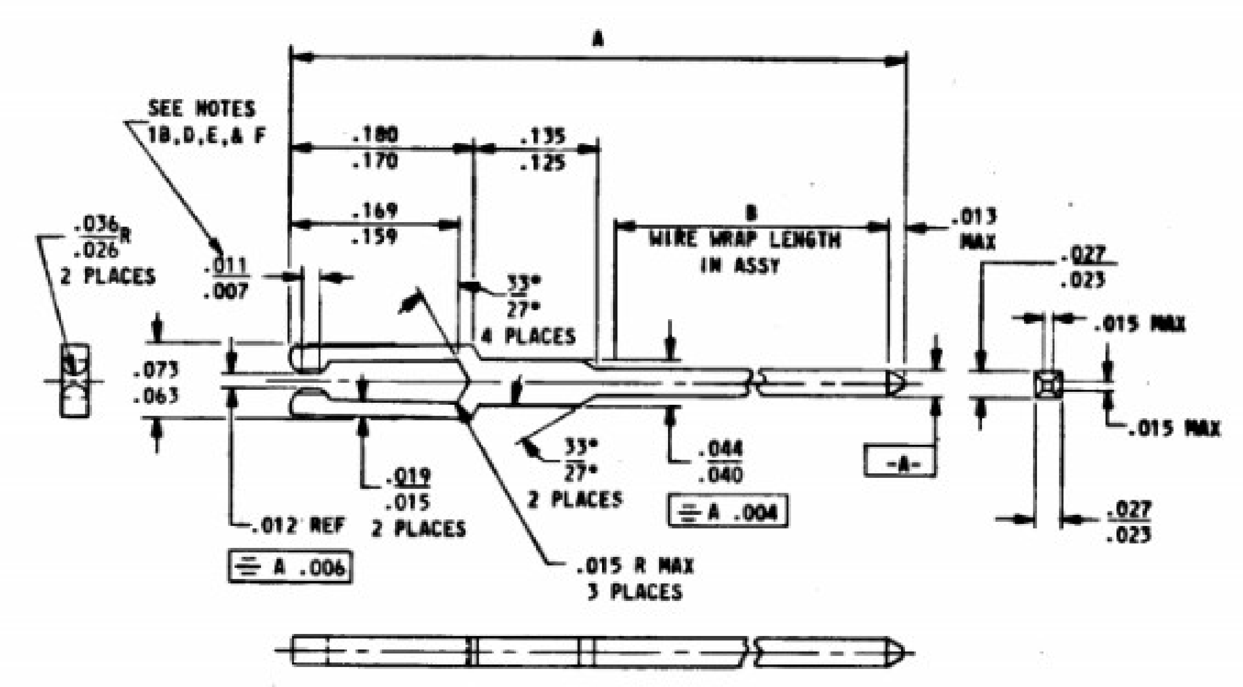
- About 80 verbs: what to do
  - V06: display decimal value
  - V42: fine align IMU
  - V99: enable engine
- About 90 nouns: what to act on
  - N43: latitude/longitude/altitude
  - N47: vehicle weight
  - N70: star code

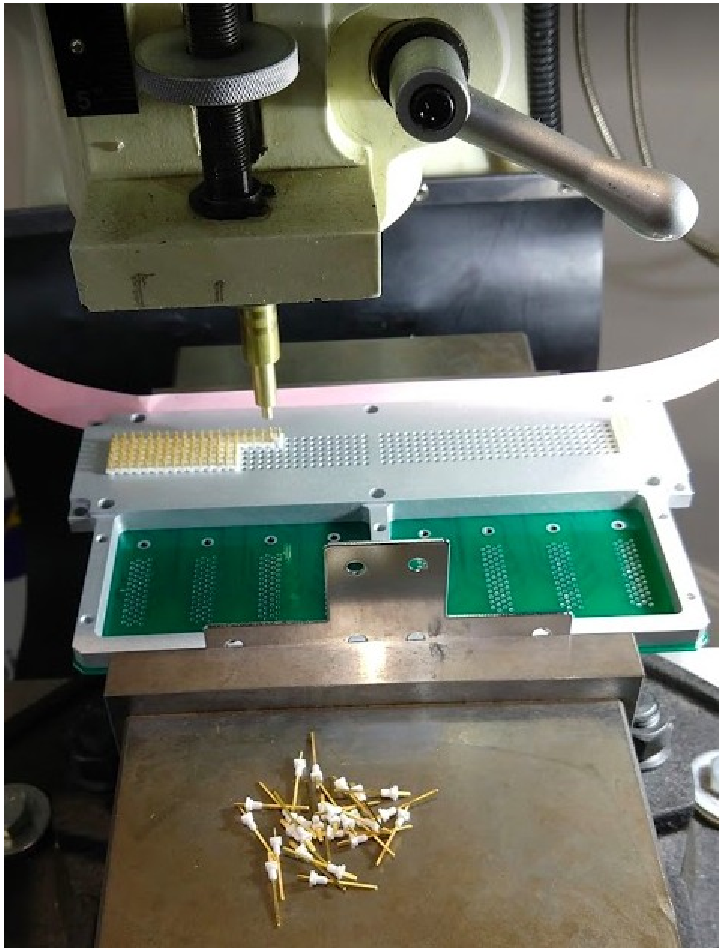
Connecting to the AGC



Obsolete “Mini-wasp” connectors

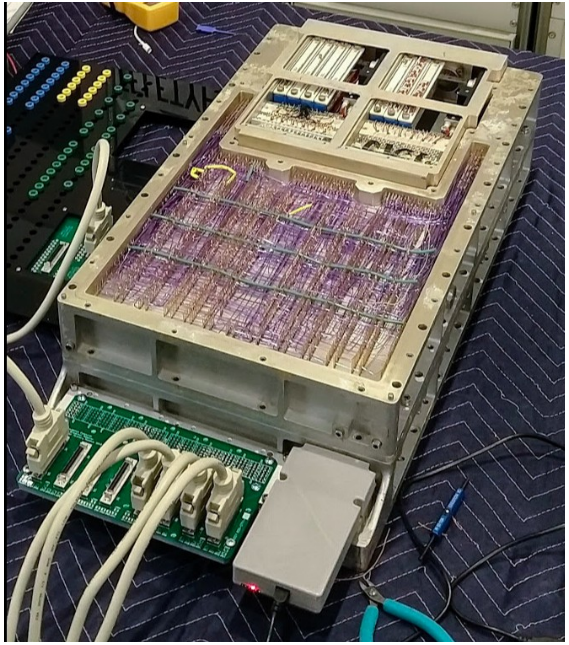
- New pins manufactured by Samtec

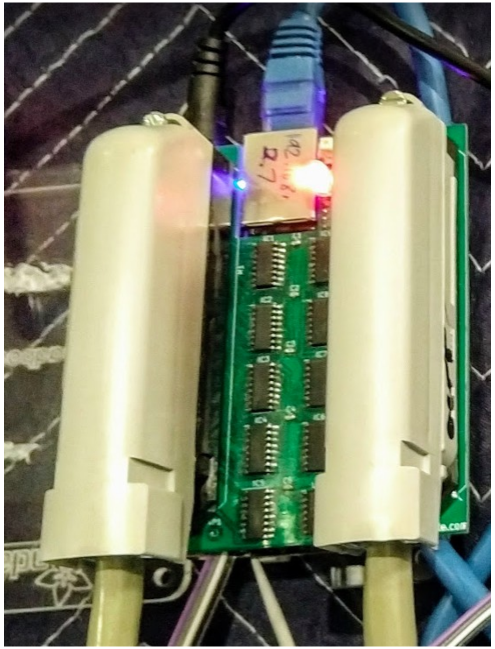


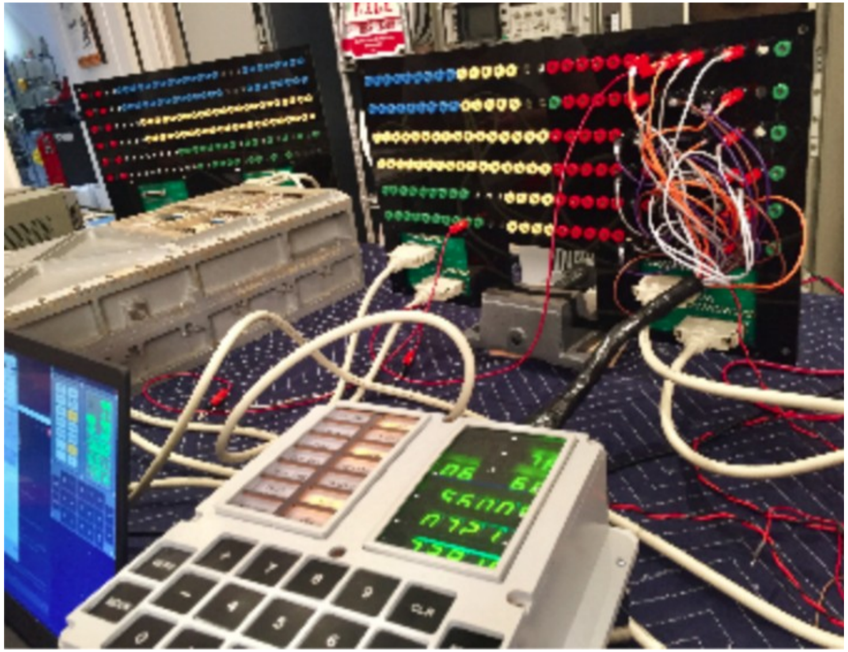


Peripherals

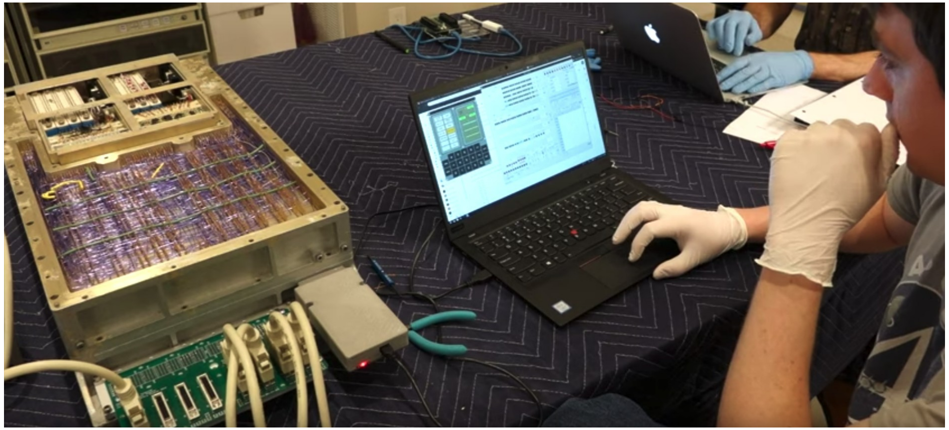
- FPGA boards, monitor software on laptop
- Interface boards, plugboard

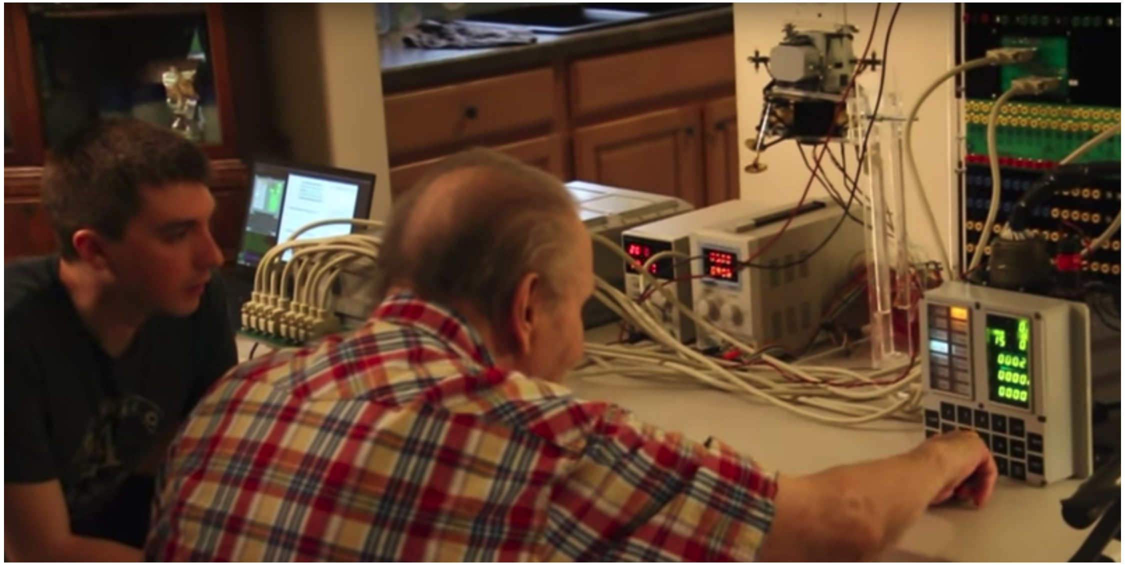






AGC up and running!





AGC software development

“The effort needed for the software turned out to be grossly underestimated.”

— David Hoag, Director of Apollo Guidance and Navigation

- 1400 person-years of effort

Programming

- Complex software engineering
  - Real-time OS with job scheduling
  - Interpreter
  - Mission software
- All in assembly language

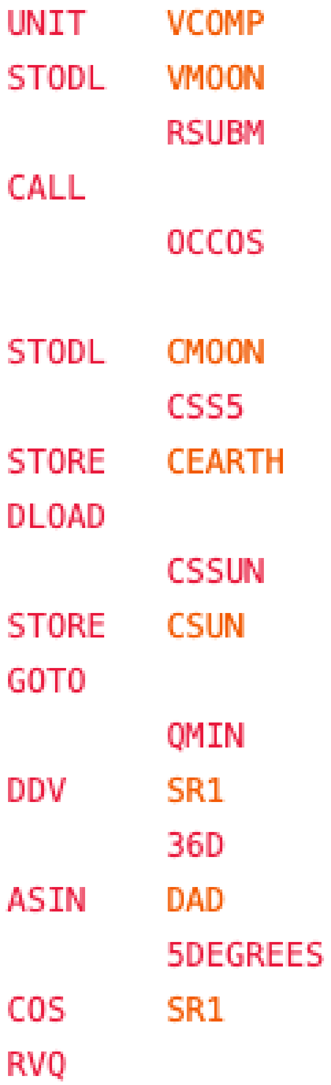
Margaret Hamilton

The executive (OS)

- Eight jobs running at once
- Priority-based job scheduling
- Checkpoint / restart
- Waitlist of real-time tasks

The interpreter

- Virtual machine, 70 new op codes
  - Easier to program, saves memory
- Designed for navigation programming
  - Scalar / vector / matrix operations
  - Double, triple precision
  - Trig functions



```
UNIT     VCOMP
STODL    VMOON
         RSUBM
CALL
         OCCOS

STODL    CMOON
         CSS5
STORE    CEARTH
DLOAD
         CSSUN
STORE    CSUN
GOTO
         QMIN
DDV      SR1
         36D
ASIN     DAD
         5DEGREES
COS      SR1
RVQ
```

Development environment

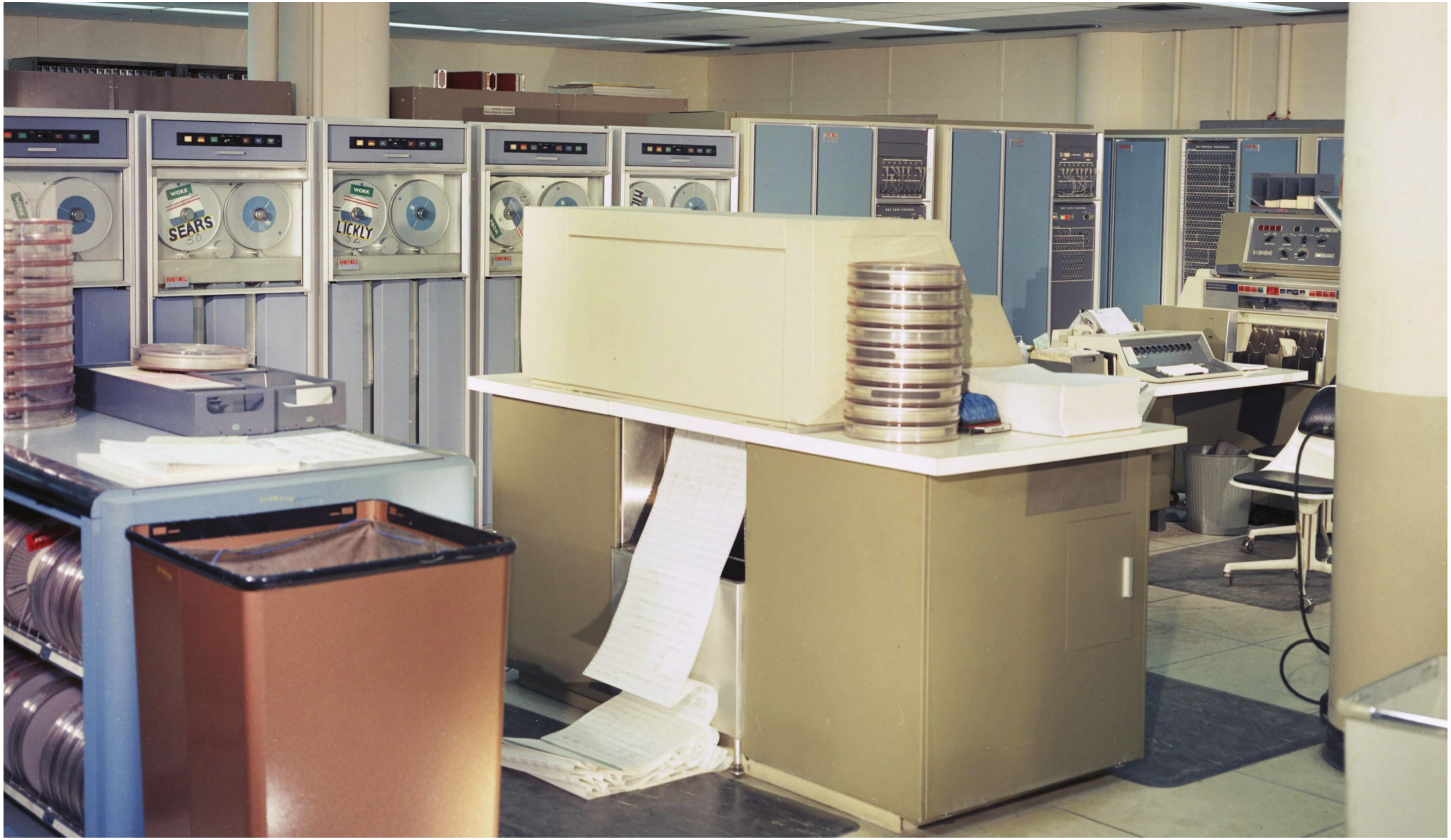


Photo:
Draper Labs

Mission software

- Lunar module: Retread, Aurora, Luminary
  - About 34 programs.
    - P52: IMU realignment
    - P63-P68: Descent and landing on Moon
    - P20: Rendezvous
    - P70-P79: Aborts and backups
- Command module: Sundisk, Sunburst, Solarium, Colossus
  - About 37 different programs: launch, to Moon, return to Earth

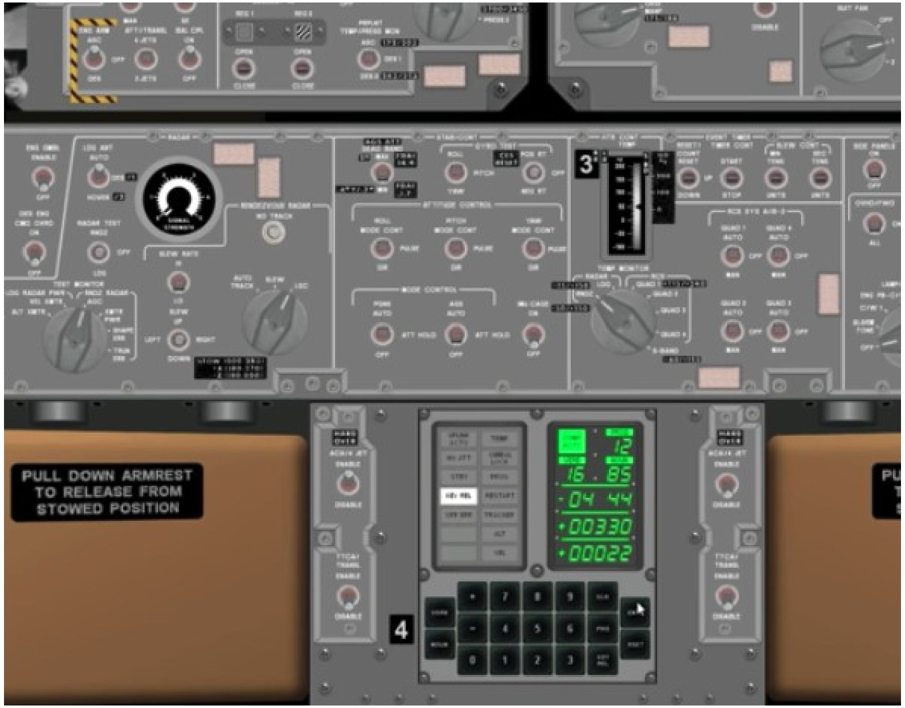
1201-1202 program alarm

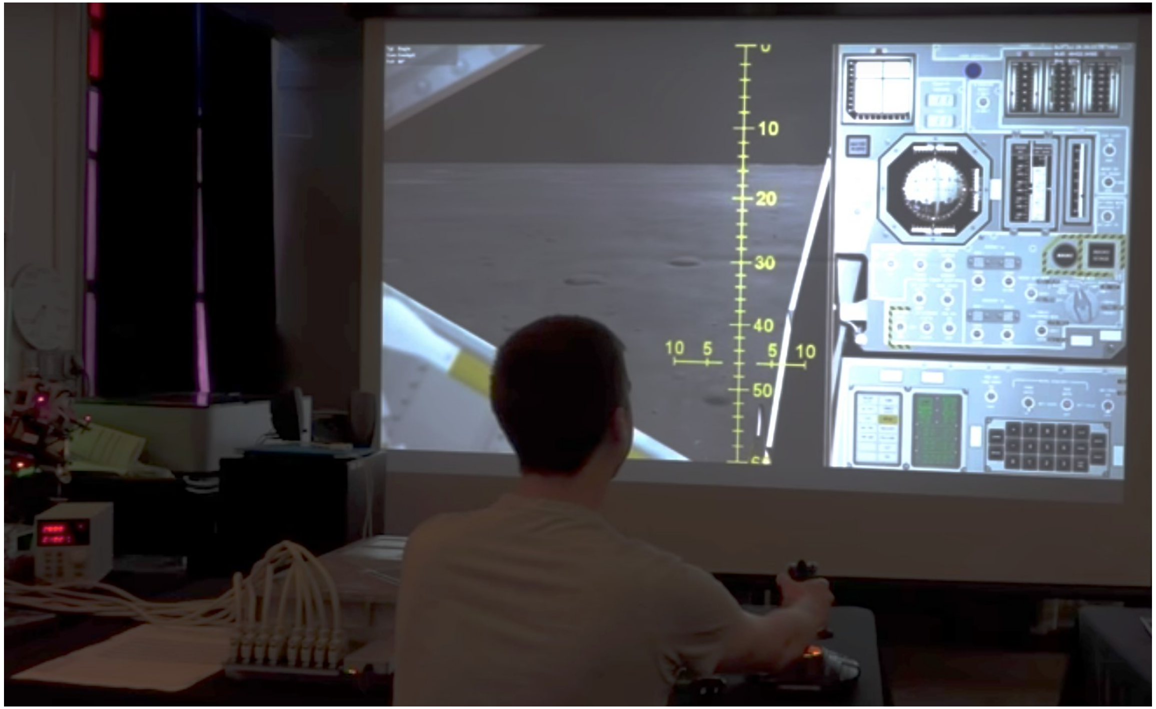
- During Apollo 11 landing, alarms went off
  - Computer overload caused 1201 and 1202 alarms
  - Could have aborted the landing!
  - Rendezvous radar problem: 1000s interrupts/second
- Checkpoint/restart design saved the Moon landing
  - AGC restarted five times while keeping LM flying
  - AGC dropped low-priority tasks, blanked DSKY

Tektronix 7854 OSCILLOSCOPE
SELF TEST COMPLETE
7A22
7B85
7B92A
SCOPE-MOBILE CART MODEL 3
TEKTRONIX, INC., BEAVERTON, ORE., U.S.A.

Simulated Moon landing

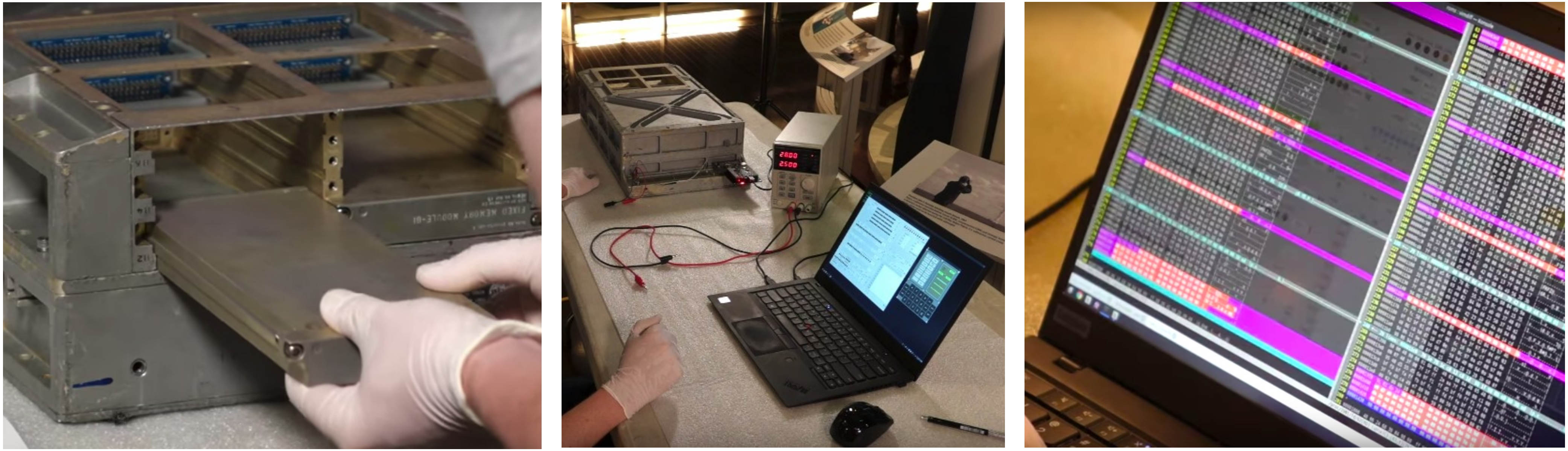
- Lunar module simulator with real AGC and software





Photos from NASSP, CuriousMarc video

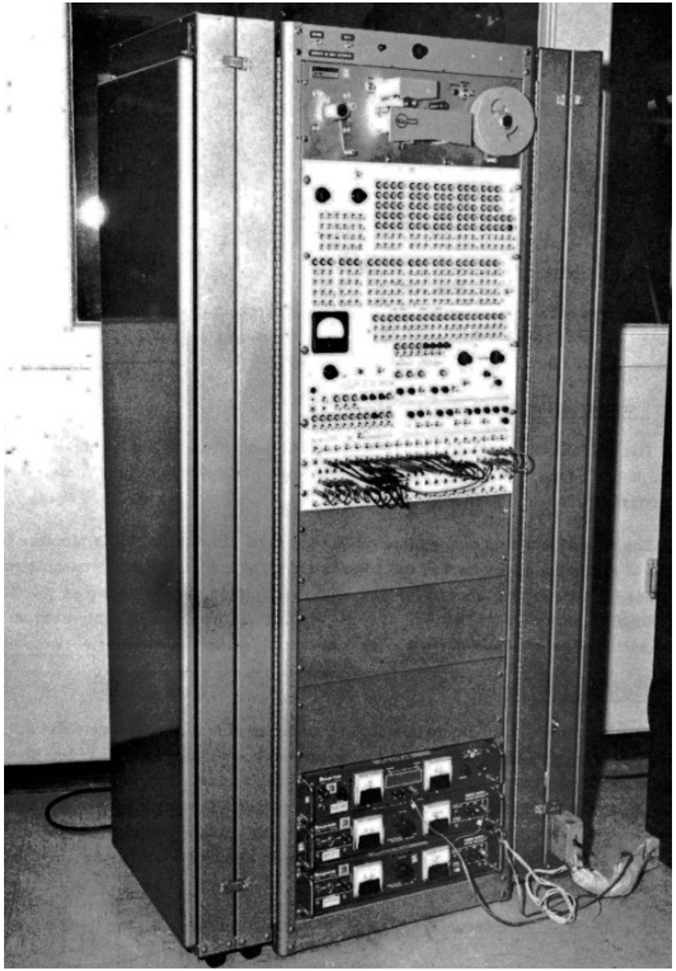
Archived software from ropes



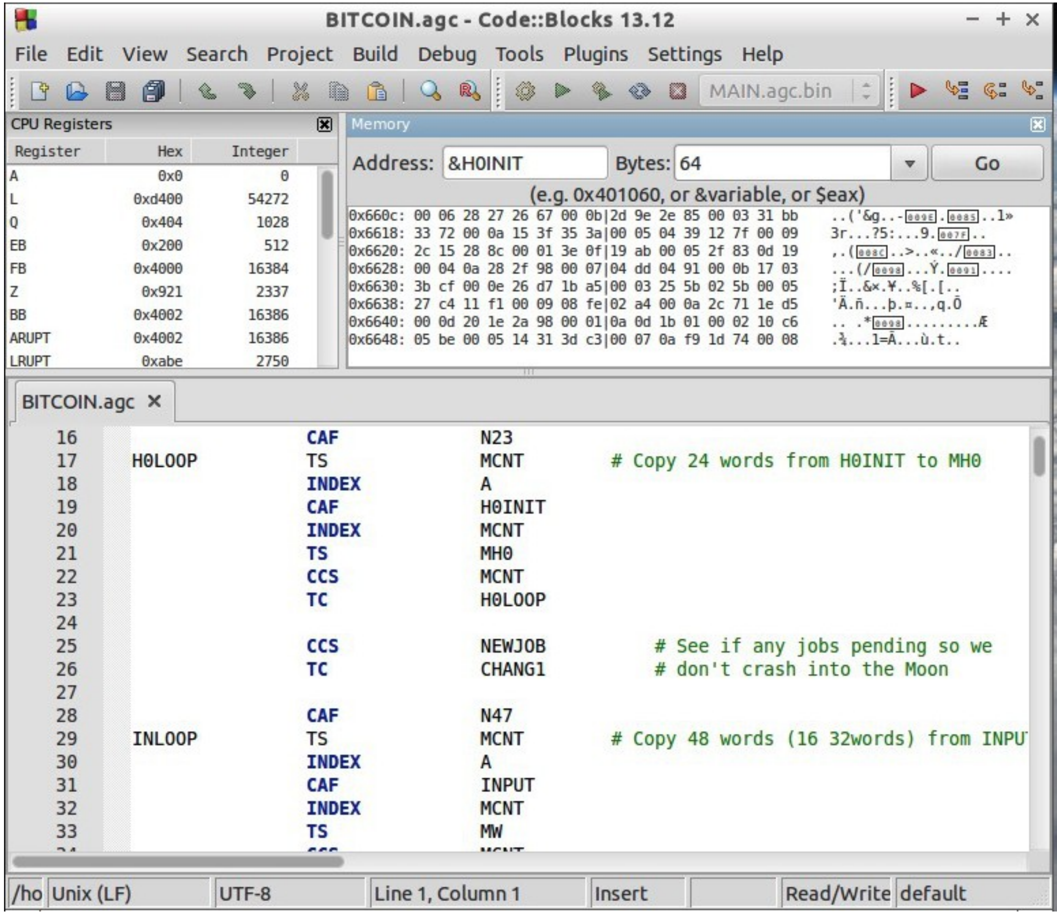
Photos from CuriousMarc video

Programming the AGC: then

- The “monitor”
  - Connected to AGC test connector
  - Breakpoints
  - Examine memory



Programming the AGC: now


BITCOIN.agc - Code::Blocks 13.12
File Edit View Search Project Build Debug Tools Plugins Settings Help
MAIN.agc.bin
CPU Registers
Memory
BITCOIN.agc ×

Register	Hex	Integer
A	0x0	0
L	0xd400	54272
Q	0x404	1028
EB	0x200	512
FB	0x4000	16384
Z	0x921	2337
BB	0x4002	16386
ARUPT	0x4002	16386
LRUPT	0xabe	2750

Address: &H0INIT Bytes: 64 Go

(e.g. 0x401060, or &variable, or $eax)

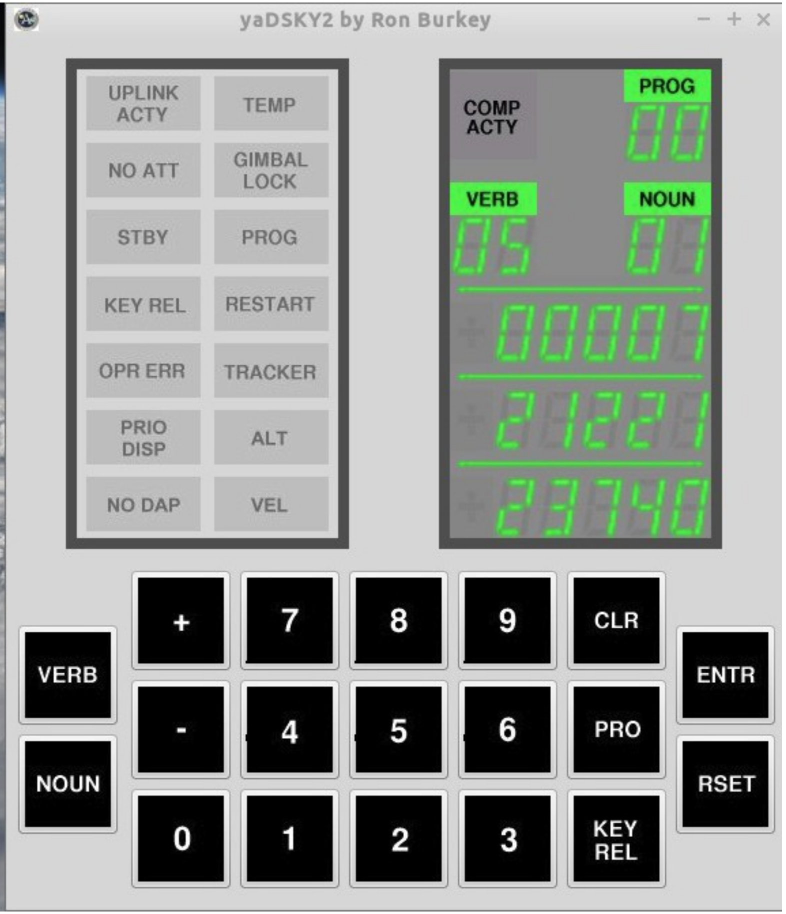
```
0x660c: 00 06 28 27 26 67 00 0b|2d 9e 2e 85 00 03 31 bb    ..('&g..-009E.0085..1»
0x6618: 33 72 00 0a 15 3f 35 3a|00 05 04 39 12 7f 00 09    3r...?5:...9.007F..
0x6620: 2c 15 28 8c 00 01 3e 0f|19 ab 00 05 2f 83 0d 19    ,.(008C..>..«../0083..
0x6628: 00 04 0a 28 2f 98 00 07|04 dd 04 91 00 0b 17 03    ...(/0098...Ý.0091....
0x6630: 3b cf 00 0e 26 d7 1b a5|00 03 25 5b 02 5b 00 05    ;Ï..&×.¥..%[.[..
0x6638: 27 c4 11 f1 00 09 08 fe|02 a4 00 0a 2c 71 1e d5    'Ä.ñ...þ.¤..,q.Õ
0x6640: 00 0d 20 1e 2a 98 00 01|0a 0d 1b 01 00 02 10 c6    .. .*0098.........Æ
0x6648: 05 be 00 05 14 31 3d c3|00 07 0a f9 1d 74 00 08    .¾...1=Ã...ù.t..
```

```
                CAF         N23
H0LOOP          TS          MCNT        # Copy 24 words from H0INIT to MH0
                INDEX       A
                CAF         H0INIT
                INDEX       MCNT
                TS          MH0
                CCS         MCNT
                TC          H0LOOP

                CCS         NEWJOB          # See if any jobs pending so we
                TC          CHANG1          # don't crash into the Moon

                CAF         N47
INLOOP          TS          MCNT        # Copy 48 words (16 32words) from INPU
                INDEX       A
                CAF         INPUT
                INDEX       MCNT
                TS          MW
```

/ho Unix (LF) UTF-8 Line 1, Column 1 Insert Read/Write default

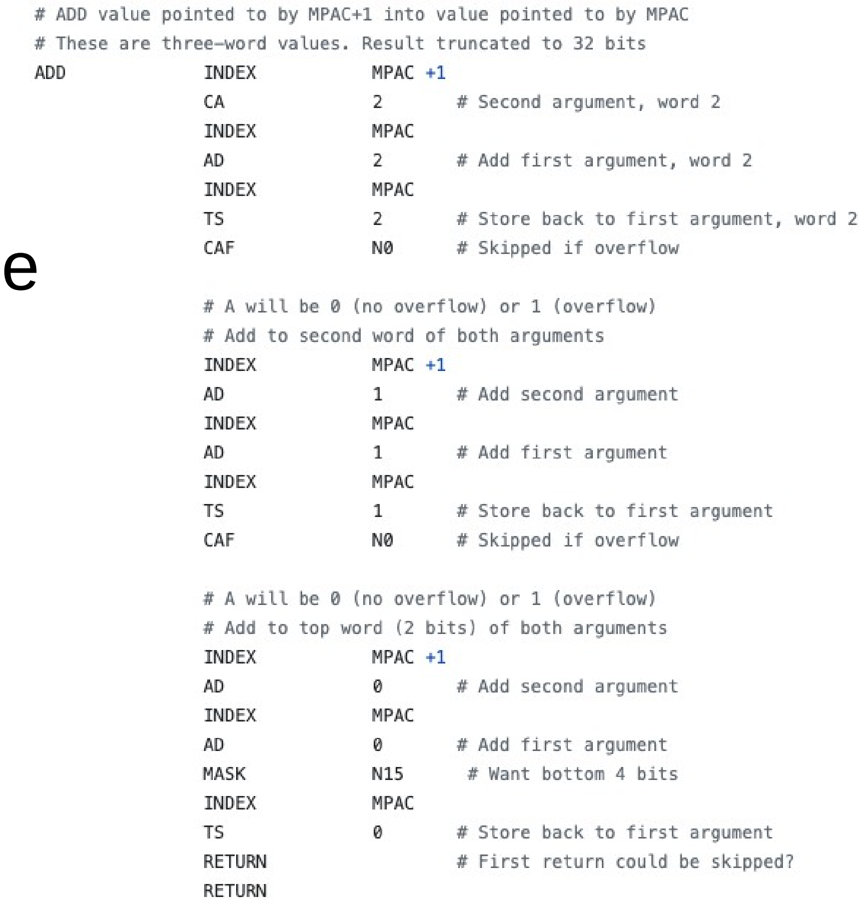


Instruction set

- 3-bit opcode, 12-bit address
  - Bank switching to access more memory
  - 34 instructions: prefix, hacks
- Weird instructions
  - CCS: count, compare, and skip (4-way jump)
  - TS: transfer A to storage, also handle overflow, jump
  - Special memory locations for shifting

Bitcoin mining

- SHA-256 in AGC assembly
  - 15-bit words inconvenient
  - Data barely fit in a memory page
- 5.15 seconds / hash
- Time to mine: a million times the age of the universe



```
# ADD value pointed to by MPAC+1 into value pointed to by MPAC
# These are three-word values. Result truncated to 32 bits
ADD             INDEX           MPAC +1
                CA              2       # Second argument, word 2
                INDEX           MPAC
                AD              2       # Add first argument, word 2
                INDEX           MPAC
                TS              2       # Store back to first argument, word 2
                CAF             N0      # Skipped if overflow

                # A will be 0 (no overflow) or 1 (overflow)
                # Add to second word of both arguments
                INDEX           MPAC +1
                AD              1       # Add second argument
                INDEX           MPAC
                AD              1       # Add first argument
                INDEX           MPAC
                TS              1       # Store back to first argument
                CAF             N0      # Skipped if overflow

                # A will be 0 (no overflow) or 1 (overflow)
                # Add to top word (2 bits) of both arguments
                INDEX           MPAC +1
                AD              0       # Add second argument
                INDEX           MPAC
                AD              0       # Add first argument
                MASK            N15      # Want bottom 4 bits
                INDEX           MPAC
                TS              0       # Store back to first argument
                RETURN                  # First return could be skipped?
                RETURN
```

Bitcoin mining

- SHA-256 in AGC assembly
  - 15-bit words inconvenient
  - Data barely fit in a memory page
- 5.15 seconds / hash
- Time to mine: a million times the age of the universe

Conclusion

- AGC essentially created IC industry
  - Apollo used 60% of ICs in 1963
- Advanced hardware and software
  - Real-time OS, checkpointing, fly-by-wire
- Limited computing power, but got to the Moon
  - Moore’s law: what can we do today?

More info

- youtube.com/CuriousMarc — Marc’s videos
- ibiblio.org/apollo — Virtual AGC project
- Wall Street Journal:

  “An Apollo Spacecraft Computer is Brought Back to Life”
- righto.com — my blog
  - ken.shirriff@gmail.com — my email
- Sponsors:

  samtec PCBWay

SUMMARY

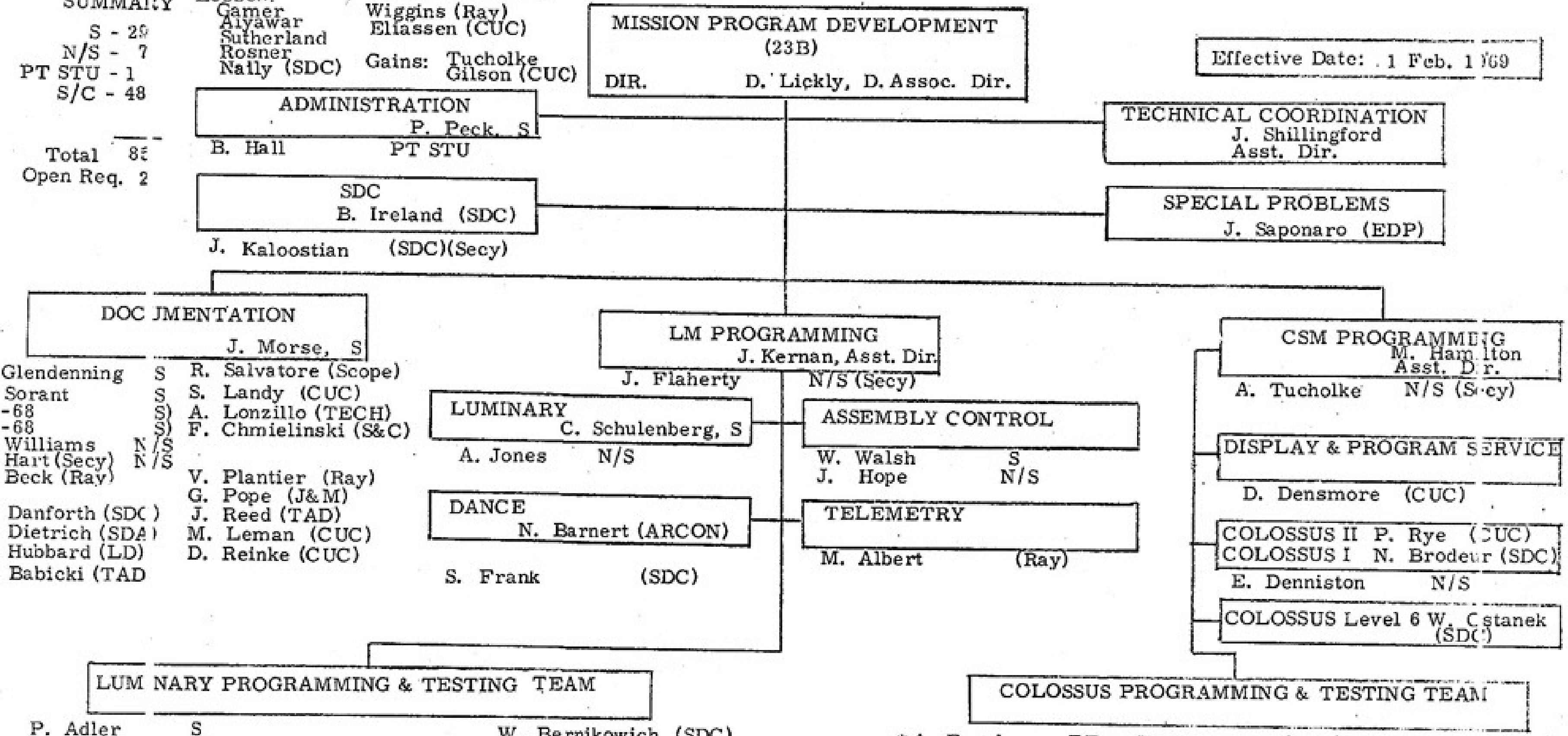
S - 29
N/S - 7
PT STU - 1
S/C - 48

Total 85
Open Req. 2

Losses:
Garner
Aiyawar
Sutherland
Rosner
Nally (SDC)
Schinas (ARCON)
Wiggins (Ray)
Eliassen (CUC)

Gains: Tucholke
Gilson (CUC)

Effective Date: 1 Feb. 1969



MISSION PROGRAM DEVELOPMENT
(23B)
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ADMINISTRATION
P. Peck, S
B. Hall PT STU

TECHNICAL COORDINATION
J. Shillingford
Asst. Dir.

SDC
B. Ireland (SDC)
J. Kaloostian (SDC)(Secy)

SPECIAL PROBLEMS
J. Saponaro (EDP)

DOCUMENTATION
J. Morse, S

J. Glendenning S
A. Sorant S
(86-68 S)
(87-68 S)
A. Williams N/S
R. Hart (Secy) N/S
G. Beck (Ray)

W. Danforth (SDC)
P. Dietrich (SDA)
H. Hubbard (LD)
C. Babicki (TAD

R. Salvatore (Scope)
S. Landy (CUC)
A. Lonzillo (TECH)
F. Chmielinski (S&C)

V. Plantier (Ray)
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S. Frank (SDC)

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COLOSSUS I N. Brodeur (SDC)
E. Denniston N/S

COLOSSUS Level 6 W. Ostanek
(SDC)

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C. Braunhardt	S	R. Finkelstein	S	P. Volante	(SDC)		
R. Covelli	S	F. Kervin	S	P. White	(SDC)		
D. Eyles	S			C. Gilson	(CUC)		
N. Fisher	S			D. Hsiung	(CUC)		

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E. Hughes	S	A. Bartlett	(SDC)	P. Wolff	(SDC
*S. Zeldin	S	T. Crocker	(SDC)	J. Goode	(SDC
M. Besas	S	R. Haslam	(SDC)		
M. Cramer	S	*S. Jennings	(SDC)	J. Stoppelman	(CUC
		J. Laird	(SDC)		
J. Vella	S	E. McCarthy	(SDC)	H. Tobin	(ARCO
V. Demery	S	N. Neville	(SDC)	*K. Vincent	(ARCO
C. Beals	(SDC)				

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