WHEN 100 FLOPS/WATT WAS A GIANT LEAP

THE APOLLO GUIDANCE COMPUTER HARDWARE, SOFTWARE AND APPLICATION IN MOON MISSIONS

Mark C Miller, LLNL (miller86@llnl.gov)

Presented at ATPESC
August 6th 2019
OUTLINE

• Background
• Hardware Architecture
• The Software Effort
• Brief Detour
• Mission Applications
Current generation HPC/CSE software developers will recognize many common themes:

- Flops/Watt power constraints
- Checkpoint/Restart
- Performance Portability
- Co-Design
- Domain Specific Languages
- Role and impact of Non-Volatile Memory (NVM)
Virtual AGC Project: https://www.ibiblio.org/apollo/

3-Part Blog Series on Better Scientific Software Site (bssw.io)

Part 1 | Part 2 | Part 3
OUTLINE

• Background
• Hardware Architecture
• The Software Effort
• Brief Detour
• Mission Applications
WHAT WAS THE APOLLO PROGRAM?

• 10 year project, starting in 1961 to land people on the moon

• 7 Lunar Missions from Jul. 1969 – Dec. 1972

• The Apollo Guidance Computer (AGC) was instrumental in the success
Early Sixties
State of the Art
Computers

- 4,000 ft³
- 8 tons
- 125 Kilowatts
- MTBF ≈ Days
- Reboot ≥ 30 mins
- UI = Punch Cards & Printouts
- Time slice multi-tasking
- ~1 Flops/Watt
Early Sixties
State of the Art
Computers

- 4,000 ft$^3$
- 8 tons
- 125 Kilowatts
- MTBF $\approx$ Days
- Reboot $\geq$ 30 mins
- UI = Punch Cards & Printouts
- Time slice multi-tasking
- $\sim$1 Flops/Watt
1966 BLOCK II AGC

- 1 cubic foot volume
- 70 lbs weight
- 55 Watts power
- MTBF ≳ Months
- Reboot ≈ 7 seconds
- UI = Verb/Noun ELD (DSKY)
- Priority Based Multi-Tasking
- ~259 Flops/Watt
APOLLO SPACECRAFT
APOLLO SPACECRAFT

- Ascent
- Descent
- Attitude Control Thusters
- Main Engines
APOLLO SPACECRAFT
ROLE OF THE COMPUTER
ROLE OF THE COMPUTER

• In powered or coasting flight, manage the State Vector
  • Position & Position Rates
    • X, Y, Z & ΔX, ΔY, ΔZ
  • Attitude & Attitude Rates
    • R(oll), P(itch), ya(W) & ΔR, ΔP, ΔW

• Real-time, Accurately, Reliably
• Autonomously

• In spite of many constraints and challenges...
  • Sensor noise, bias and drift
  • Avoiding orientations causing IMU gimbal lock
  • Moon’s lumpy gravity field
  • Changing center of mass (fuel slosh & loss)
  • Minimize fuel consumption
  • Communication lapses and blackouts
  • Allowing for failures & contingencies
EXAMPLE MANEUVER:
LUNAR ORBIT INSERTION (LOI)

- Velocity = 2 miles/sec
- Distance from moon = 60 miles
- RT signal to Earth = 2.5 sec
- Insertion burn on far side
OUTLINE

• Background
• Hardware Architecture
• Guidance Software
• Brief Detour
• Mission Applications
AGC HARDWARE OVERVIEW

SPECs

• 16 bit word size (15 + odd parity)
• 1.024 MHz Clock
• 12-pulse micro-seq’d instructions
• 4 central reg’s + ~15 special reg’s

TECHNOLOGY

• 2,800 ICs
• dual 3-input NOR
**PURCHASE ORDER**

Massachusetts Institute of Technology
Cambridge 39, Massachusetts

PAGE 1 of 2

DATE: May 28, 1962

REQUISITION NUMBER

ACCOUNT NUMBER: 55-191-37-23

ILLUSTRATIVE ORDER

The Purchase Order Number IL120534 should appear on invoices.

### SHIP TO

**Fairchild Semi-Condutor Corp.**

**TO:** 36 North Road
Bedford, Massachusetts

**ATTN:** Mr. Bruce Giron

**66 Albany Street**

**R.J. Duggan W5-151**

### PLEASE FURNISH THE FOLLOWING MATERIALS OR SERVICES

<table>
<thead>
<tr>
<th>DATE REQUIRED</th>
<th>SHIP VIA</th>
<th>MFG</th>
<th>QTY</th>
<th>DESCRIPTION</th>
<th>DFS</th>
<th>PRICE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1000</td>
<td>&quot;B&quot; Grade Gate Element in TO47 package, Fairchild P/N SL 1015 per MIT print C-88794 change 1, @ $31.10 each</td>
<td></td>
<td>31100.00</td>
</tr>
</tbody>
</table>

### 1. To conform with MIT requirements, Fairchild P/N 1015 will have lead orientation in accordance with C-88794-B as agreed upon by Mr. R. Duggan of MIT, and R. Graham, N. Siegel, and B. Giron of Fairchild on May 25, 1962.
AGC HARDWARE OVERVIEW

SPECS
• 16 bit word size (15 + odd parity)
• 1.024 MHz Clock
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• 4 central reg’s + ∼15 special reg’s
• 2K words Erasable Memory (RAM)

TECHNOLOGY
• 2,800 ICs
• dual 3-input NOR
• Coincident-Current Core
AGC HARDWARE OVERVIEW

SPECS
• 16 bit word size (15 + odd parity)
• 1.024 MHz Clock
• 12-pulse micro-seq’d instructions
• 4 central reg’s + ~15 special reg’s
• 2K words Erasable Memory (RAM)
• 36K words Fixed Memory (ROM)

• Both RAM and ROM were NVM

TECHNOLOGY
• 2,800 ICs
• dual 3-input NOR
• Coincident-Current
• Woven Rope Core
AGC HARDWARE OVERVIEW
CPU

Fixed / Erasable Memory
Timing, I/O
AGC ARCHITECTURE OVERVIEW

• 4 Central registers
  • A: accumulator w/overflow bit
  • Z: program counter
  • Q: div-remainder / return address
  • L: lower-product

• Other special purposes registers
  • ROM / RAM memory banking
  • Editing (shift) registers
  • Zero / NEWJOB (000678)
  • Not directly programmable

• 8 basic + 33 extended instructions
<table>
<thead>
<tr>
<th>line</th>
<th>label</th>
<th>opcode</th>
<th>address</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0184</td>
<td>P63SPOT3</td>
<td>CA</td>
<td>BIT6</td>
<td>IS THE LR ANTENNA IN POSITION 1 YET</td>
</tr>
<tr>
<td>0185</td>
<td></td>
<td>EXTEND</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0186</td>
<td></td>
<td>RAND</td>
<td>CHAN33</td>
<td></td>
</tr>
<tr>
<td>0187</td>
<td></td>
<td>EXTEND</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0188</td>
<td></td>
<td>BZF</td>
<td>P63SPOT4</td>
<td>BRANCH IF ANTENNA ALREADY IN POSITION 1</td>
</tr>
<tr>
<td>0189</td>
<td></td>
<td>CAF</td>
<td>CODE500</td>
<td>ASTRONAUT: PLEASE CRANK THE SILLY THING AROUND</td>
</tr>
<tr>
<td>0190</td>
<td></td>
<td>TC</td>
<td>BANKCALL</td>
<td></td>
</tr>
<tr>
<td>0191</td>
<td></td>
<td>CADR</td>
<td>GOPERF1</td>
<td></td>
</tr>
<tr>
<td>0192</td>
<td></td>
<td>TCF</td>
<td>GOTOP00H</td>
<td>TERMINATE</td>
</tr>
<tr>
<td>0193</td>
<td></td>
<td>TCF</td>
<td>P63SPOT3</td>
<td>PROCEED SEE IF HE'S LYING</td>
</tr>
<tr>
<td>0194</td>
<td>P63SPOT4</td>
<td>TC</td>
<td>BANKCALL</td>
<td>ENTER INITIALIZE LANDING RADAR</td>
</tr>
<tr>
<td>0195</td>
<td></td>
<td>CADR</td>
<td>SETPOS1</td>
<td></td>
</tr>
<tr>
<td>0196</td>
<td></td>
<td>TC</td>
<td>POSTJUMP</td>
<td>OFF TO SEE THE WIZARD...</td>
</tr>
<tr>
<td>0197</td>
<td></td>
<td>CADR</td>
<td>BURNBABY</td>
<td></td>
</tr>
</tbody>
</table>
### VIRTUAL REGISTER SET

- MPAC (virtual accumulator)
- OVFIND (virtual overflow bit)
- ADRLOC (virtual program counter)
- QPRET (virtual Q/L)
- X1, X2, S1, S2 (index, temp)
- PUSHLOC/PUSHLIST (small stack)

### VIRTUAL INSTRUCTION SET

- S|D|T|VLOAD & S|D|T|VSTORE
- S|D|T|VAD & S|D|T|VSU
- SQRT
- DOT
- NORM
- SIN/COS/ASIN/ACOS

A form of compression to tradeoff memory space for time
Problem: Compute \( z = a M (x + y) \)
where \( a \) is a scalar and \( M \) a \( 3 \times 3 \) matrix

**Program** (requires **7** words of storage)

<table>
<thead>
<tr>
<th>Operation Codes</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MXV</strong></td>
<td>1) The first address of an equation is used to load an accumulator; VAD requests a vector load.</td>
</tr>
<tr>
<td><strong>VXSC</strong></td>
<td></td>
</tr>
<tr>
<td><strong>X Y M A</strong></td>
<td>2) Each op code results in a subroutine call with the corresponding address left in a standard location.</td>
</tr>
<tr>
<td><strong>STORE Z</strong></td>
<td>3) After all op codes have been &quot;executed,&quot; the remaining address is used to store the result. Since the result of the last operation is a vector, a vector will be stored in ( Z ).</td>
</tr>
</tbody>
</table>
NUMERICS OF THE AGC

WHOLE NUMBERS

• 16 bit, 1’s compliment, big endian
• 1 bit for parity (bit 16) & sign (bit 15)
• 14 bits for magnitude range 0…2^{14}-1
• Full range of -16,383_{10} to +16,383_{10}

\[ P | S | 2^13 | 2^{12} | 2^{11} | \ldots | 2^1 | 2^0 \]

FRACTIONAL NUMBERS

• Fixed Point Representation
• Coders must ensure proper scaling!!
• Just like an Engineer’s Slide Rule
NUMERICS OF THE AGC
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\[
P | S | 2^{13} | 2^{12} | 2^{11} | \ldots | 2^1 | 2^0
\]

FRACTIONAL NUMBERS

\[
P | S | 2^{-1} | 2^{-2} | 2^{-3} | \ldots | 2^{-13} | 2^{-14}
\]

• Fixed Point Representation
• Coders must ensure proper scaling!!
• Just like an Engineer’s Slide Rule
• Single, double, triple precision
• +,x,÷ = 35.1, 70.2, 133.4 \mu sec
Flops/x Computing Metrics Comparison

- flops/kb
- flops/watt
- flops/kg
- flops/m3
- flops/$

AGC, IBM 360-20, IBM AC922 (Summit)
THE AGC EXECUTIVE (PROCESS MANAGER)

"TASKS"

• Short, finely tuned
  • < 5 ms (150-200 instructions)
• Scheduled by time (in the future)
• Some tasks only schedule a “job”

“JOBS”

• Priority Scheduled
• 12 words of state (4 regs + other)
• Jobs adjust own priority up/down
WAYPOINT AND RESTART

• Critical routines were restart protected

• Waypoints periodically updated in erasable memory

• Consumed 4% of fixed memory, additional coding and testing complexity
I/O DEVICES

Command Module

Lunar Module
FAULT TOLERANCE INCORPORATED AT MANY LEVELS

• Power system glitch detection
• Parity check every memory ref
• Job hog/freeze detection (NEWJOB night watchman)
• Interrupt lockout detection
• Program Alarms (e.g. Exceptions)
• System Restarts (< 7 seconds)
• System self-checks
• MTBF $\rightarrow$ 40,000 hours (due to quality ICs)
• Modern systems using triple redundant hardware & voting
OUTLINE

• Background
• Hardware Architecture
• Guidance Software
• Brief Detour
• Mission Applications
435P EDT AUG 9 61 BB257 PB375
W NFA084 GOVT PD NF WASHINGTON DC 9 405P EDT
OR STARK DRAPER, DIR

INSTRUMENTAL LABORATORY MASSACHUSETTS INST OF TECHNOLOGY
CAMBRIDGE MASS

PLEASED TO ADVISE THAT THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
ON TODAY ANNOUNCED THAT MIT'S INSTRUMENTATION LABORATORY HAS BEEN SELECTED TO DEVELOP THE GUIDANCE NAVIGATION SYSTEM OF THE PROJECT APOLLO SPACECRAFT. APOLLO IS CAPABLE OF CARRYING THREE MEN TO THE MOON AND BACK. MIT IS THE FIRST MEMBER OF THE APOLLO TEAM TO BE CHOSEN. BIDS ARE NOW UNDERWAY FOR THE PRIME CONTRACTOR'S JOB. IN ADDITION TO APOLLO THE INSTRUMENTATION LABORATORY WILL ALSO DEVELOP THE GROUND SUPPORT AND CHECKOUT EQUIPMENT. CONTRACT COVERING THE FIRST YEAR IS AN ESTIMATED $4 MILLION.
EXTREME CO-DESIGN

• None of these components were known when MIT was awarded the PGNCS contract
• NASA didn’t decide upon Lunar Orbit Rendezvous (LOR) until a year later
• Everything was being developed essentially simultaneously
Contracts

Sub-Contract:

Work Authorization Associated
with Design, Technical Control
and Resident effort

Informal Design Data Flow

Design Approval & Controls

Technical Coordination
THE ESSENTIAL STEP MIT SOFTWARE ENGINEERS NEEDED TO PERFORM

• Assemble a “flight program” & release it to Raytheon for rope core weaving
  • 2 months to weave the ropes
  • 2 months to install, test, run crew rehearsals, etc.

• For ~30 planned flights (uncrewed and crewed), some with unique guidance requirements
• Mission divided into phases by velocity changes (e.g. "burns" of the main engines)
• A lunar mission involved ~11 burns
• For each unique maneuver, there was a major mode program to handle it
Lunar Module Descent Profile

Braking Phase: Program 63

Approach Phase:
Program 64

Terminal Descent: Program 66
EXAMPLE OF GUIDANCE ROUTINE SOFTWARE
DEVELOPMENT WORKFLOW – EPHEMERIS ROUTINES

• Knowing the position of the moon (Ephemeris) at any moment
  • Accurately, over a sufficiently long time period (2 weeks), minimizing resource usage

• Where do you get the “ground truth” data to test an algorithm?
  • Classically studied problem (Newton, Euler, Lagrange, Laplace, Delaunay…)
  • Brown’s Lunar Theory (1897) + Tables (1919) + data from main-frame codes using Fourier series

• Polynomial fit to X, Y, Z positional data
  • 8 double precision coefficients for each of X, Y and Z  → 48 words
  • AGC Interpreter subroutine  → 86 words
  • Initially in MAC language Honeywell 1800 mainframe
## INFRASTRUCTURE SOFTWARE

<table>
<thead>
<tr>
<th>Program Name</th>
<th>Purpose</th>
<th>Size (AGC words)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive(^{25})</td>
<td>Priority-driven large/long-running process manager</td>
<td>~350</td>
</tr>
<tr>
<td>Waitlist(^{26})</td>
<td>Time-sequenced small/short-running process manager</td>
<td>~300</td>
</tr>
<tr>
<td>Down-Telemetry(^{29})</td>
<td>Transmit system data to ground</td>
<td>~200</td>
</tr>
<tr>
<td>Restart(^{30,31,32})</td>
<td>Error recovery and restart protection</td>
<td>~1225</td>
</tr>
<tr>
<td>Interpreter(^{27})</td>
<td>Space guidance domain-specific programming language interpreter</td>
<td>~2200</td>
</tr>
<tr>
<td>DSKY I/O(^{28})</td>
<td>Cockpit displays and keypad</td>
<td>~3500</td>
</tr>
<tr>
<td>Combined Total</td>
<td>22% of fixed memory</td>
<td>~7775</td>
</tr>
</tbody>
</table>
APOLLO’S DIGITAL AUTO PILOTS: A PERFORMANCE PORTABILITY CHALLENGE

- Many different hardware configurations
- One implementation
KALMAN FILTERING AND THE DIGITAL AUTO PILOTS (DAP)

• Prediction phase: Use idealized model for spacecraft motion

• Comparison phase: Measured state from sensors compared with predicted

• Control decisions based on the difference

• Performance Portability: Switch settings and pre-programmed parameters
If the time required to drive $\dot{\hat{E}}$ to the 5.625 deg./sec. rate be less than 0.020 sec., then no jets are fired.

\[ -E - \frac{0.5}{a_{\text{netneg}}} \hat{E}^2 + DB_1 = 0 \]

Zone $A$:
- $E = -11.25$ deg.
- $0 = DB_1$
- $E = 5.625$ deg./sec.
- $0 = -DB_2$

Zone $B$:
- $E = 0$
- $DB_1 = 0$
- $DB_2 = 0$

Zone $C$:
- $E = 5.625$ deg./sec.
- $DB_1 = -DB_2$

$E = 0$

FINELAW applies to the dotted area; ROUGHLAW applies to the region external to it.

Coast region
Thrust region


**BLOCK II - AUTOPILOT CONFIGURATION DATA**

DAP data loaded into components R1 and R2 upon request by flashing V06N46.

### R1 = ABCDE (DAPDATR1)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Config.</td>
<td>X-transl for Quad A/C</td>
<td>X-transl for Quad B/D</td>
<td>Attitude Deadband</td>
<td>Maneuver Rate</td>
</tr>
<tr>
<td>0=No DAP</td>
<td>0=Disable A/C</td>
<td>0=Disable B/D</td>
<td>0=+/−0.5 deg</td>
<td>0=0.05 deg/s</td>
</tr>
<tr>
<td>1=CSM</td>
<td>1=Use A/C</td>
<td>1=Use B/D</td>
<td>1=+/−5.0 deg</td>
<td>1=0.2 deg/s</td>
</tr>
<tr>
<td>2=CSM &amp; LM</td>
<td>2=0.5 deg/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3=CSM &amp; SIVB</td>
<td>3=2.0 deg/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6=CSM &amp; LM (ascent stage only)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### R2 = ABCDE (DAPDATR2)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll Quad Select</td>
<td>Quad A Status</td>
<td>Quad B Status</td>
<td>Quad C Status</td>
<td>Quad D Status</td>
</tr>
<tr>
<td>0=Use B/D</td>
<td>0=Disable</td>
<td>0=Disable</td>
<td>0=Disable</td>
<td>0=Disable</td>
</tr>
<tr>
<td>1=Use A/C</td>
<td>1=Use</td>
<td>1=Use</td>
<td>1=Use</td>
<td>1=Use</td>
</tr>
</tbody>
</table>
AGC SOFTWARE “STACK”
TESTING

- All-digital simulator: (AGC + Devices + Spacecraft “Environment”)
  - 1 HW-800, 2 HW-1800, 2 IBM 360-75 (4,500 equiv. HW-1800 hours/month)

- Several other levels of testing
  - Hybrid Simulator: Real AGC + Analog Computer (two story building)
  - Flight simulators & Crew Rehearsals

- Actual flight testing in mission plans
<table>
<thead>
<tr>
<th>Project</th>
<th>1965 ($M)</th>
<th>2019 ($M)</th>
<th>2019 $M/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo (10 yr)</td>
<td>25,000</td>
<td>203,000</td>
<td>20,300</td>
</tr>
<tr>
<td>PGNCS (10 yr)</td>
<td>600</td>
<td>~5000</td>
<td>500</td>
</tr>
<tr>
<td>Software (5 yr)</td>
<td>60</td>
<td>~500</td>
<td>100</td>
</tr>
</tbody>
</table>
“The need for formal validation rose with the size of the software. Programs of 2,000 words took between 50 and 100 test runs to be fully debugged, and full-size flight program took from 1,000 to 1,200 runs.”
“SOFTWARE ENGINEERING”

- Margaret Hamilton, lead developer of Lunar Module flight program introduced this term...

“...to bring the software [effort] legitimacy so that it and those building it would be given due respect"
“No one doubted the quality of the software…It was the process used in development that caused great concern. Five lessons were identified:

1. up-to-date documentation is crucial
2. verification must proceed through several levels
3. requirements must be clearly defined and carefully managed
4. good development plans should be created and executed
5. more programmers do not mean faster development
OUTLINE

• Background
• Hardware Architecture
• Guidance Software
• Brief Detour
• Mission Applications
Mercury 7 Astronauts
Apollo GN&C System (MIT-IL)
Apollo Moonwalkers
Mercury 13
Valentina Tereshkova – 3 days in orbit, 1963
A BRIEF DETOUR: WOMEN AND COMPUTERS

• 1640-1960: “Computer” $\rightarrow$ “one who calculates”

• Tedious calculation was “women’s” work (“kilogirl”)

• Before 1960: Computers were almost exclusively women
Langley, West Computing Group (1958)
Female Share of Bachelor's Degrees in Computer Science, 1970-2016

Source: US Department of Education
A BRIEF DETOUR
WOMEN
IN THE AGC PROJECT

Margaret Hamilton, Phyllis Rye, Saydean Zeldin, Elain Denniston
A BRIEF DETOUR
PEOPLE OF COLOR ASTRONAUTS & IN THE AGC PROJECT

William Mallory
Ramon Alonso
Robert Pinckney
Capt. Ed Dwight
Maj. Robert Lawrence
A BRIEF DETOUR: WERNHER VON BRAUN

• Creator of V2 Rocket
• Member of NAZI Party; arrested by SS for
• Captured and brought to US with ~1,600 others in 1945
• Led development of F1 engine and Saturn booster
• Championed racial integration in Wallace’s Alabama
OUTLINE

• Background
• Hardware Architecture
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• Mission Applications
USER INTERFACE

• VERB – NOUN

• 3, 5 char line display

• Indicator Lights

• Two in CM, one in LM one in Huston
### APOLLO 11

- Russian Luna 15
- Program alarms & restarts
- Hot I/O Device
- Boulder Field & Manual Inputs
- Ascent engine arm CB
OTHER MISSION EXPERIENCES

• Apollo 7
  • Schirra wants to fly re-entry manually

• Apollo 8
  • Lovell accidentally corrupts memory

• Apollo 9
  • First use of an EMP
  • Odd-ball configuration for LM test

• Apollo 10
  • Problems with barbecue roll
  • Incorrect AGS setting at staging

• Apollo 12
  • Lightning strike at launch
  • Pin-point landing near Surveyor III

• Apollo 13
  • Beneficiaries of what-if thinking

• Apollo 14
  • Abort switch fix

• Apollo 15
  • Terrain model for landing radar
ARGON-11C: RUSSIAN GUIDANCE COMPUTER

- Hybrid Integrated Circuits
- 14 bit data words, 17 bit “commands”
- 128 words RAM / 4 k-words ROM (9 kb)
- 5.2 K-Flops
- Triple redundant logic w/voting
- 34 kg / 75 watts
- 1968: Zond 7, First Russian circumlunar flight
COMPUTING WAS AN ESSENTIAL TOOL
USED IN MANY ASPECTS OF THE APOLLO PROJECT
COMPUTING AND SPACEFLIGHT

• Simulation and modeling used in all major vehicle components
• Digital and Analog computers for Training simulators
• Real time computing complex (RTCC) for mission planning, tracking, weather
• Apollo both drove innovations in computing and benefited from them
• Advances in computing helped the U.S. win the Space Race
RESOURCE LINKS

• bssw.io blog post
• Mercury 13 (Netflix doc)
• AGC Restoration
• AGC Source Code on GitHub
• Virtual AGC Project
• Ultimate AGC Talk
• Spaceflight Computing History

• AGC Software Cost Model
• Hidden Figures (the book)
• Hack The Moon