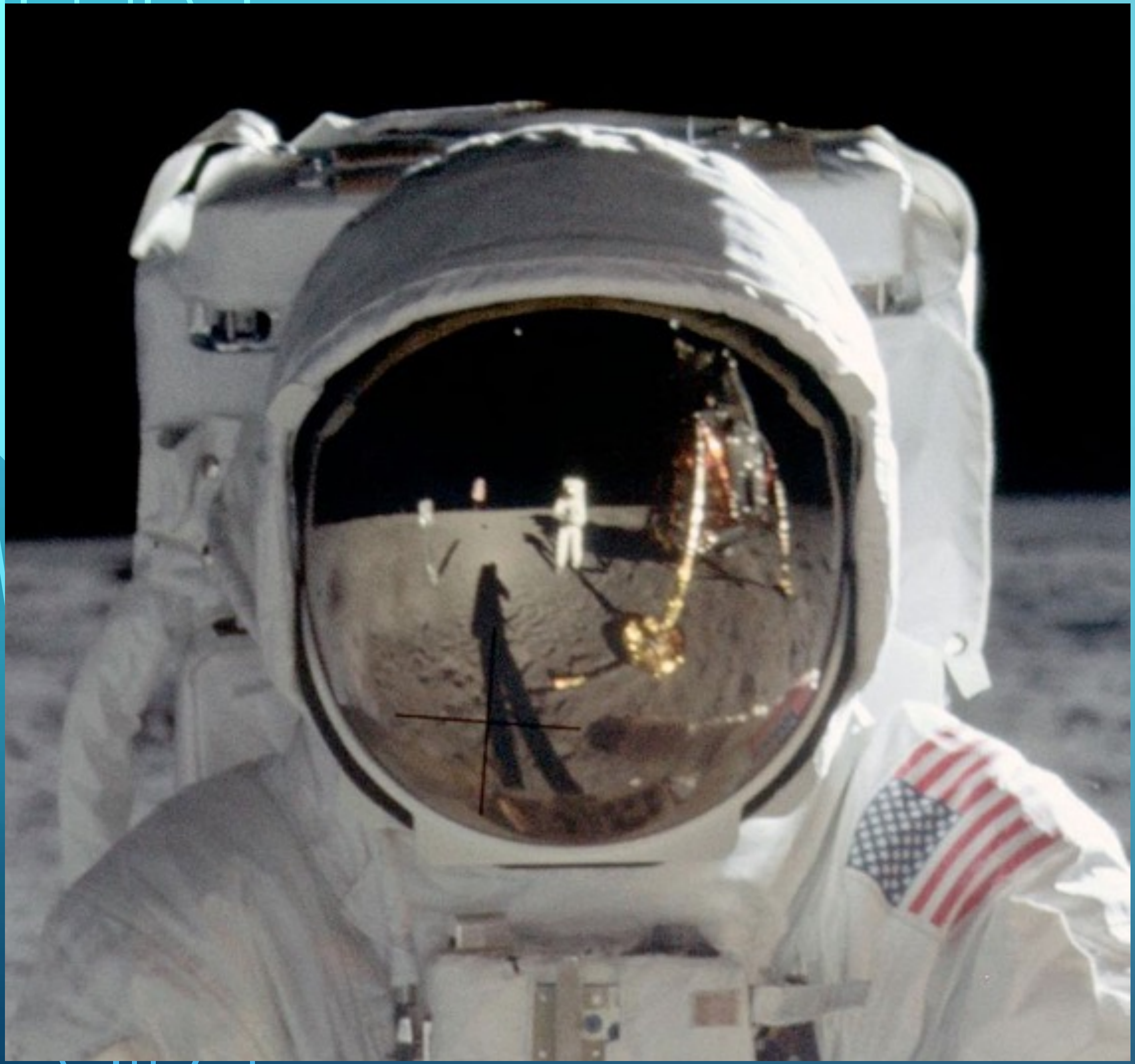


WHEN 100 FLOPS/WATT WAS A GIANT LEAP

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

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

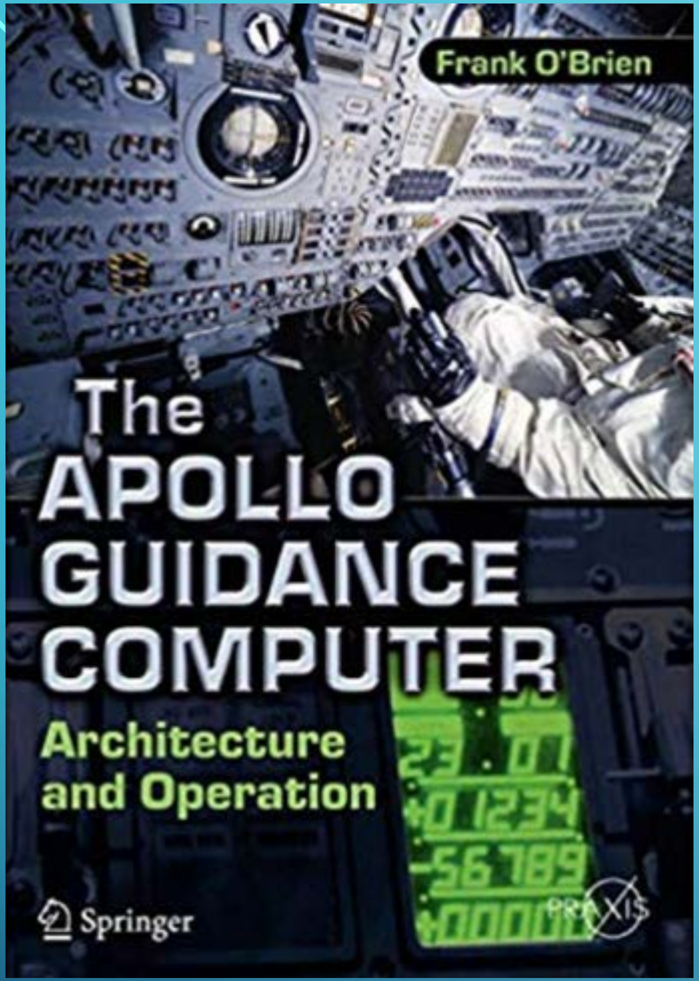
Presented at ATPESC
August 6th 2019

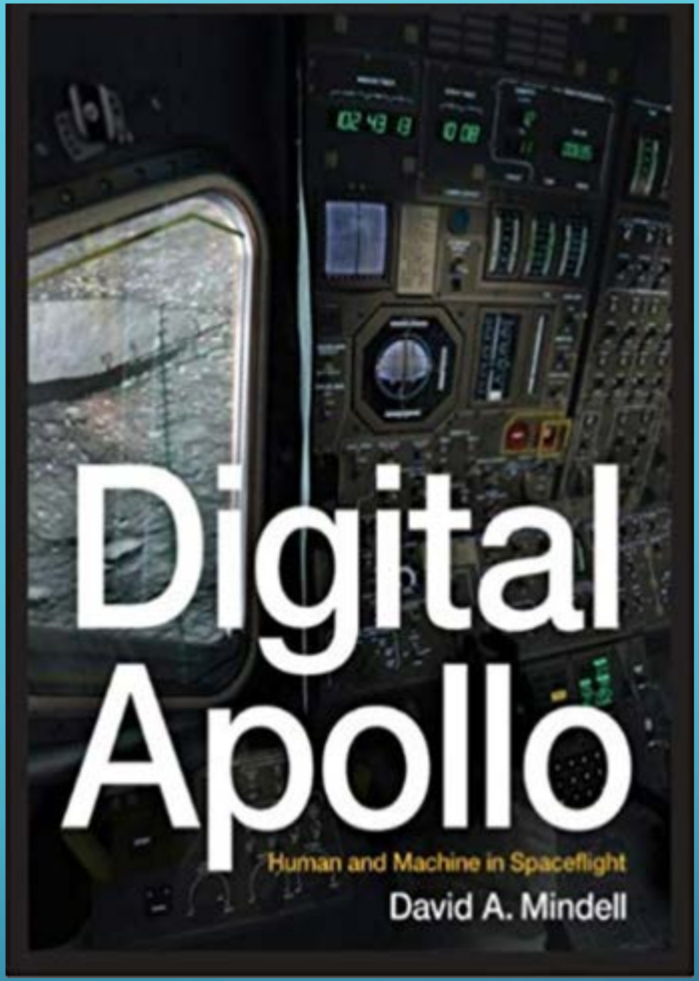
OUTLINE

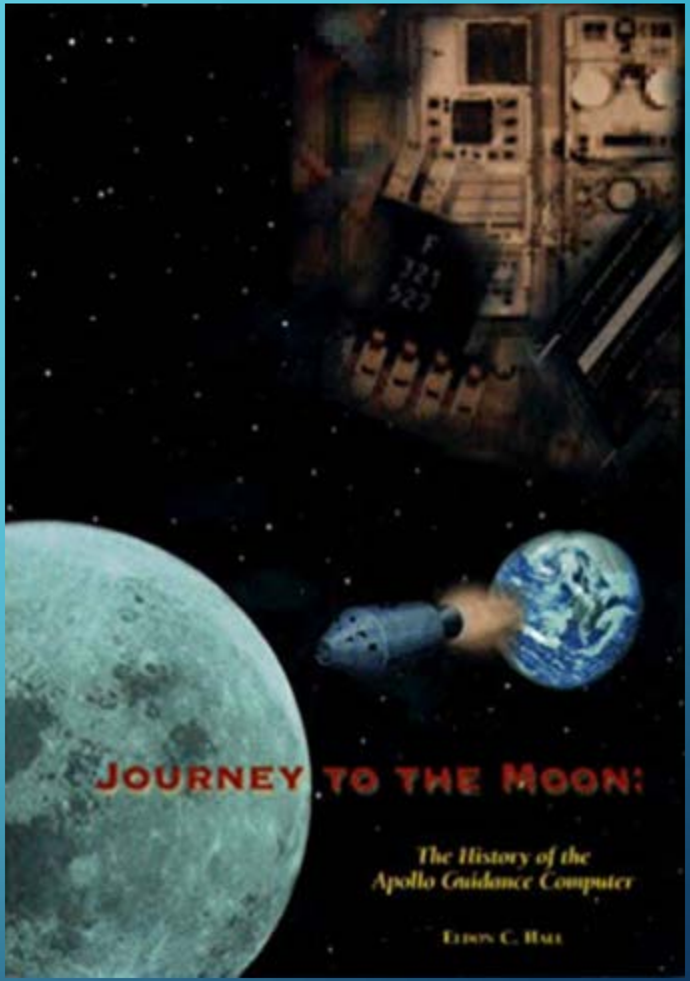
- Background
- Hardware Architecture
- The Software Effort
- Brief Detour
- Mission Applications

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
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turday Evening, October 5, 1957 (UP)—Means United Press Price: Five Cents

Russians Win Race To Launch Earth Satellite

Man On Threshold Of Space Travel

By DANIEL F. GILMORE
United Press Staff Correspondent

LONDON (UP)—The pulsating radio "beep" of the first manmade earth satellite signalled today to the world that man had crossed the threshold into the age of travel through space.

The Soviet Union announced it had won the race into space by launching an earth satellite Friday, a 184-pound, 22-inch globe now orbiting the earth at 18,000 miles an hour, 560 miles up.

Millions of persons throughout the world heard the "beep...beep... beep..." rebroadcast today by local stations and realized that man had taken his first faltering steps into the new era.

Launching of the satellite was a tremendous victory for science. It was a more tremendous victory for Soviet propaganda to be able to trumpet to the world the Russians were the first to break through the frontiers of space.

Bolsters ICBM Claims

— WEATHER —

WEST VIRGINIA—Partly cloudy with highest in the 60s today and Sunday. Lowest tonight 50 west and 40 east portions.

VIRGINIA—Fair with lowest 45 to 50 west and north and 50 to 55 southeast portions tonight, Sunday mostly sunny and a little warmer. Tides on the coast and lower bay will run a foot or two above normal.

How To Spot Satellite

By UNITED PRESS

Here's how to look for the Russian earth satellite which will be whizzing through the sky at 18,000 miles an hour.

The best time to spot it is at dawn or dusk when the sky is semi-dark. There is a chance that it could be seen if it travels across the face of the moon at night.

The best instruments to use are ordinary binoculars or telescopes. Powerful telescopes won't pick it up because of their narrow fields.

Through optical instruments, the satellite will look like the faintest star which can be seen with the naked eye.

Keep a sharp eye out. The satellite travels so fast it may appear on the horizon for only seconds and chances of spotting it have been estimated at one in a hundred.

Epic-Making

U.S. May Speed Up Satellite Program

By JOSEPH L. MYLER
United Press Staff Correspon

WASHINGTON (UP)—Amer scientists, caught flatfooted Russia's epic launching of the man-made moon, indicated the United States may spee its own earth satellite progra

Leaders of the U.S. satellite gram also said that it ap Russia rocketed its heavy pound satellite into a globe dling orbit with a rocket to" an intercontinental be missile.

That could mean Russia only has beaten this country frontiers of space, but also has been called the "ul weapon" for modern day wa ICBM. This country has tested a successful ICBM.

American diplomats co Russia had scored a notabl aganda victory. The milita

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 ft^3
- 8 tons
- 125 Kilowatts
- MTBF ≈ Days
- Reboot ≳ 30 mins
- UI = Punch Cards & Printouts
- Time slice multi-tasking
- ~1 Flops/Watt

NASA RTCC 1964

Early Sixties State of the Art Computers

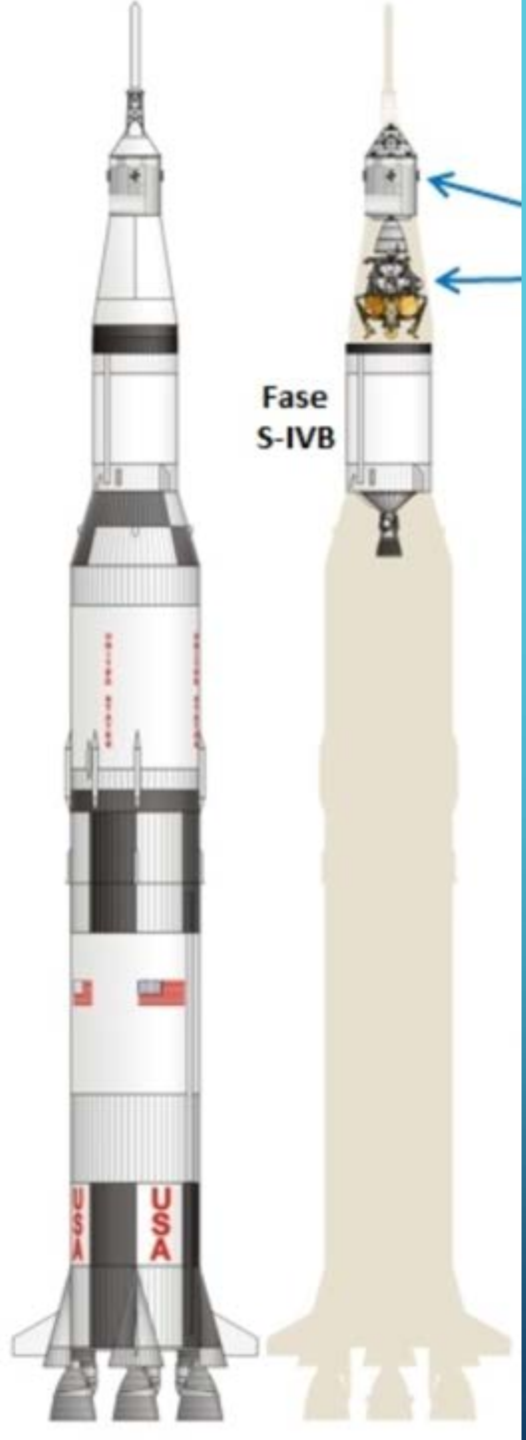
LLNL LARC1 1960 / B117

- 4,000 ft^3
- 8 tons
- 125 Kilowatts
- MTBF ≈ Days
- Reboot ≳ 30 mins
- UI = Punch Cards & Printouts
- Time slice multi-tasking
- ~1 Flops/Watt

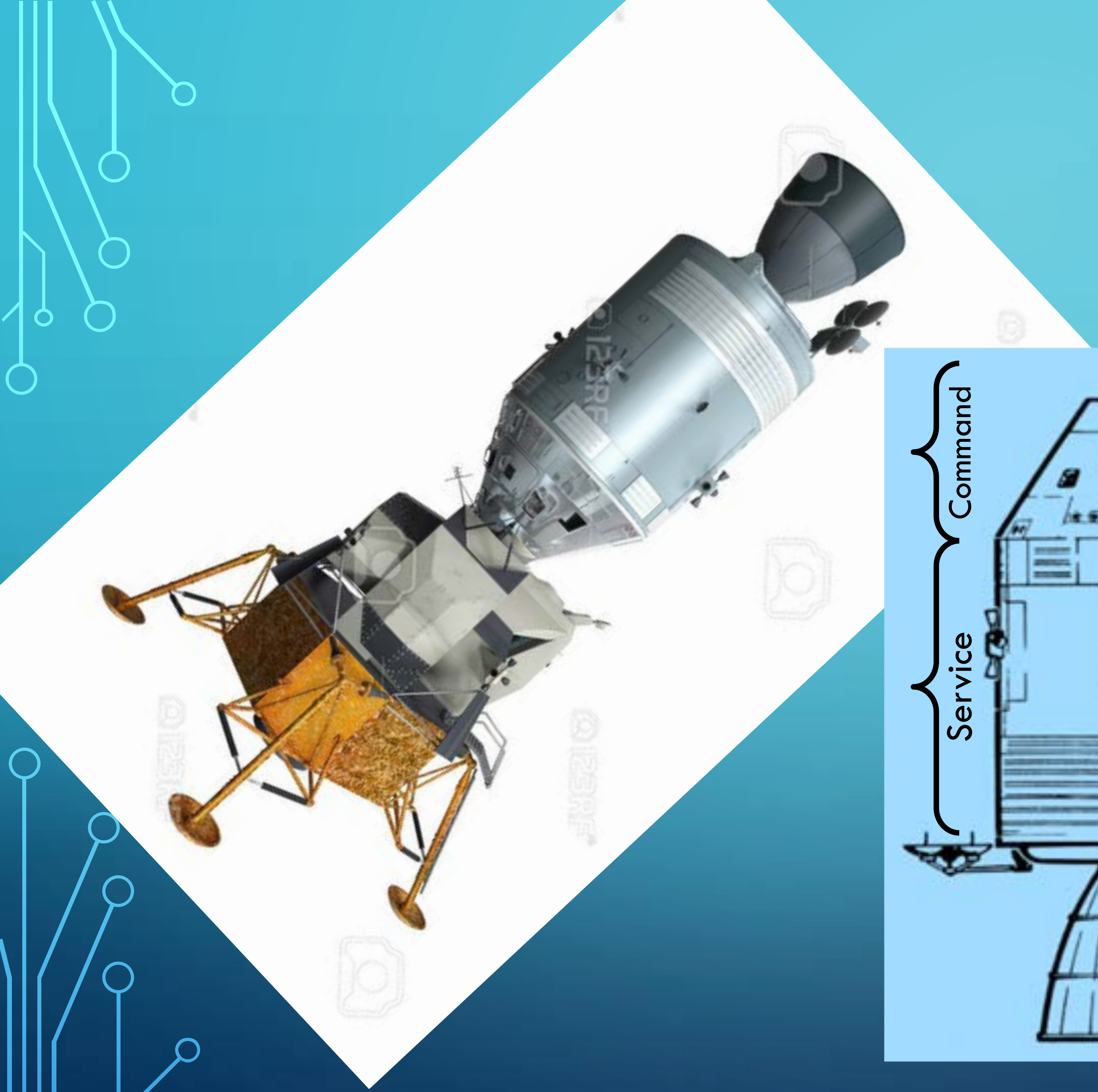
1966 BLOCK II AGC

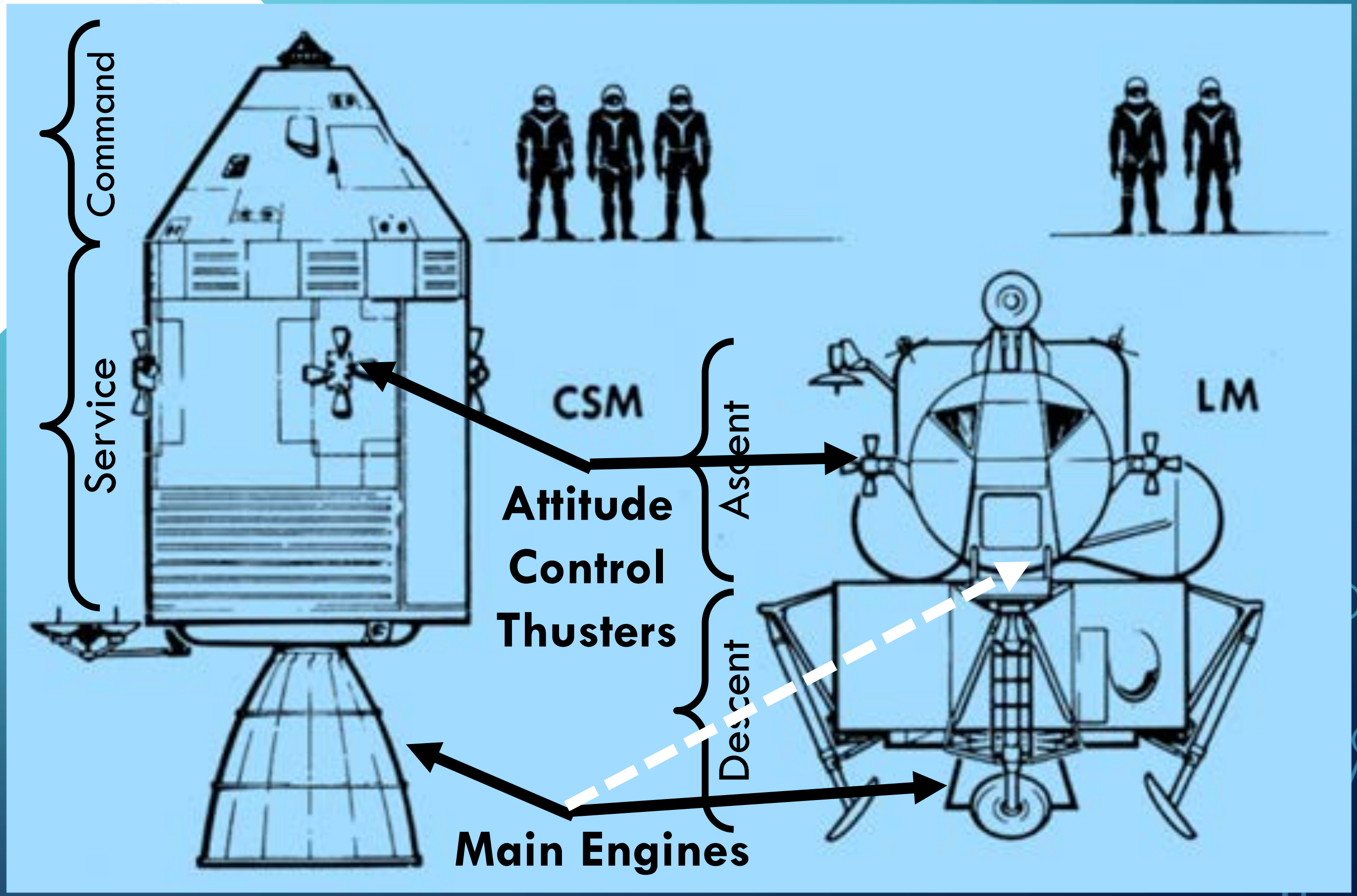
- 1 cubic foot volume
- 70 lbs weight
- 55 Watts power
- MTBF $\gtrsim$ Months
- Reboot $\approx$ 7 seconds
- UI = Verb/Noun ELD (DSKY)
- Priority Based Multi-Tasking
- ~259 Flops/Watt

APOLLO SPACECRAFT

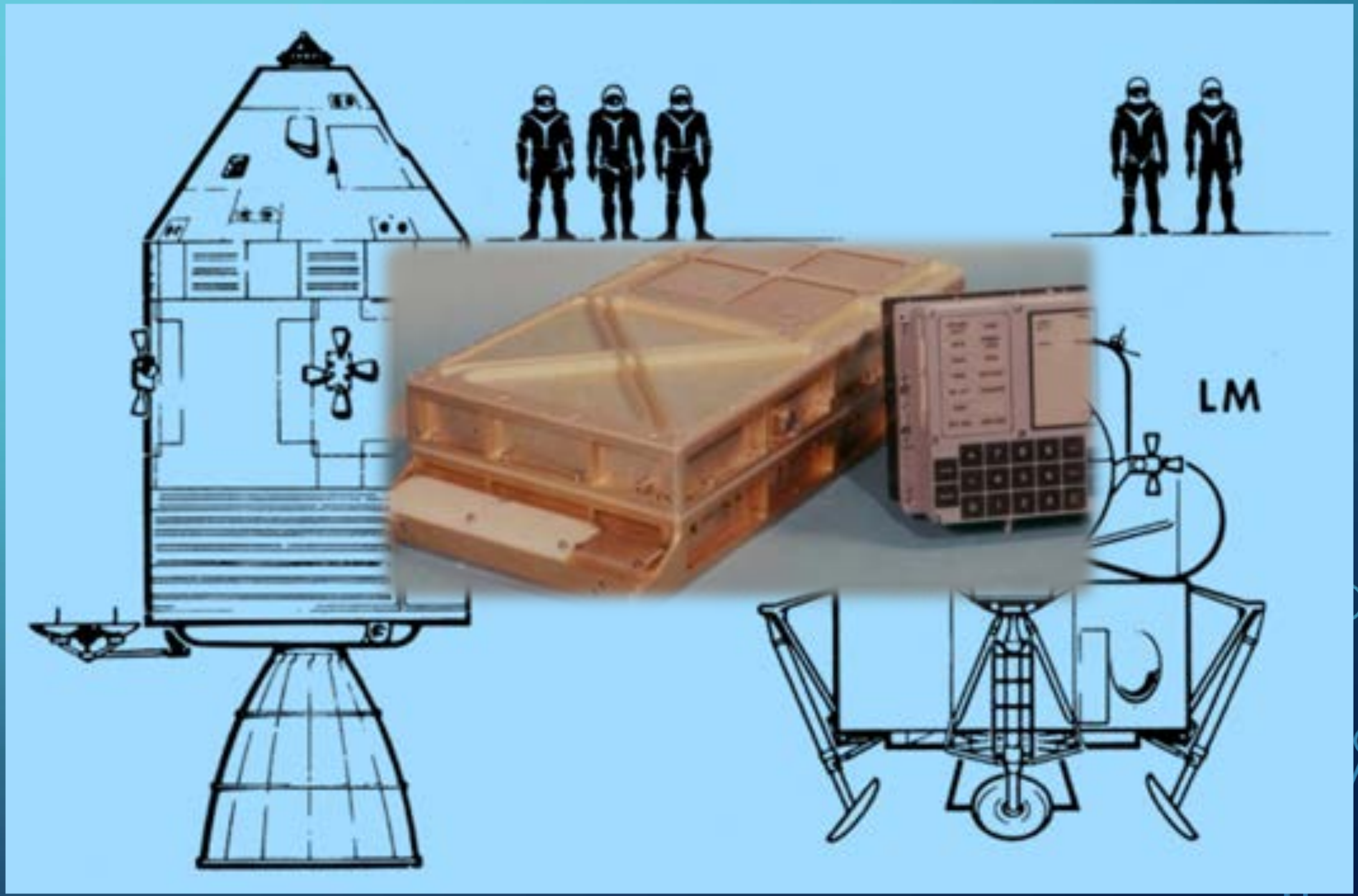


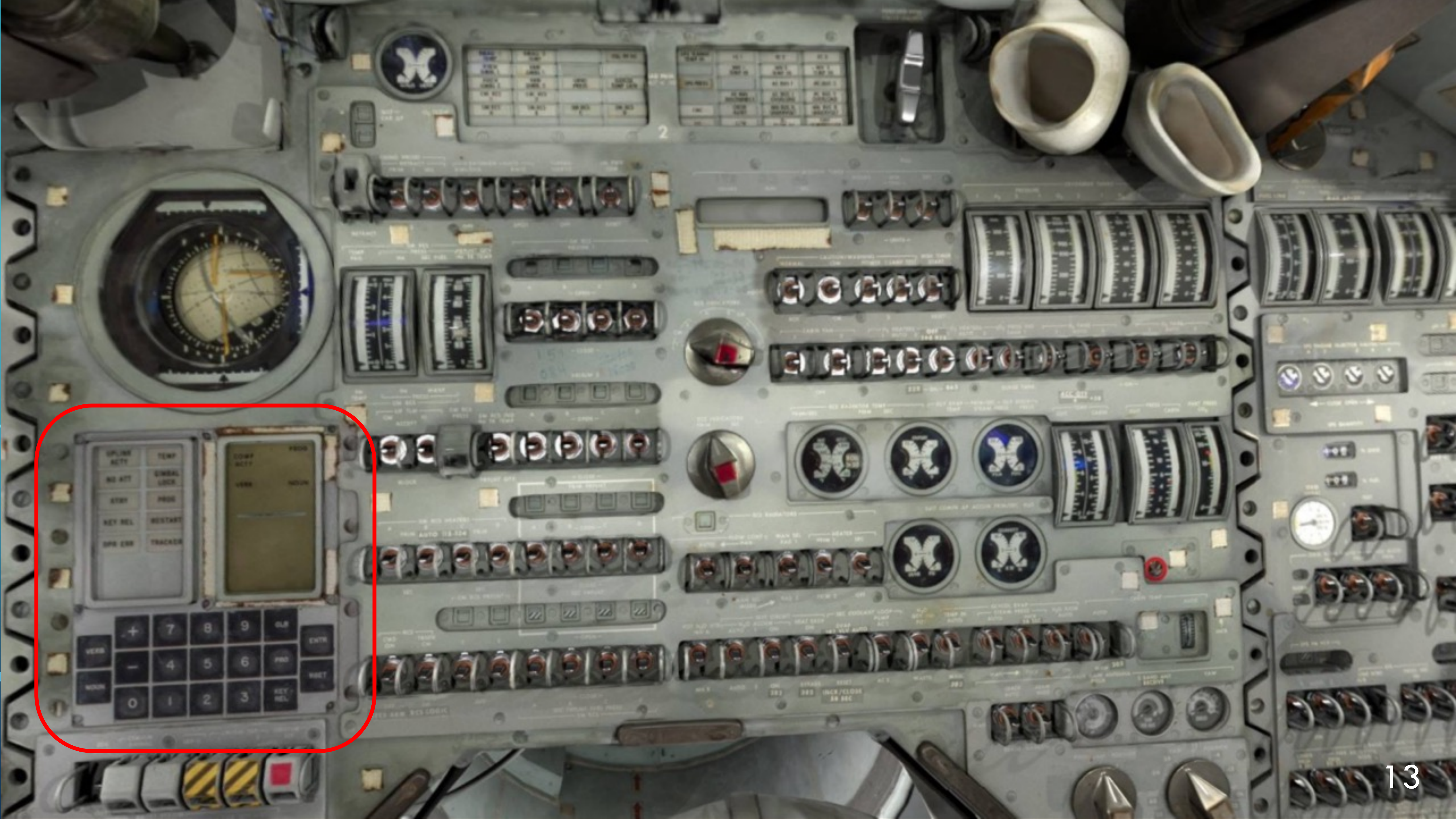
APOLLO SPACECRAFT

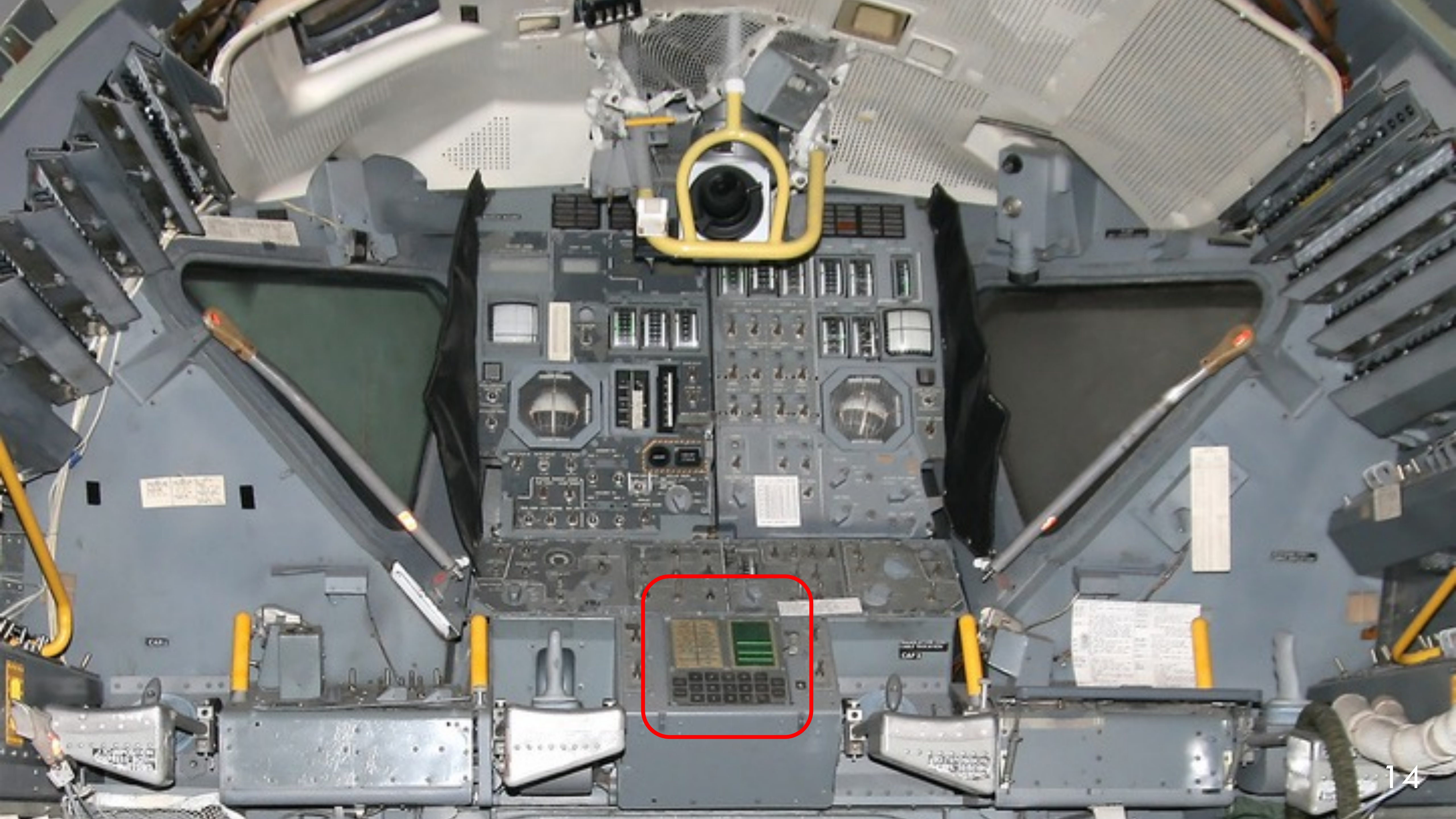




APOLLO SPACECRAFT







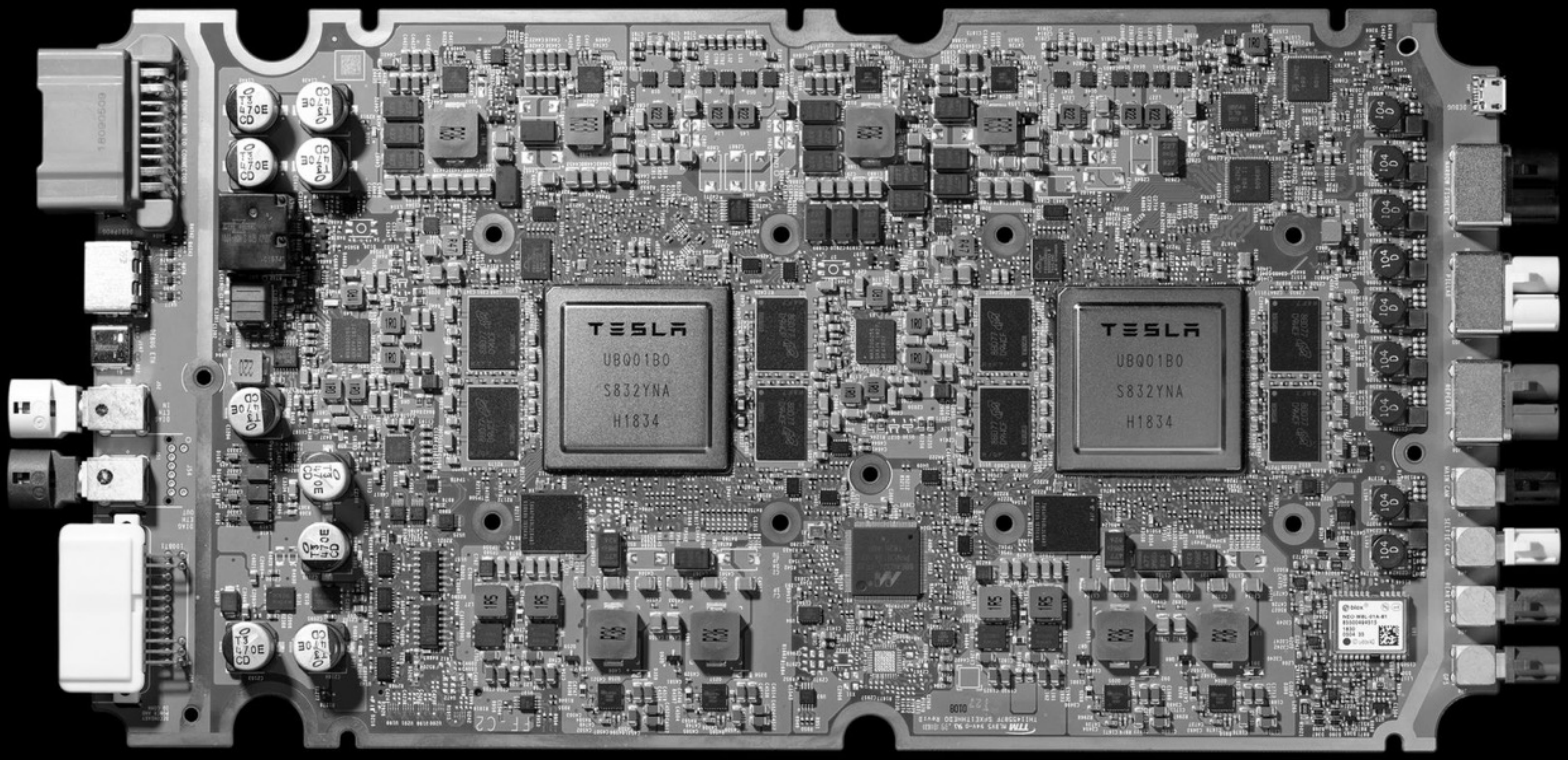
ROLE OF THE COMPUTER

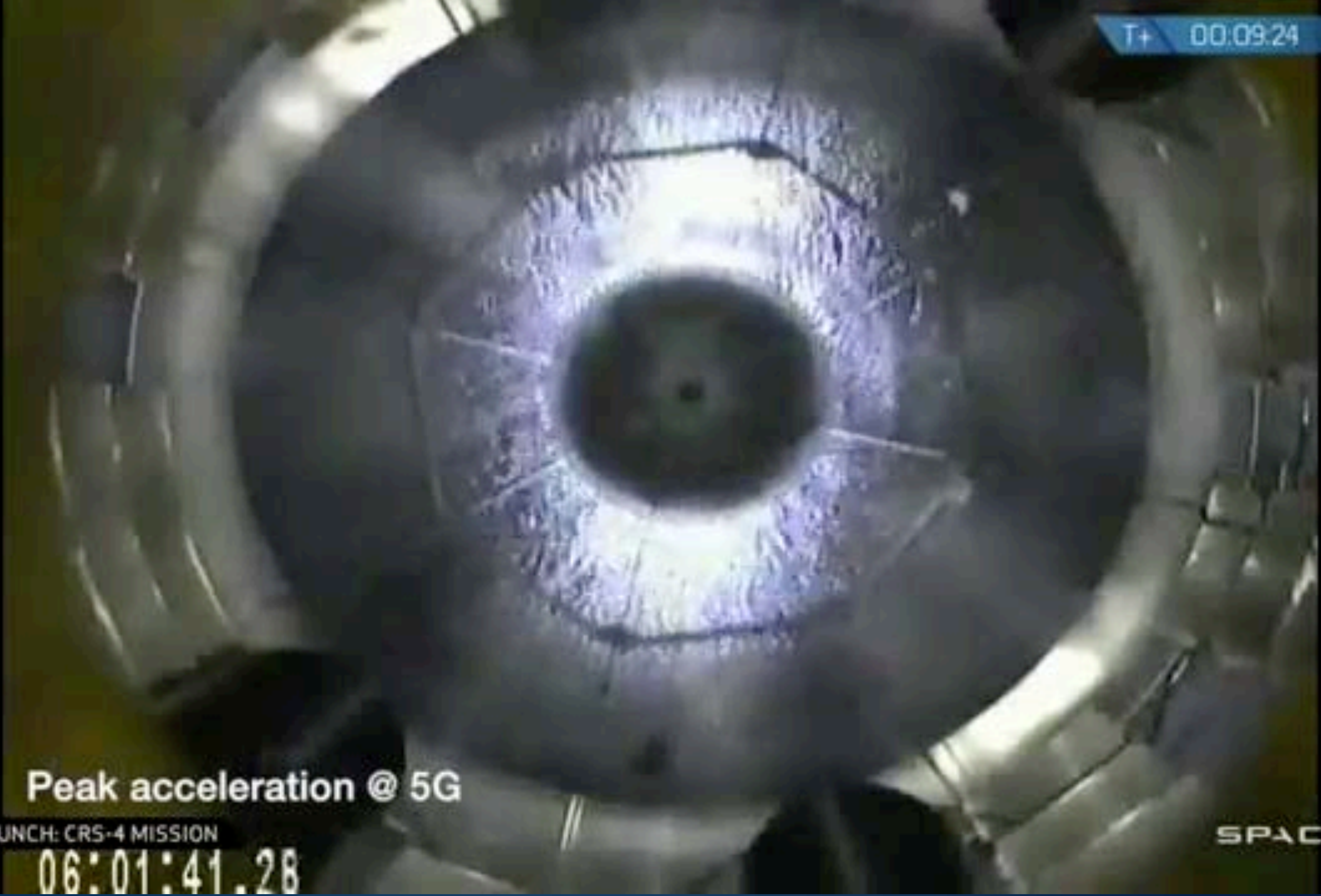
ROLE OF THE COMPUTER

- 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


TESLA
UBQ01B0
S832YNA
H1834
TESLA
UBQ01B0
S832YNA
H1834

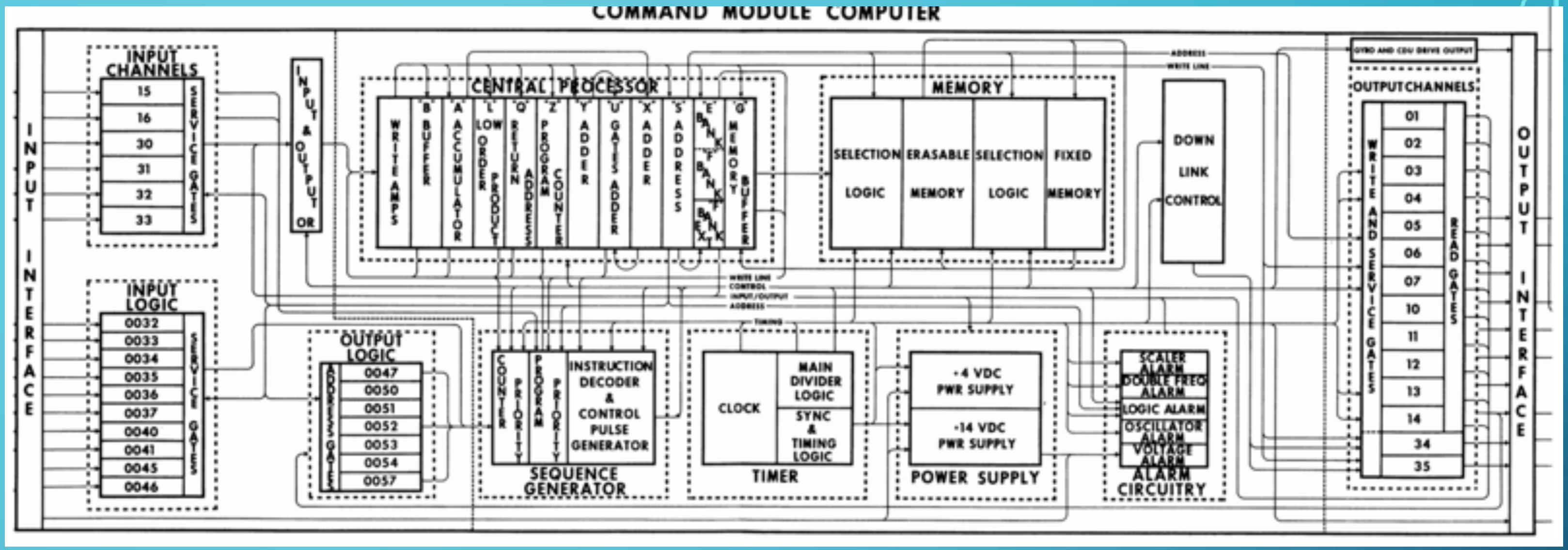


T+ 00:09:24
Peak acceleration @ 5G
LAUNCH: CRS-4 MISSION
06:01:41.28
SPACEX

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

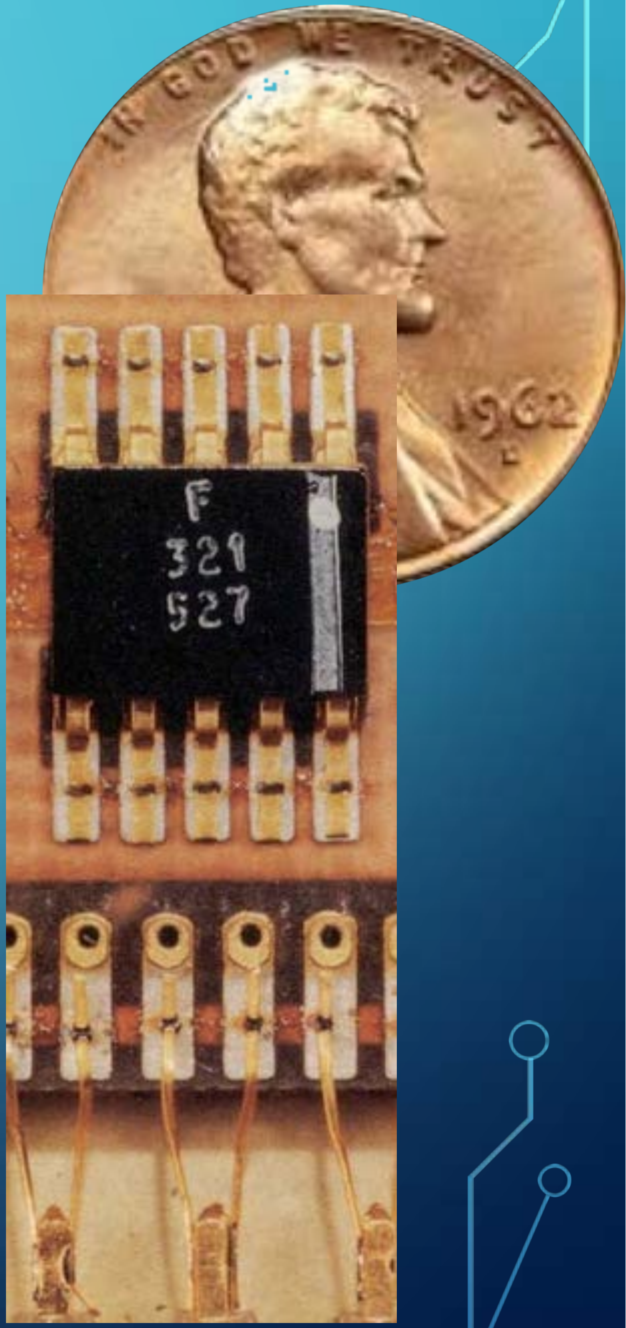
AGC HARDWARE OVERVIEW

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



Please Send Invoices In
TRIPLICATE
to Massachusetts Institute of Technology Box 69
Cambridge 39, Massachusetts

PURCHASE ORDER

Massachusetts Institute of Technology

Cambridge 39, Massachusetts

PAGE 1 of 2

PURCHASE ORDER NUMBER
IL120534
This Number Must Appear on Invoices, B/L, Shipping Memos and All Packages

ACCOUNT NUMBER
55-191-37-23

REQUISITION NUMBER

DATE May 28, 1962

TO
Fairchild Semi-Conductor Corp.
36 North Road
Bedford, Massachusetts
ATTN: Mr. Bruce Giron

SHIP TO
66 Albany Street
E.J. Duggan W5-151

PLEASE FURNISH THE FOLLOWING MATERIALS OR SERVICES:

DATE REQUIRED	SHIP VIA	F O B	TERMS
SEE BELOW	AMSD	SP	Net/30

ITEM	QUANTITY	DESCRIPTION	PRICE
1	1000	pieces "B" Grade Gate Element in TO47 package, Fairchild P/N SL 1015 per MIT print C-88794 change B, @ $31.10 each	31100.00

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. E. Duggan of MIT, and R. Graham, M. Siegel, and B. Giron of Fairchild on May 15, 1962

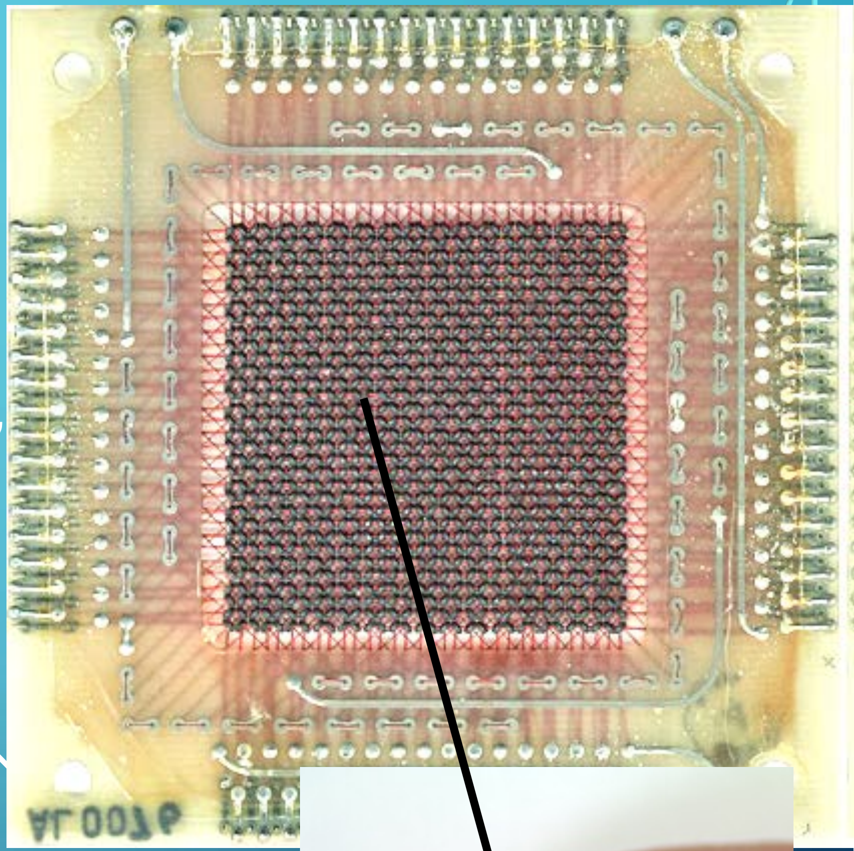
AGC HARDWARE OVERVIEW

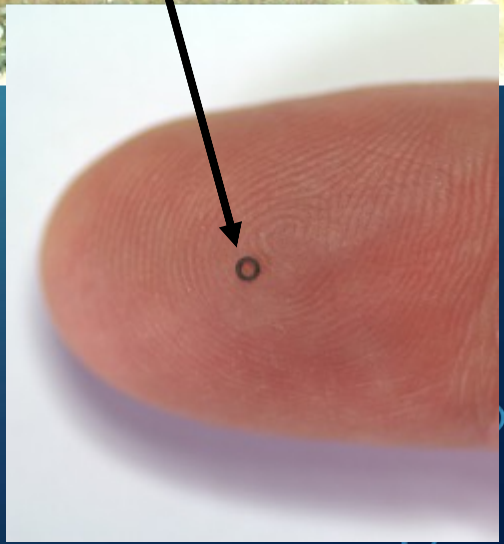
SPECS

- 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)

TECHNOLOG

- 2,800 ICs
- dual 3-input N
- Coincident-Current Core





AGC HARDWARE OVERVIEW

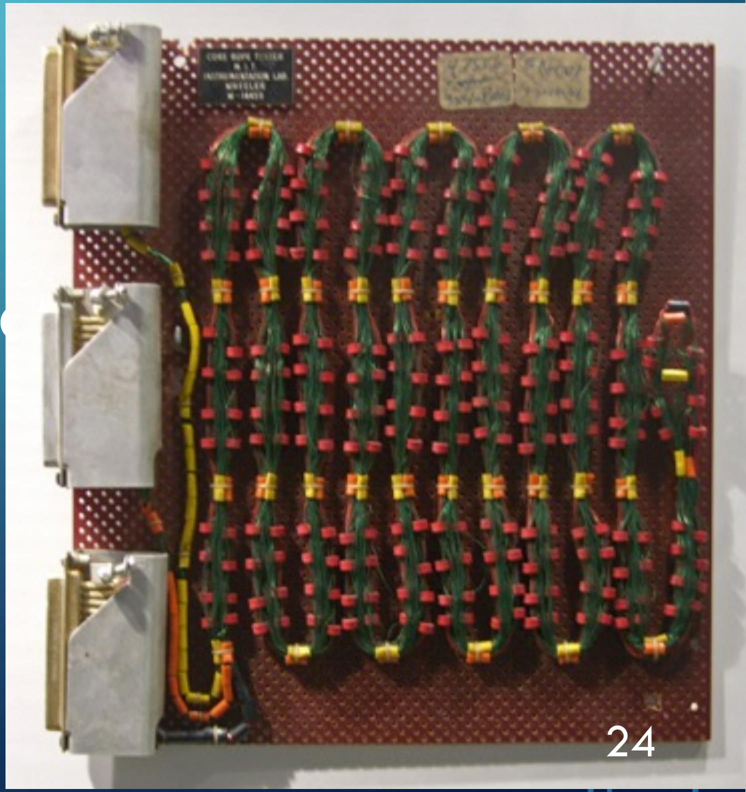
SPECS

- 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)

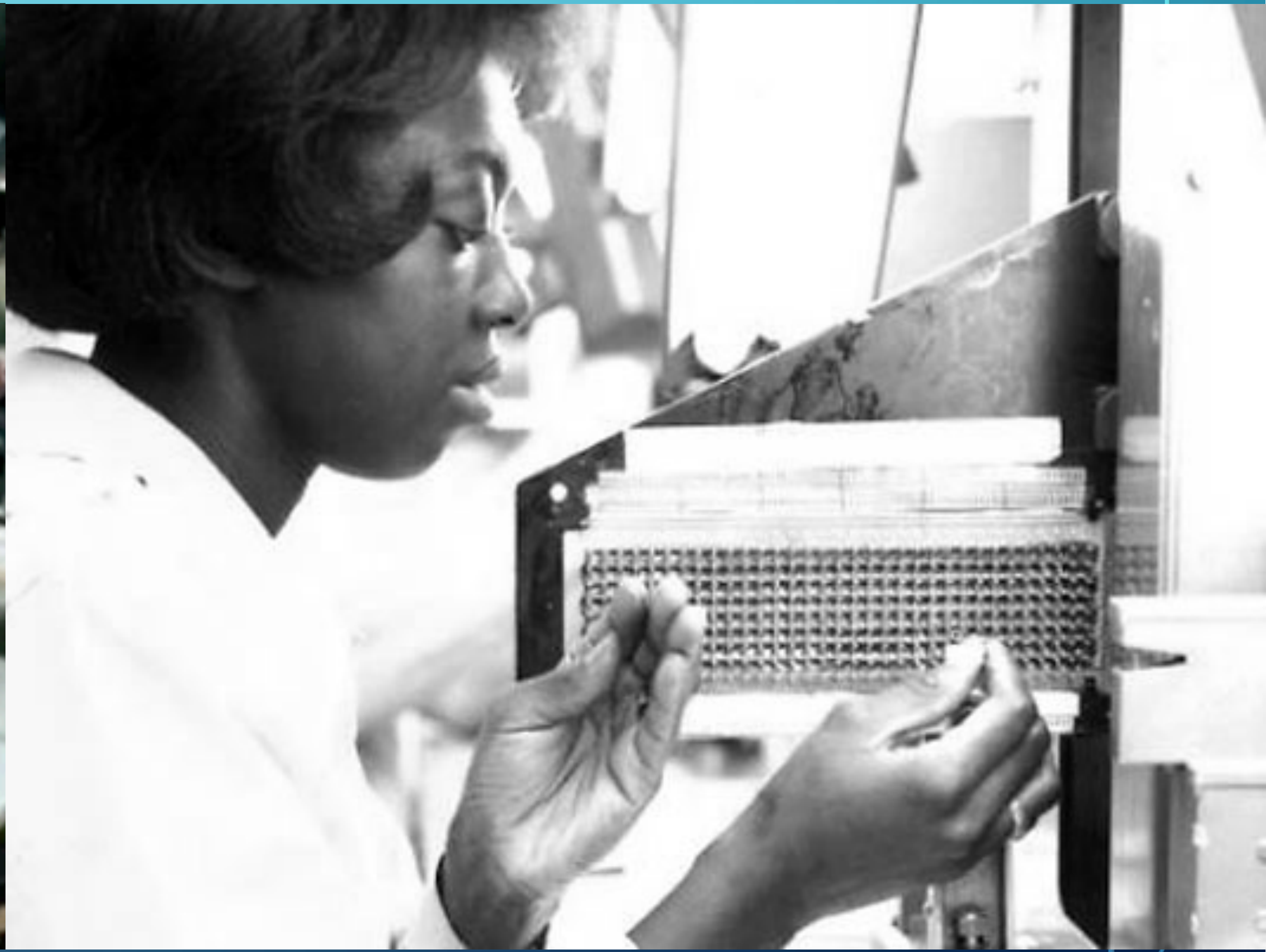
- **Both RAM and ROM were NVM**

TECHNO

- 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 (00067_8)
  - Not directly programmable
- 8 basic + 33 extended instructions

EXAMPLE CODE SNIPIT

line	label	opcode	address	comments
0184	P63SPOT3	CA	BIT6	IS THE LR ANTENNA IN POSITION 1 YET
0185		EXTEND		
0186		RAND	CHAN33	
0187		EXTEND		
0188		BZF	P63SPOT4	BRANCH IF ANTENNA ALREADY IN POSITION 1
0189		CAF	CODE500	ASTRONAUT: PLEASE CRANK THE
0190		TC	BANKCALL	SILLY THING AROUND
0191		CADR	GOPERF1	
0192		TCF	GOTOP00H	TERMINATE
0193		TCF	P63SPOT3	PROCEED SEE IF HE'S LYING
0194	P63SPOT4	TC	BANKCALL	ENTER INITIALIZE LANDING RADAR
0195		CADR	SETPOS1	
0196		TC	POSTJUMP	OFF TO SEE THE WIZARD...
0197		CADR	BURNBABY	

THE INTERPRETER: A SPACE GUIDANCE DSL (A P-CODE MACHINE LIKE JVM)

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 $\underline{z} = aM(\underline{x} + \underline{y})$
where a is a scalar and M a 3 x 3 matrix

Program (requires 7 words of storage)

MXV VXSC	Operation Codes	1) The first address of an equation is used to load an accumulator; VAD requests a vector load.
X Y M A	Operand Adresses	2) Each op code results in a subroutine call with the corresponding address left in a standard location.
STORE Z	Left-over address used to store result	3) After all op codes have been "executed," 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.

Explanation

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 $0 \ldots 2^{14}-1$
- Full range of $-16{,}383_{10}$ to $+16{,}383_{10}$

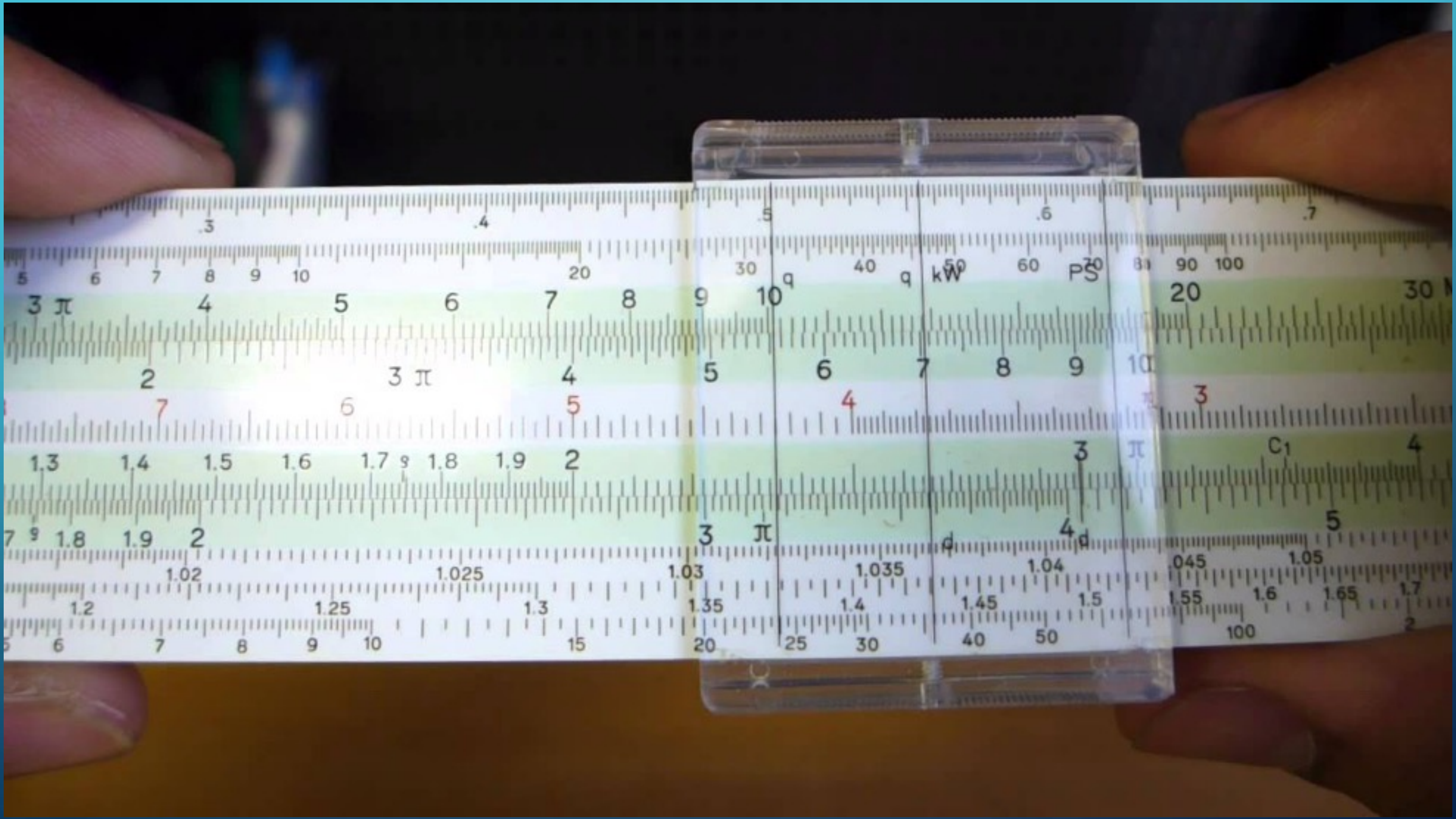
P | S | 2^{13} | 2^{12} | 2^{11} | … | 2^{1} | 2^{0} |

FRACTIONAL NUMBERS

P | S | 2^{-1} | 2^{-2} | 2^{-3} | … | 2^{-13} | 2^{-14} |

- Fixed Point Representation
- Coders must ensure proper scaling!!
- Just like an Engineer's Slide Rule

NUMERICS OF THE AGC



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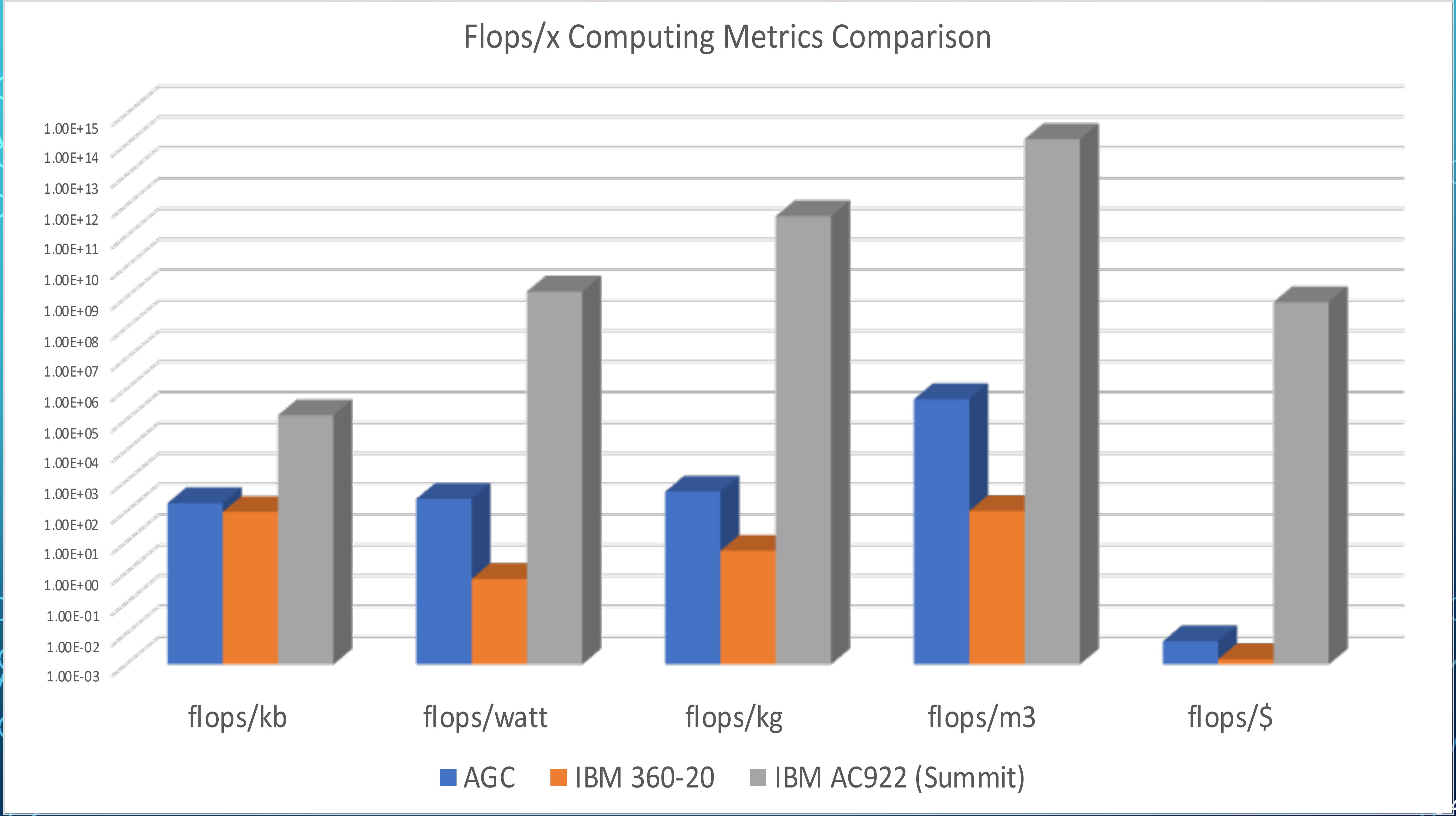
FRACTIONAL NUMBERS

P | S | 2^{-1} | 2^{-2} | 2^{-3} | … | 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 *μ*sec**



Flops/x Computing Metrics Comparison
1.00E+15
1.00E+14
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
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"

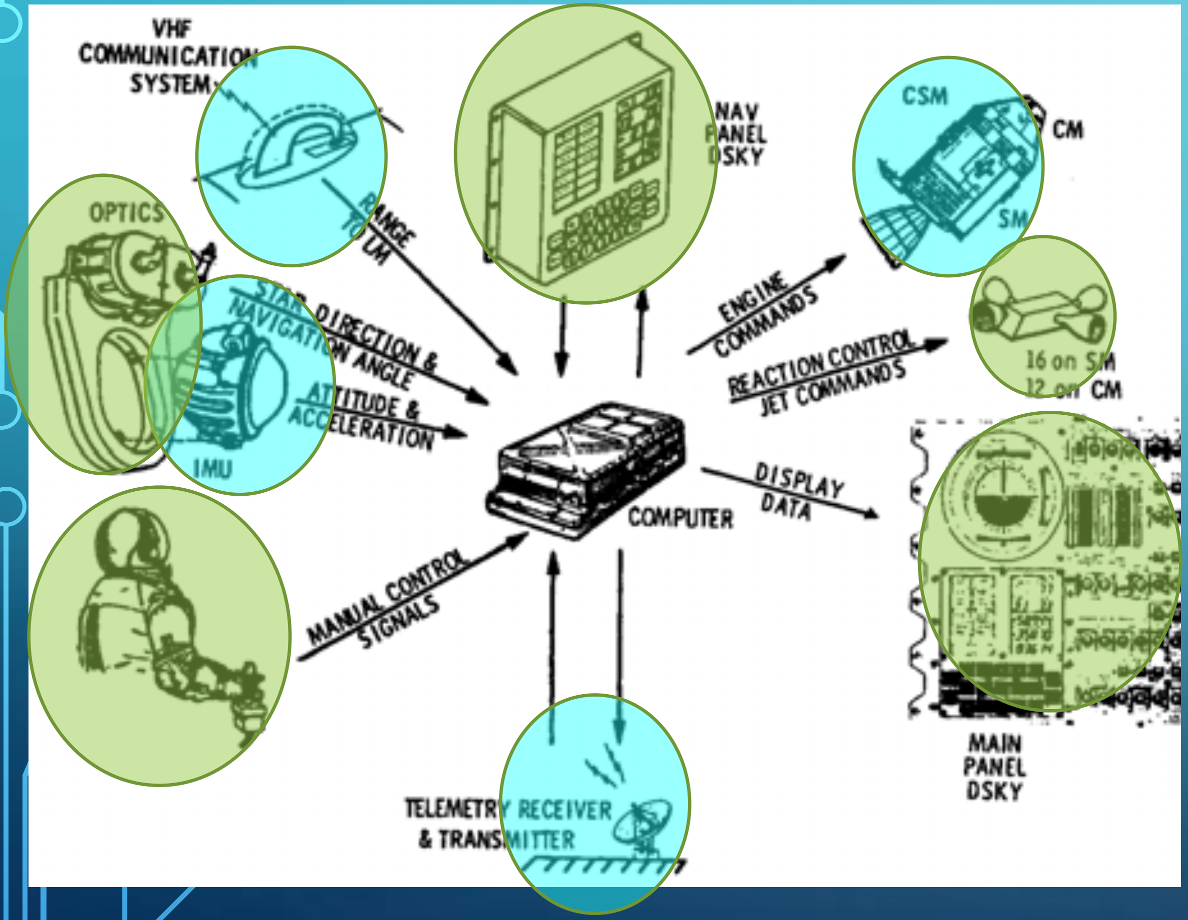
- Priority Scheduled
- 12 words of state (4 regs + other)
- Jobs adjust own priority up/down

WAYPOINT AND RESTART

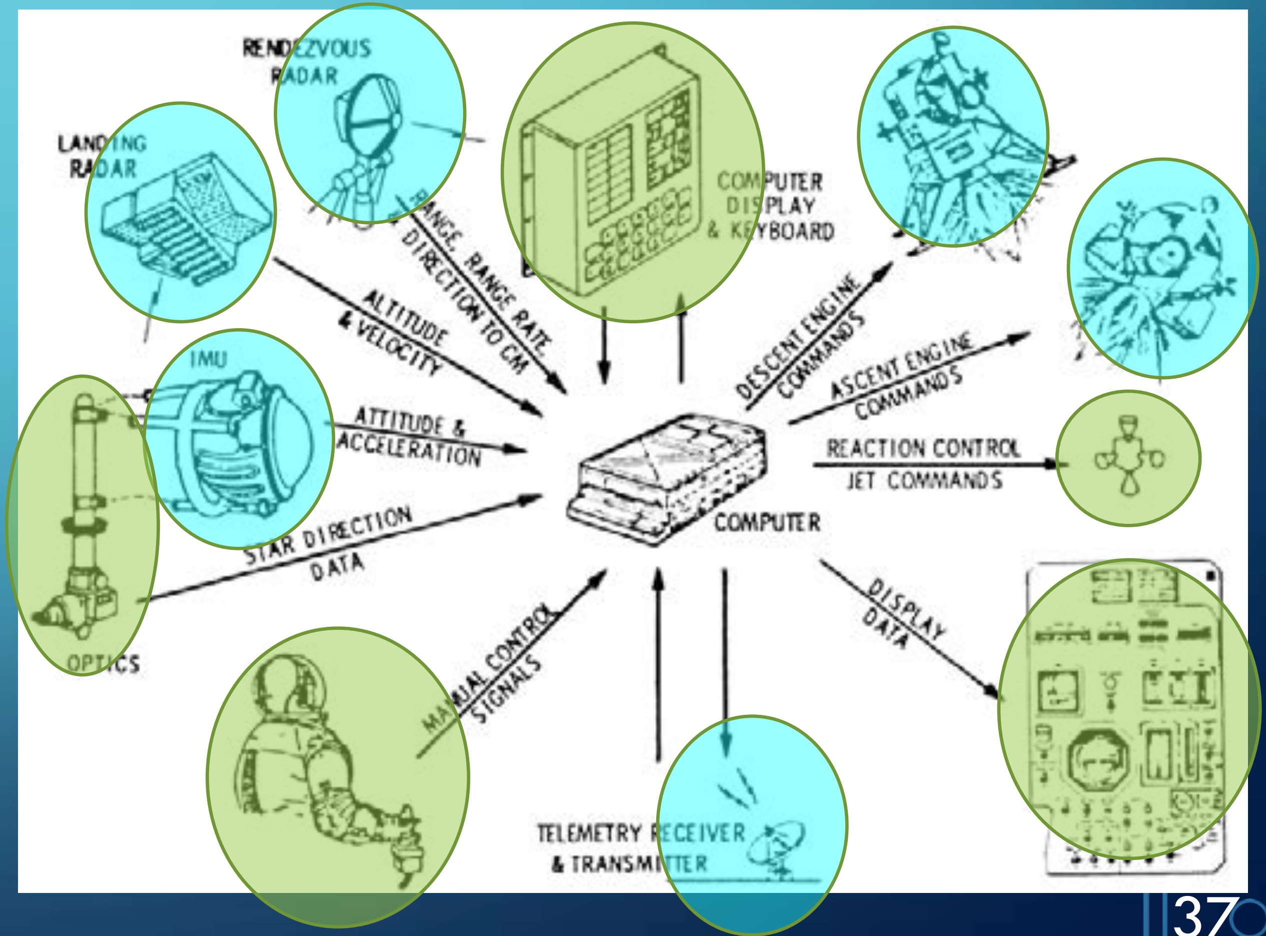
- Critical routines were restart protected
- Waypoints periodically updated in erasable memory
- Consumed 4% of fixed memory, additional coding and testing complexity

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 → 40,000 hours (due to quality ICs)
- Modern systems using triple redundant hardware & voting

OUTLINE

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- Guidance Software
- Brief Detour
- Mission Applications

WESTERN UNION
TELEGRAM

W. P. MARSHALL, PRESIDENT

CLASS OF SERVICE
This is a fast message unless its deferred character is indicated by the proper symbol.

SYMBOLS
DL = Day Letter
NL = Night Letter
LT = International Letter Telegram

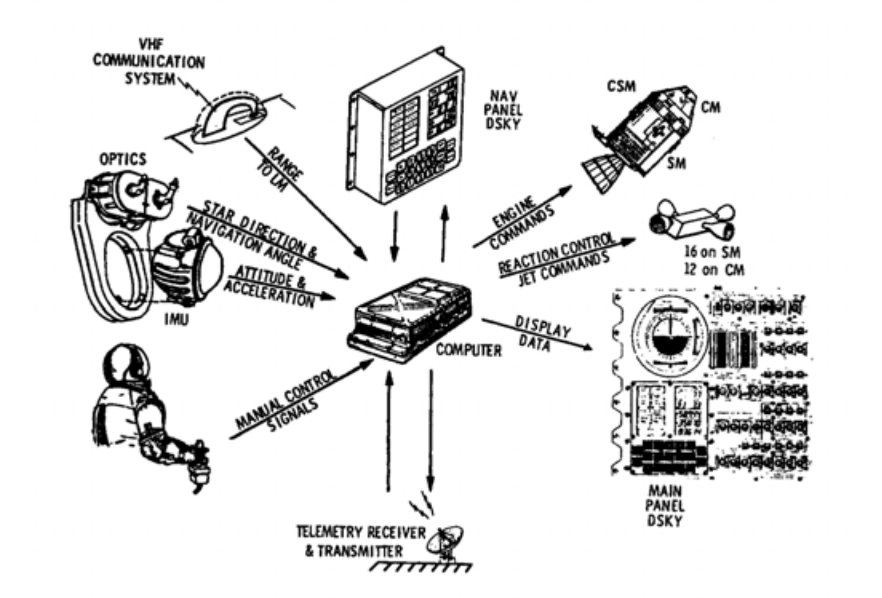
The filing time shown in the date line on domestic telegrams is LOCAL TIME at point of origin. Time of receipt is LOCAL TIME at point of destination

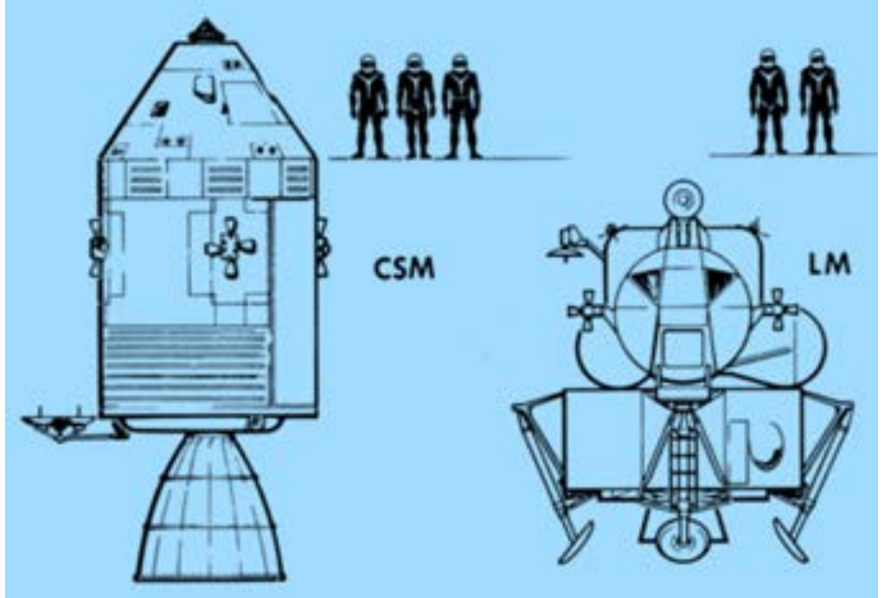
435P EDT AUG 9 61 BB257 PB375
W NFA084 GOVT PD NF WASHINGTON DC 9 405P EDT
DR STARK DRAPER, DIR
INSTRUMENTAL LABORATORY MASSACHUSETTS INST OF TECHNOLOGY
CAMBRIDGE MASS

PLEASED TO ADVISE THAT THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATI
ON TODAY ANNOUNCED THAT MIT'S INSTRUMENTATION LABORATORY HAS
BEEN SELECTED TO DEVELOP THE GIDANCE 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

LEVERETT SALTONSTALL UNITED STATES SENATOR.

EXTREME CO-DESIGN





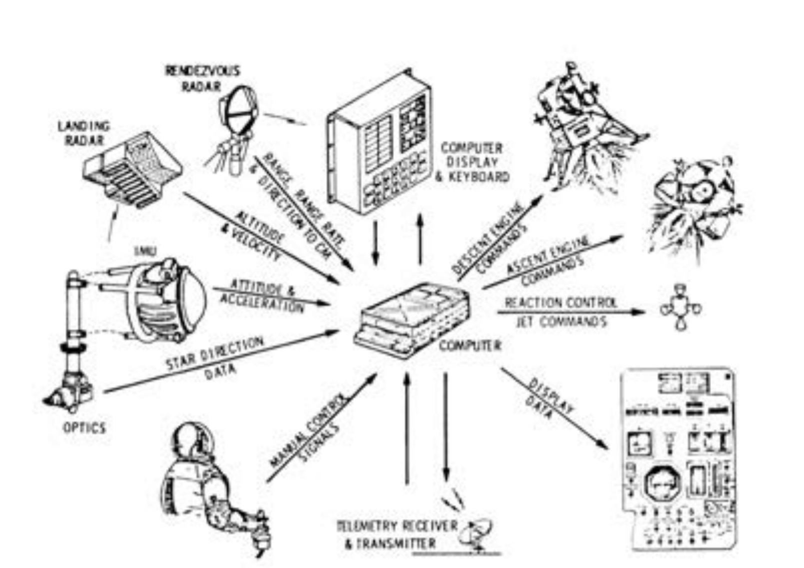
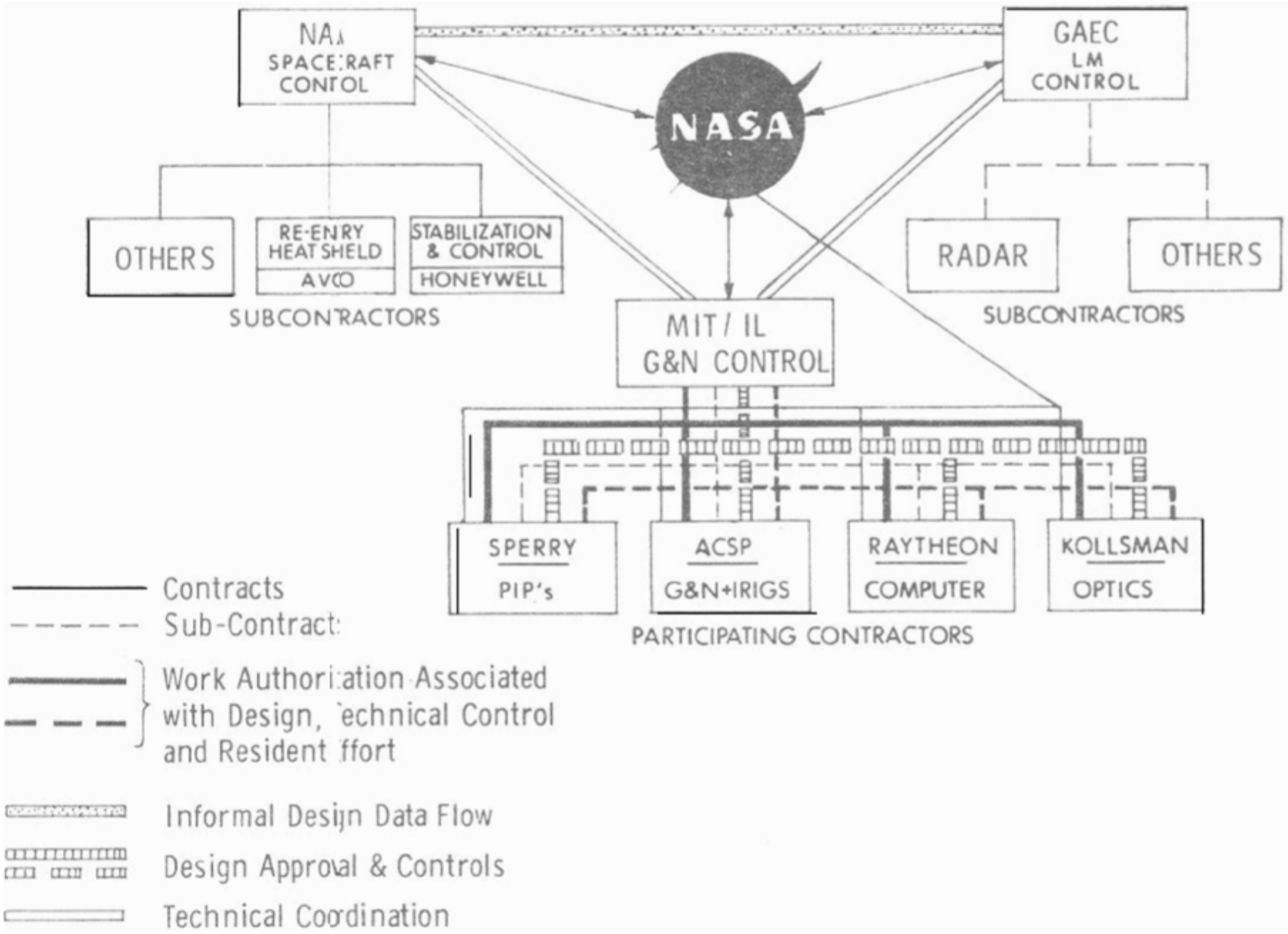


Fig. 1 The Lunar Module Computer Interfaces

- 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



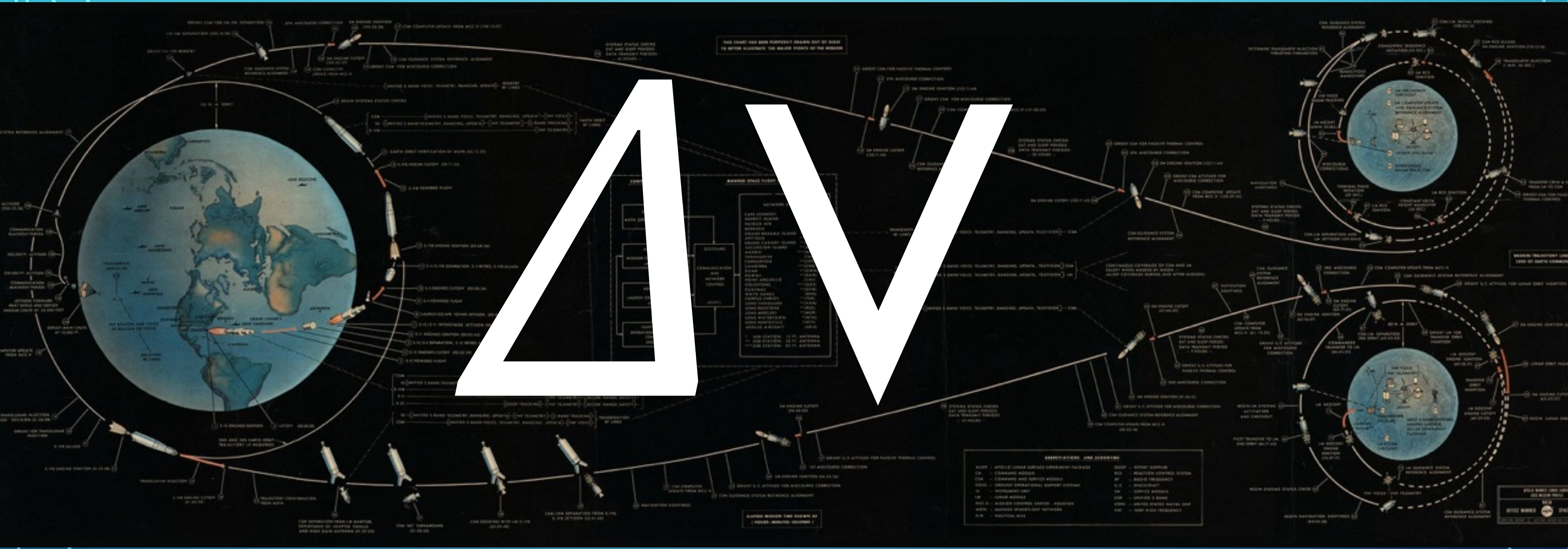
NA
SPACE:RAFT
CONTOL
GAEC
LM
CONTROL
NASA
OTHERS
RE-ENRY HEAT SHELD
AVCO
STABILIZATION & CONTROL
HONEYWELL
SUBCONTRACTORS
RADAR
OTHERS
SUBCONTRACTORS
MIT / IL
G&N CONTROL
SPERRY
PIP's
ACSP
G&N+IRIGS
RAYTHEON
COMPUTER
KOLLSMAN
OPTICS
PARTICIPATING CONTRACTORS
Contracts
Sub-Contract:
Work Authori:ation Associated with Design, echnical Control and Resident ffort
Informal Desijn 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.

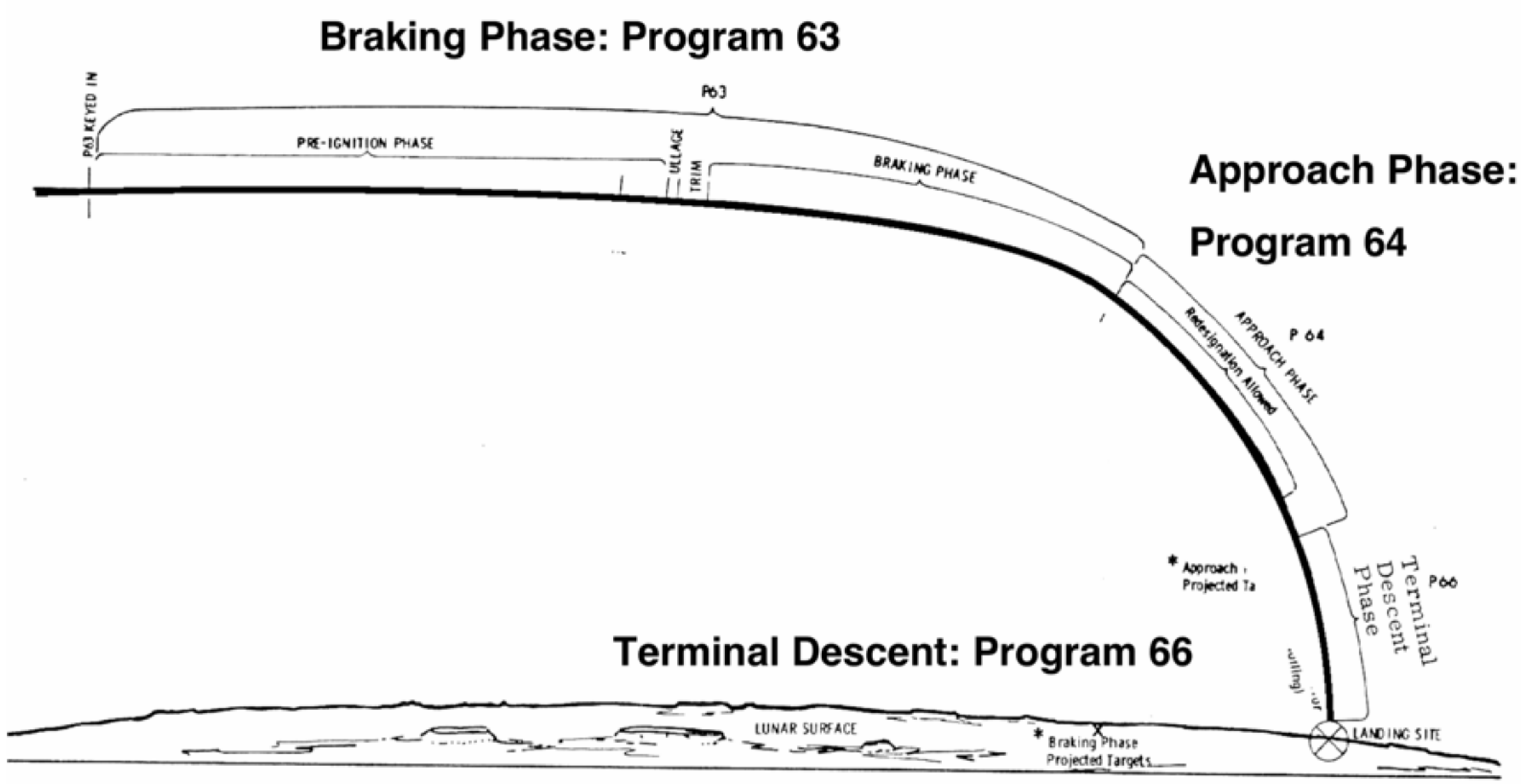
- For ~30 planned flights (uncrewed and crewed), some with unique guidance requirements

THE AGC HAD AN "APP" FOR THAT



- 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



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

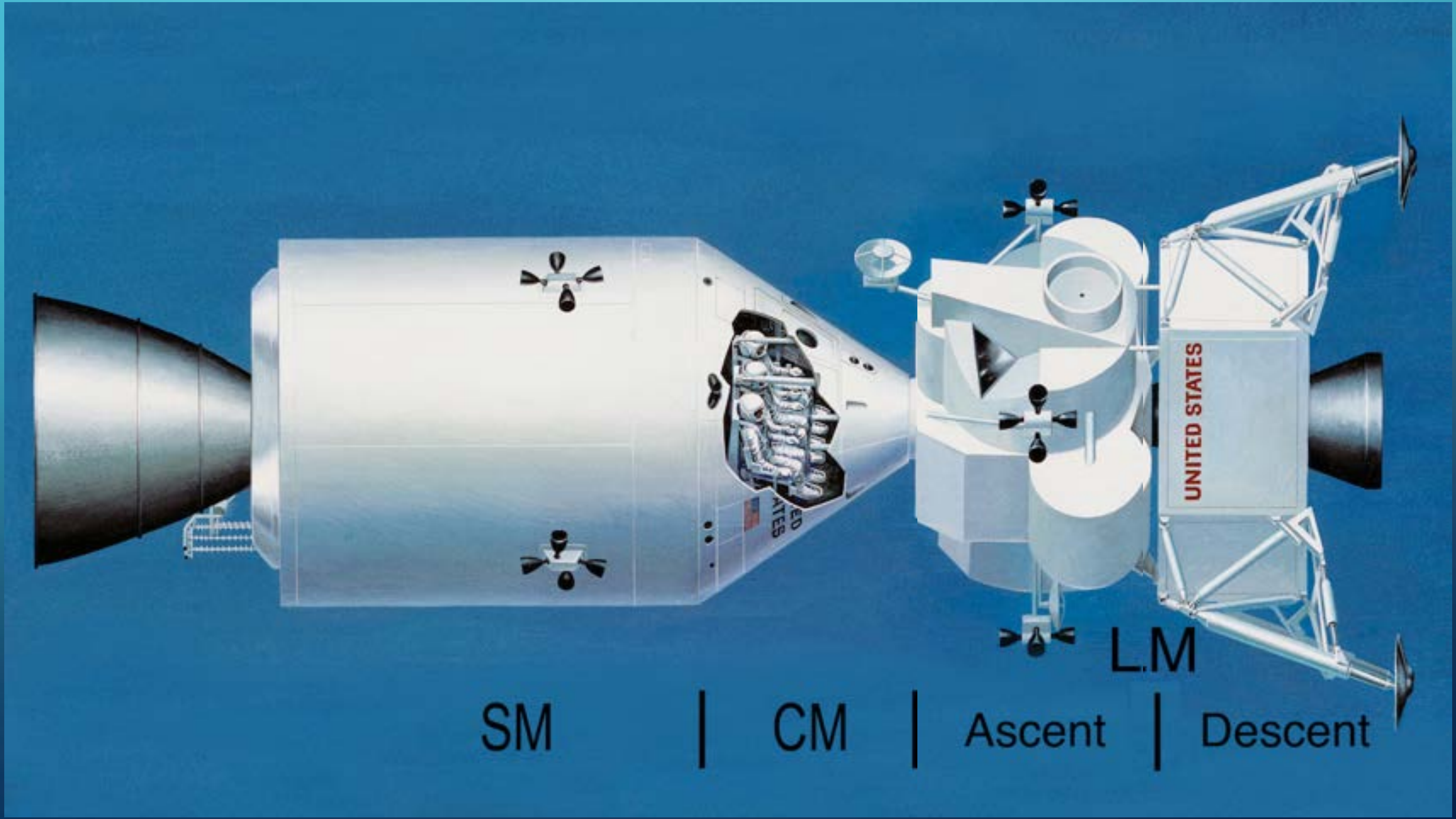
- Polynomial fit to X, Y, Z positional data
  - 8 double precision coefficients for each of X, Y and Z → **48 words**
  - AGC Interpreter subroutine → **86 words**
  - Initially in MAC language Honeywell 1800 mainframe

INFRASTRUCTURE SOFTWARE

Program Name	Purpose	Size (AGC words)
Executive[25]	Priority-driven large/long-running process manager	~350
Waitlist[26]	Time-sequenced small/short-running process manager	~300
Down-Telemetry[29]	Transmit system data to ground	~200
Restart[30,31,32]	Error recovery and restart protection	~1225
Interpreter[27]	Space guidance domain-specific programming language interpreter	~2200
DSKY I/O[28]	Cockpit displays and keypad	~3500
Combined Total	22% of fixed memory	~7775

APOLLO'S DIGITAL AUTO PILOTS: A PERFORMANCE PORTABILITY CHALLENGE

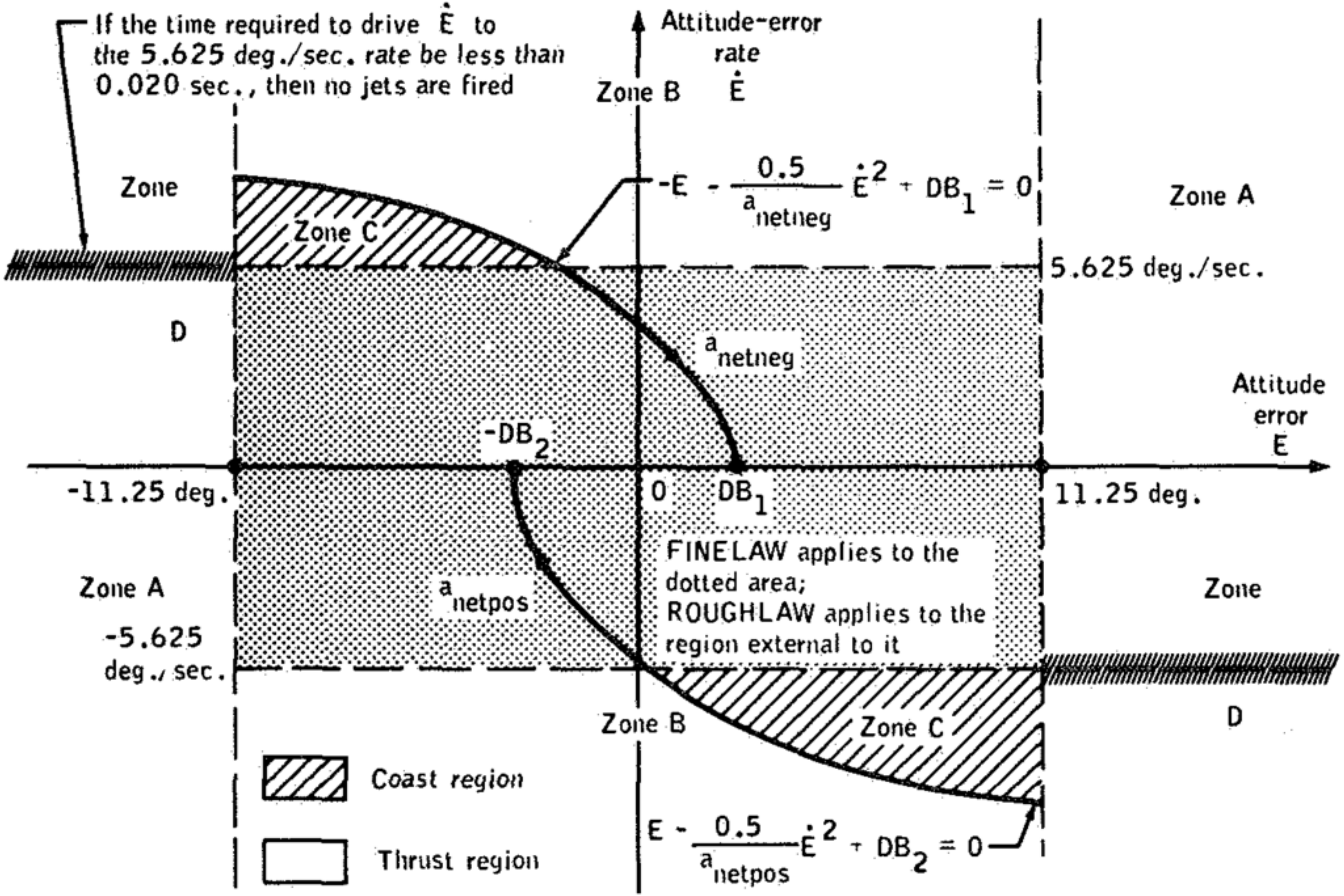
- Many different hardware configurations
- One implementation



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 Ė to the 5.625 deg./sec. rate be less than 0.020 sec., then no jets are fired
Attitude-error rate Ė
Zone B
Zone
Zone C
Zone A
-E - 0.5/a netneg Ė2 + DB1 = 0
5.625 deg./sec.
D
a netneg
Attitude error E
-DB2
-11.25 deg.
0
DB1
11.25 deg.
FINELAW applies to the dotted area;
ROUGHLAW applies to the region external to it
Zone A
a netpos
Zone
-5.625 deg./sec.
Zone B
Zone C
D
Coast region
Thrust region
E - 0.5/a netpos Ė2 + DB2 = 0

KALMAN
DIGITAL

BLOCK II — AUTOPILOT CONFIGURATION DATA (Noun 46)

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

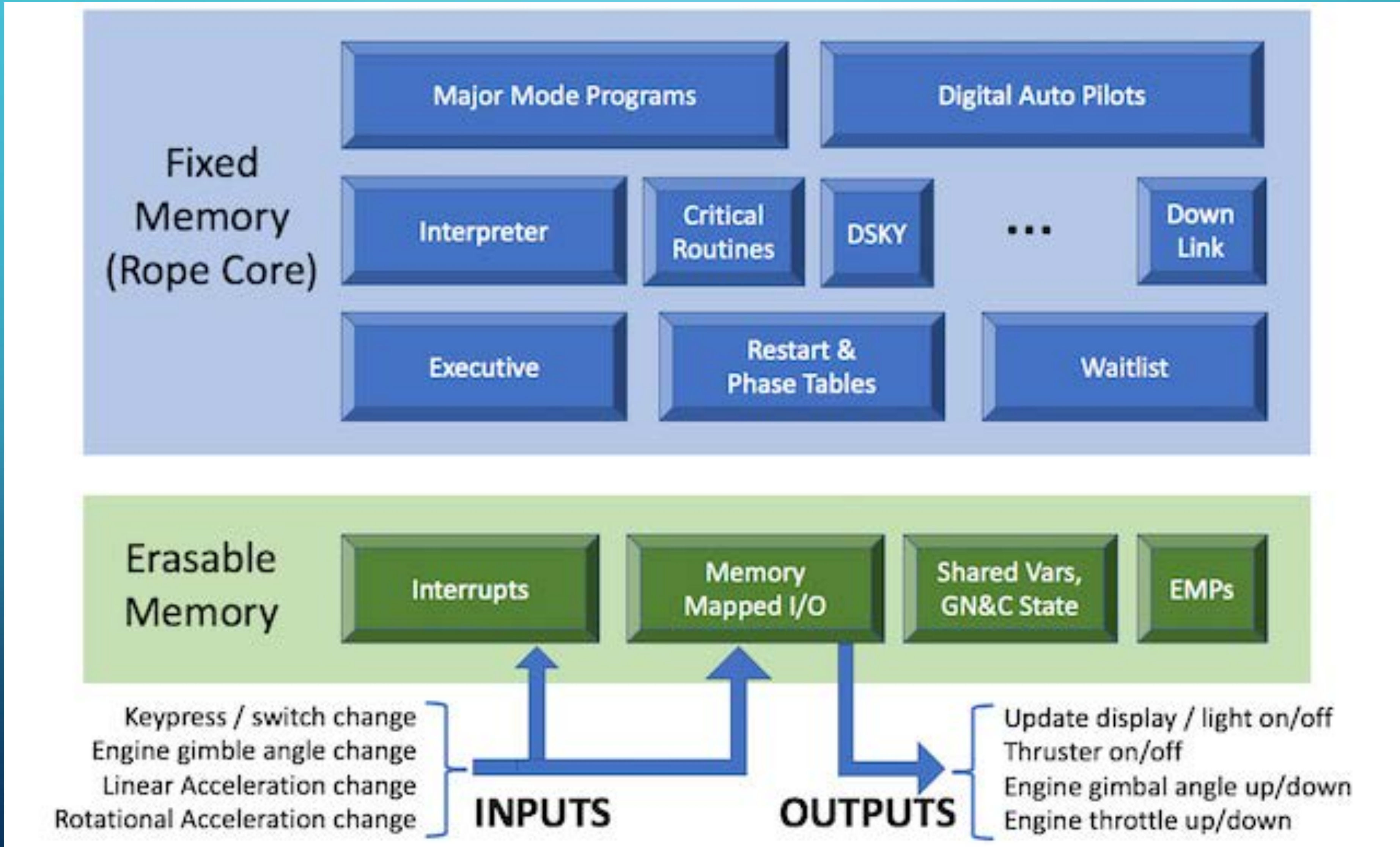
R1 = ABCDE (DAPDATR1)

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

R2 = ABCDE (DAPDATR2)

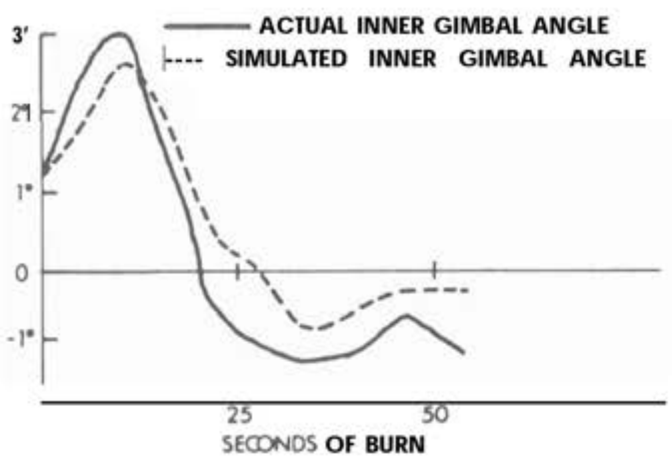
A	B	C	D	E
Roll Quad Select	Quad A Status	Quad B Status	Quad C Status	Quad D Status
0=Use B/D	0=Disable	0=Disable	0=Disable	0=Disable
1=Use A/C	1=Use	1=Use	1=Use	1=Use

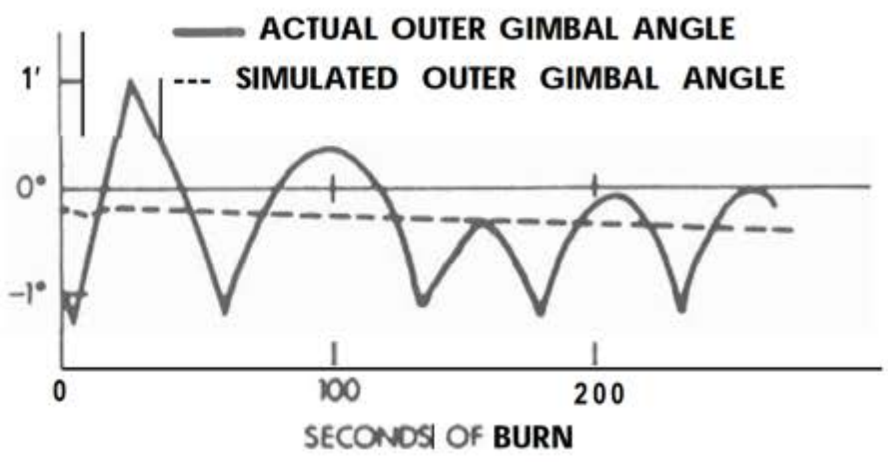
AGC SOFTWARE "STACK"

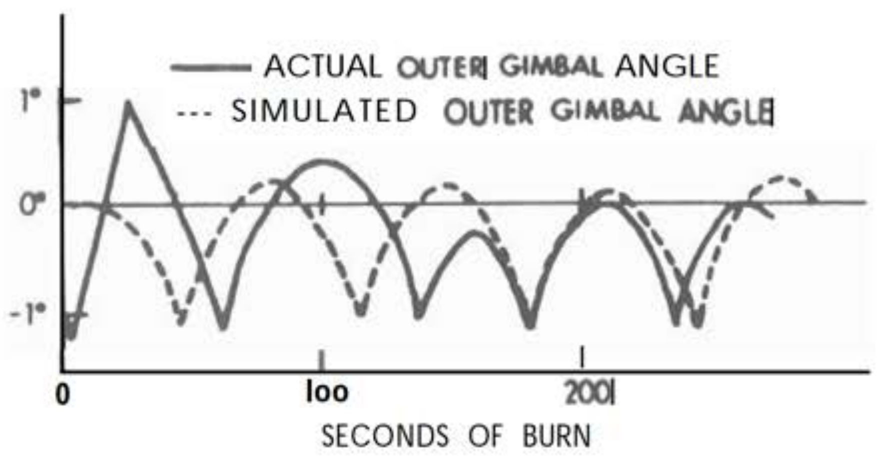


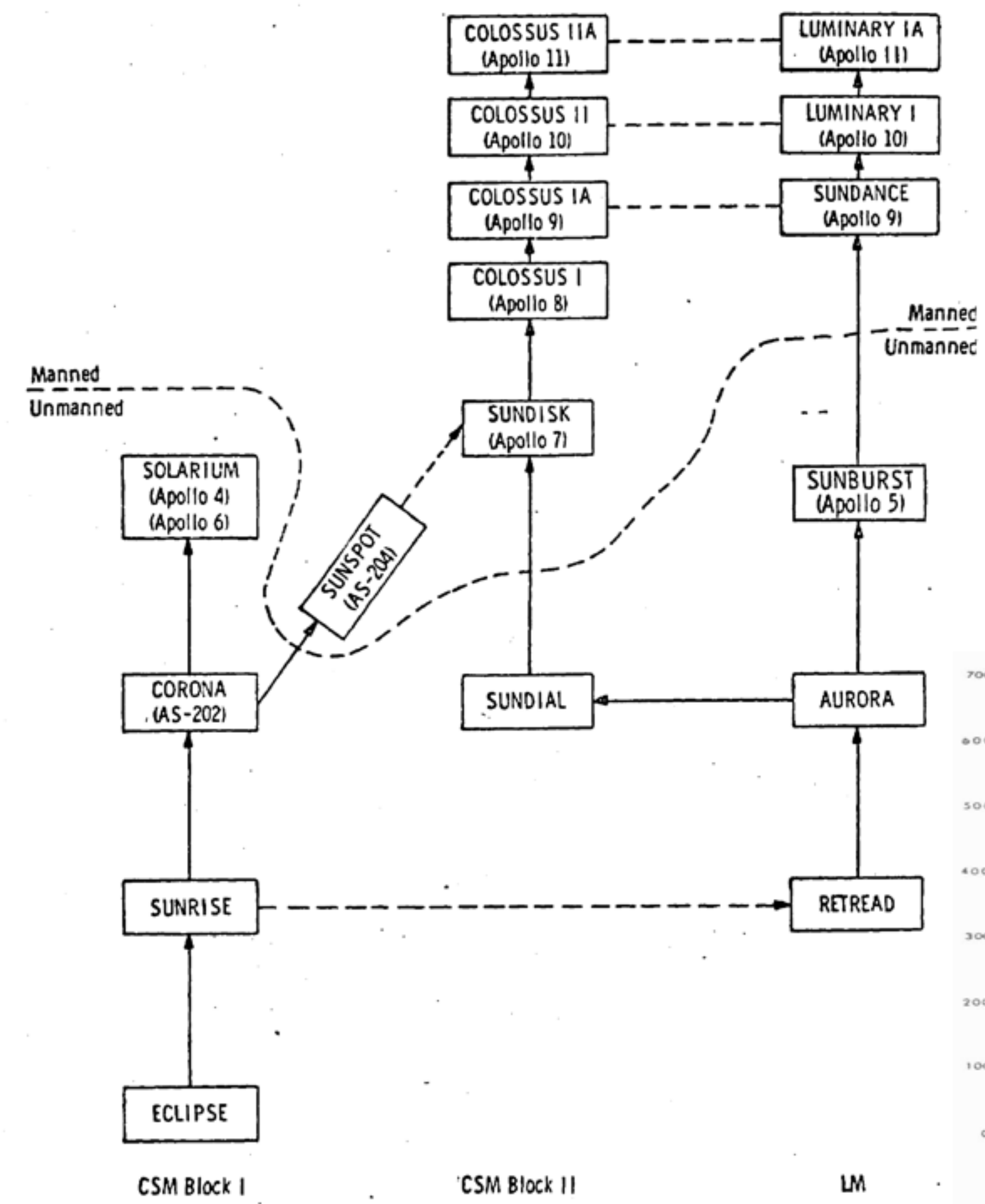
TESTING

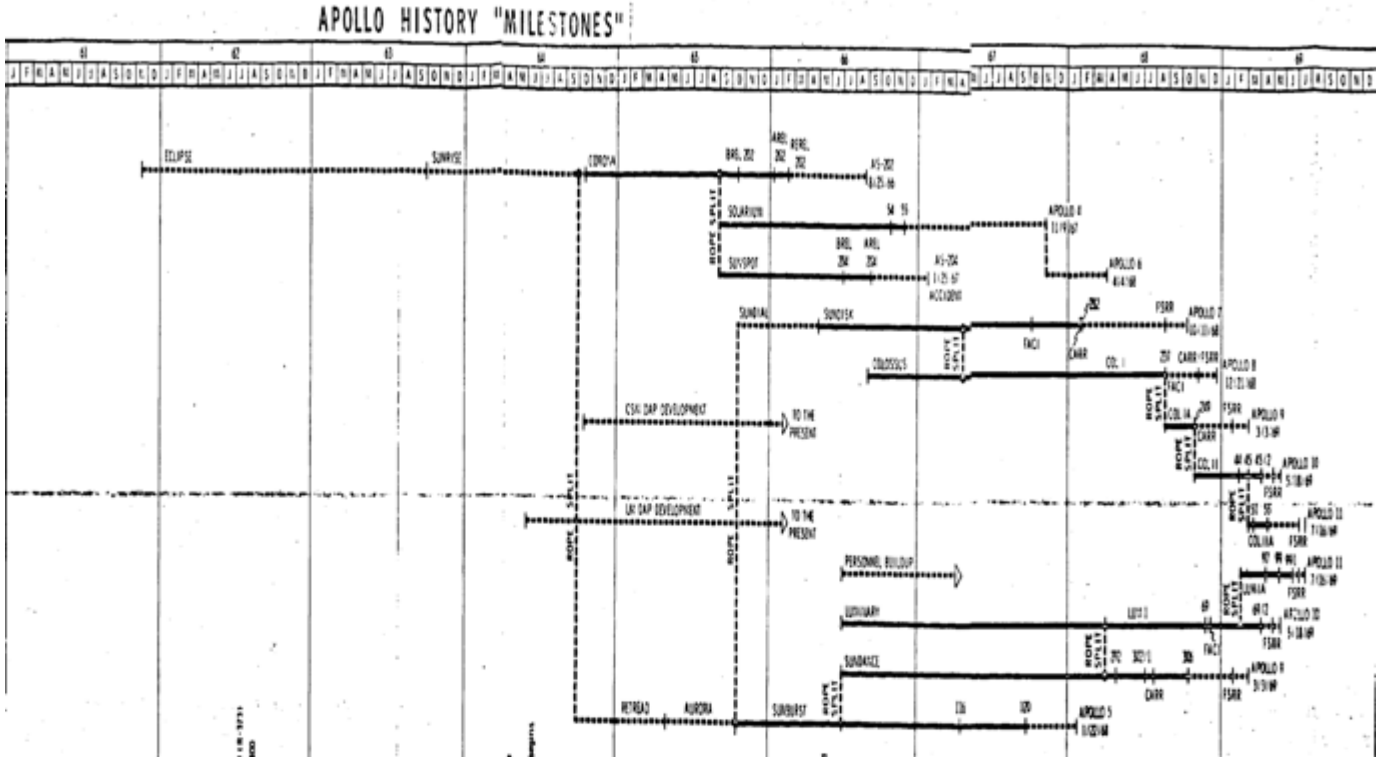
- All-digital simulator: (AGC + Devices + Spacecraft "Environment")
  - 1 HW-800, 2 HW-1800, 2 IBM 360-75 (4,500 equiv. HW-1800 hours/month)
- Several other levels of testing
  - Hybrid Simulator: Real AGC + Analog Computer (two story building)
  - Flight simulators & Crew Rehearsals
- Actual flight testing in mission plans

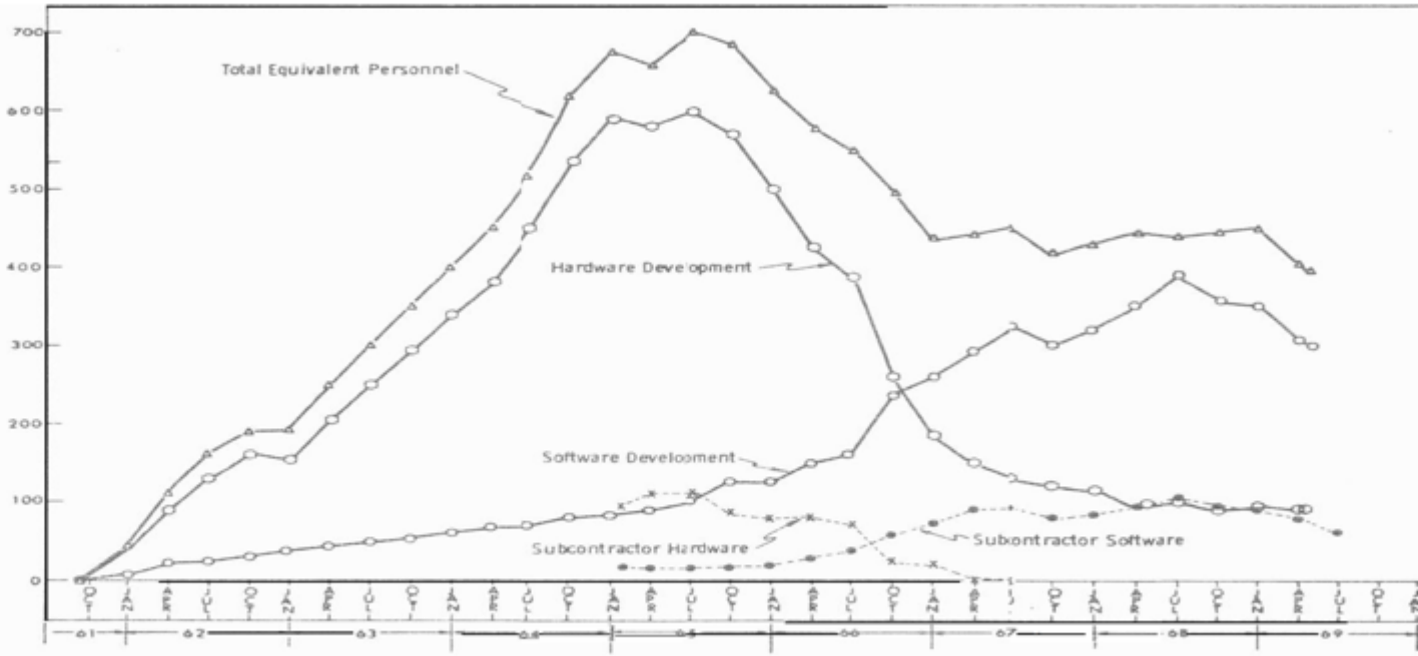


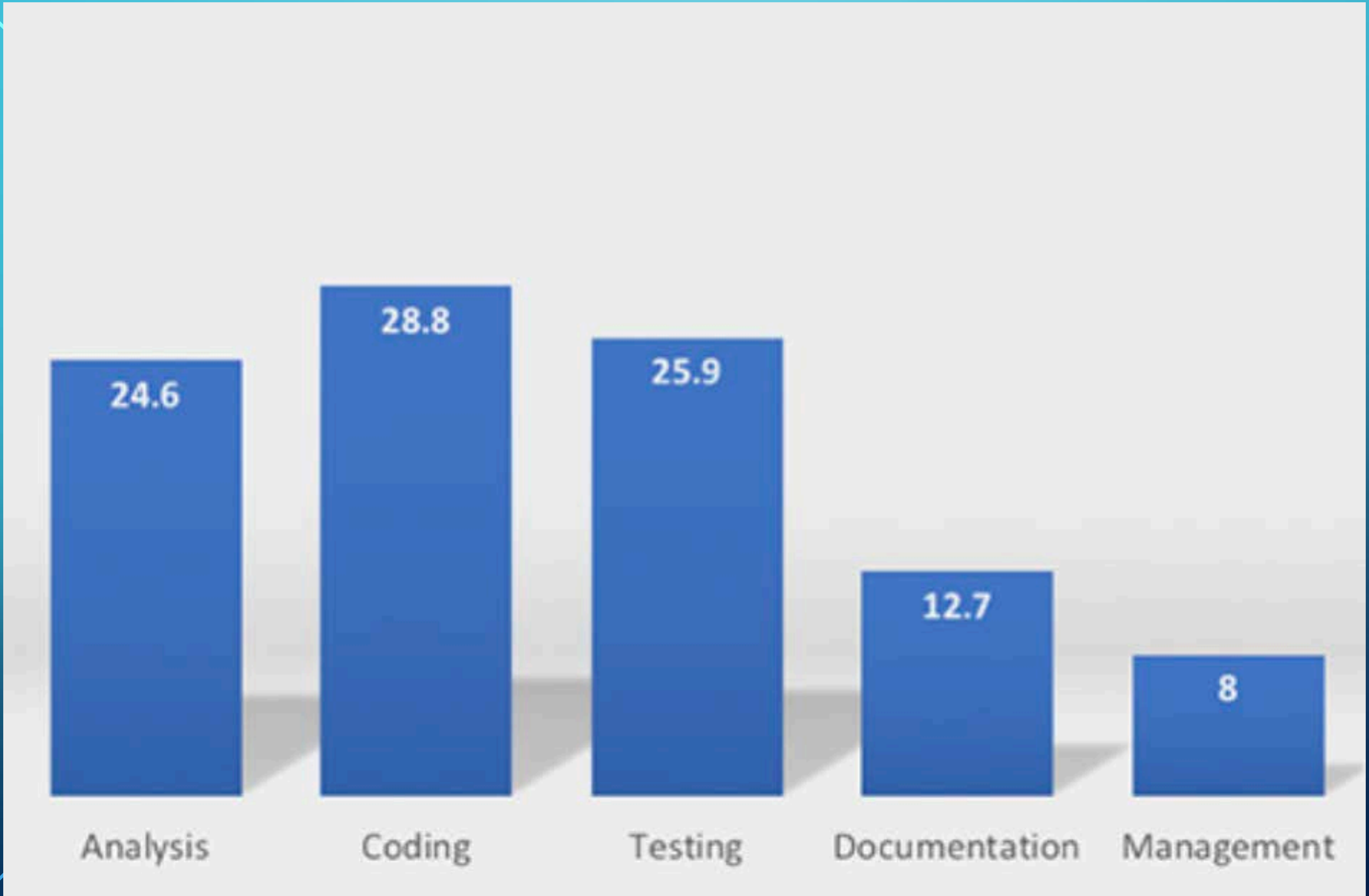





COLOSSUS IIA (Apollo 11)
LUMINARY IA (Apollo 11)
COLOSSUS II (Apollo 10)
LUMINARY I (Apollo 10)
COLOSSUS IA (Apollo 9)
SUNDANCE (Apollo 9)
COLOSSUS I (Apollo 8)
Manned
Unmanned
Manned
Unmanned
SUNDISK (Apollo 7)
SOLARIUM (Apollo 4) (Apollo 6)
SUNSPOT (AS-204)
SUNBURST (Apollo 5)
CORONA (AS-202)
SUNDIAL
AURORA
SUNRISE
RETREAD
ECLIPSE
CSM Block I
CSM Block II
LM


APOLLO HISTORY "MILESTONES"


700
600
500
400
300
200
100
0
Total Equivalent Personnel
Hardware Development
Software Development
Subcontractor Hardware
Subcontractor Software


24.6
28.8
25.9
12.7
8
Analysis
Coding
Testing
Documentation
Management

Project	1965 ($M)	2019 ($M)	2019 $M/yr
Apollo (10 yr)	25,000	203,000	20,300
PGNCS (10 yr)	600	~5000	500
Software (5 yr)	60	~500	100

"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…

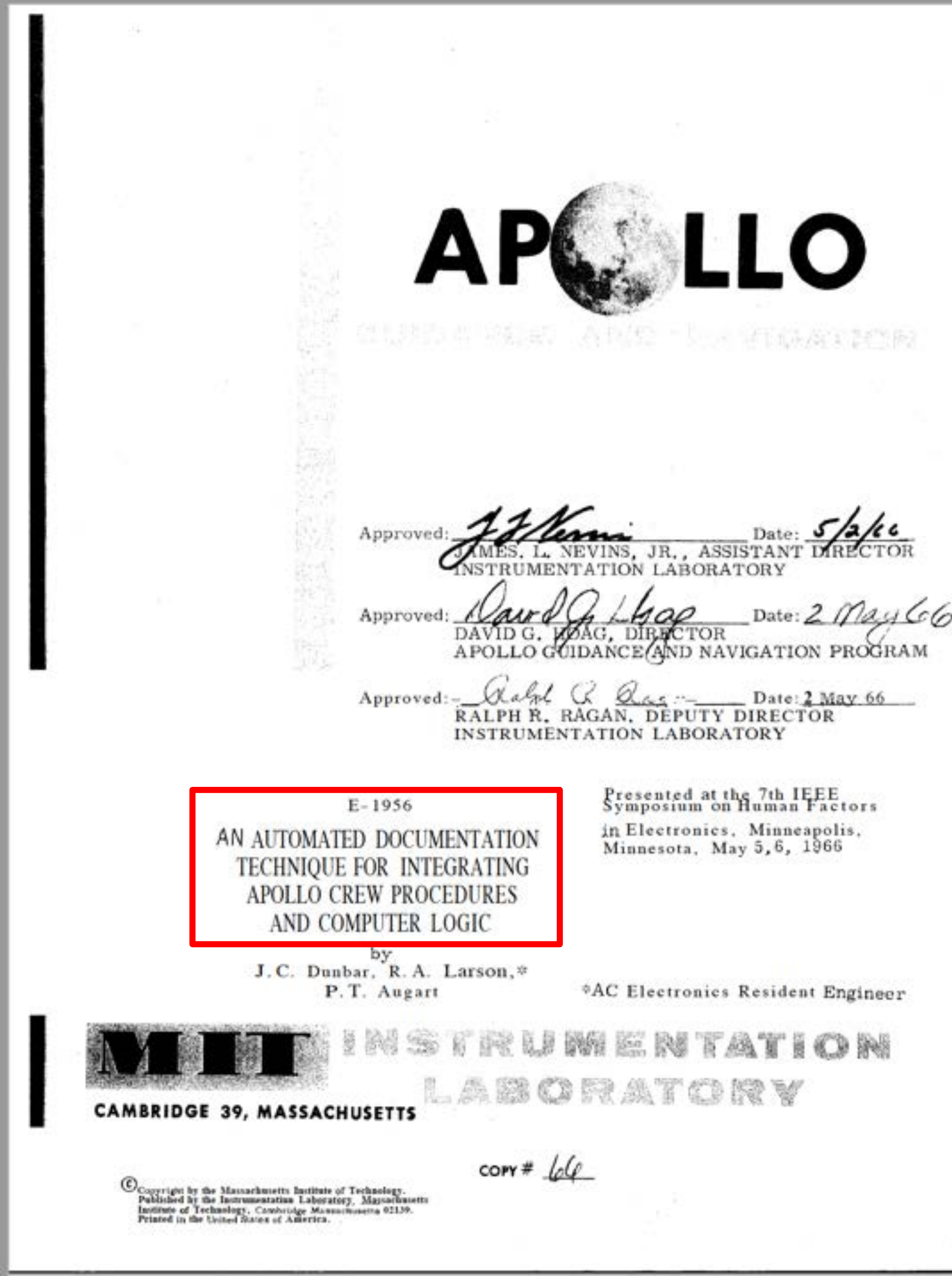
“…to bring the software [effort] legitimacy so that it and those building it would be given due respect"

“No one doubted the quality of the s

process used in development that ca

Five lessons were identified:

1. up-to-date documentation is crucia
2. verification must proceed through s
3. requirements must be clearly defin
4. good development plans should be
5. more programmers do not mean fa



APOLLO

Approved: ______ Date: 5/2/66
JAMES L. NEVINS, JR., ASSISTANT DIRECTOR
INSTRUMENTATION LABORATORY

Approved: ______ Date: 2 May 66
DAVID G. HOAG, DIRECTOR
APOLLO GUIDANCE AND NAVIGATION PROGRAM

Approved: ______ Date: 2 May 66
RALPH R. RAGAN, DEPUTY DIRECTOR
INSTRUMENTATION LABORATORY

E-1956

AN AUTOMATED DOCUMENTATION TECHNIQUE FOR INTEGRATING APOLLO CREW PROCEDURES AND COMPUTER LOGIC

by

J. C. Dunbar, R. A. Larson,*
P. T. Augart

Presented at the 7th IEEE Symposium on Human Factors in Electronics, Minneapolis, Minnesota, May 5,6, 1966

*AC Electronics Resident Engineer

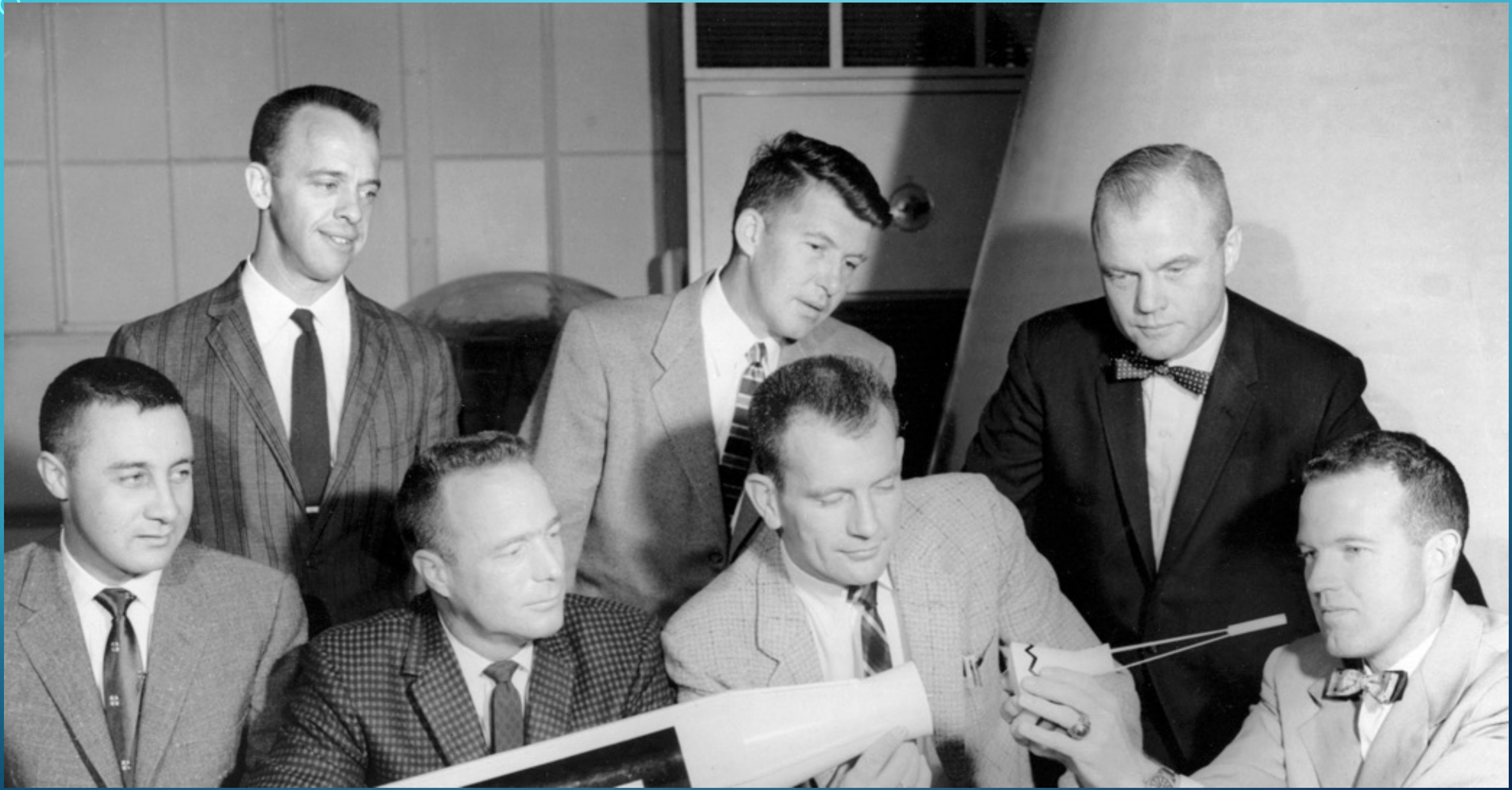
MIT INSTRUMENTATION LABORATORY

CAMBRIDGE 39, MASSACHUSETTS

COPY # 66

OUTLINE

- Background
- Hardware Architecture
- Guidance Software
- Brief Detour
- Mission Applications



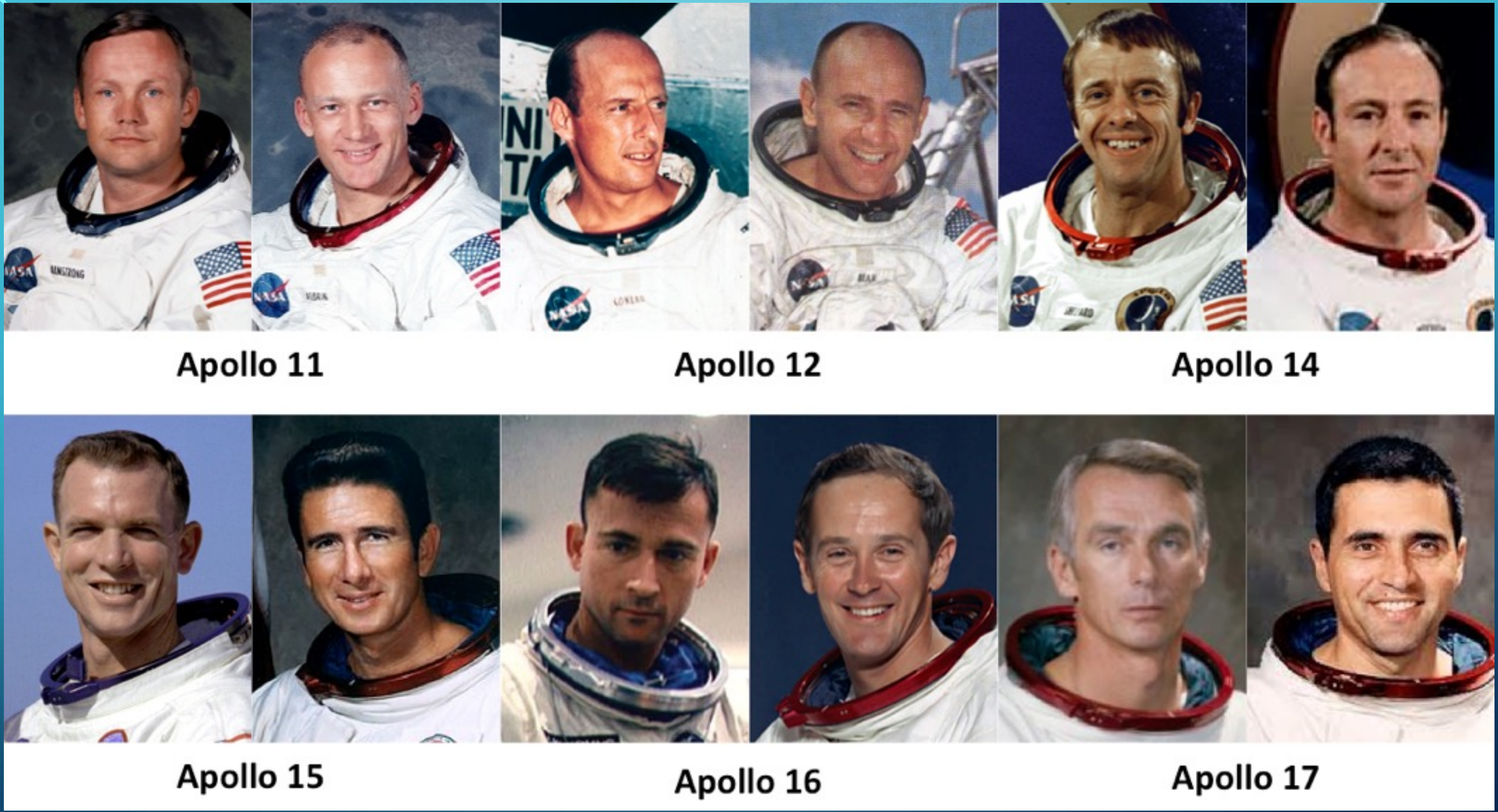
Mercury 7 Astronauts

Gemini Astronauts

Apollo GN&C System (MIT-IL)

Apollo Astronauts

Apollo Mission Control



Apollo Moonwalkers


RHEA HURRLE ALLISON
JANE HART
MARY WALLACE FUNK II
JEAN HIXSON
MYRTLE CAGLE
IRENE LEVERTON
SARAH LEE GORELICK
JAN DIETRICH
MARION DIETRICH
GENE NORA STUMBOUGH
BERNICE TRIMBLE STEADMAN
GERALDINE SLOAN

Mercury 13

Valentina Tereshkova – 3 days in orbit, 1963

A BRIEF DETOUR: WOMEN AND COMPUTERS

- 1640-1960: "Computer" → "one who calculates"
- Tedious calculation was "women's" work ("kilogirl")
- Before 1960: Computers were almost exclusively women

Harvard Observatory - 1890

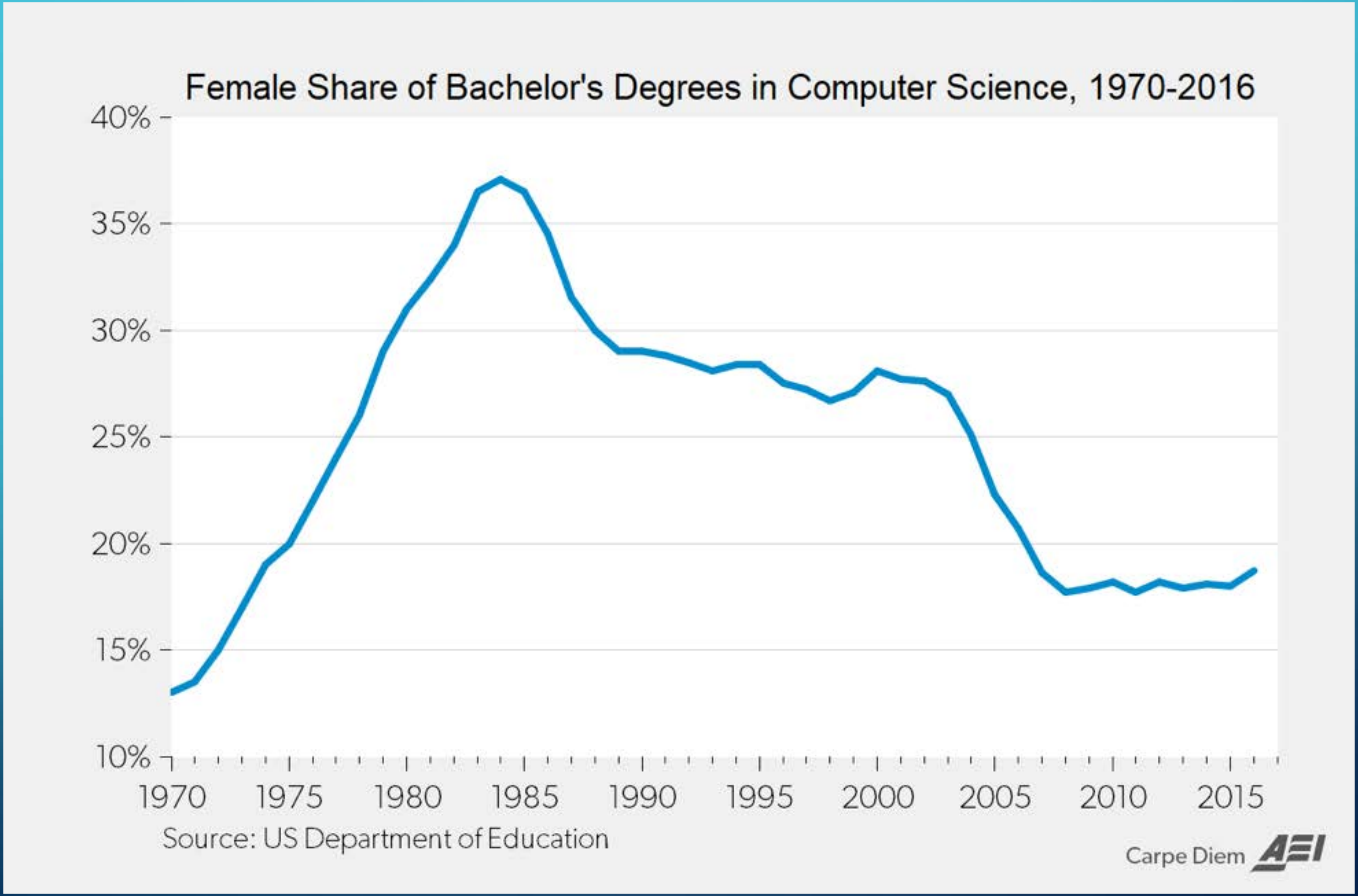
Oak Ridge - 1942

Los Alamos - 1943

Bletchly Park - 1944

Jet Propulsion Lab - 1953

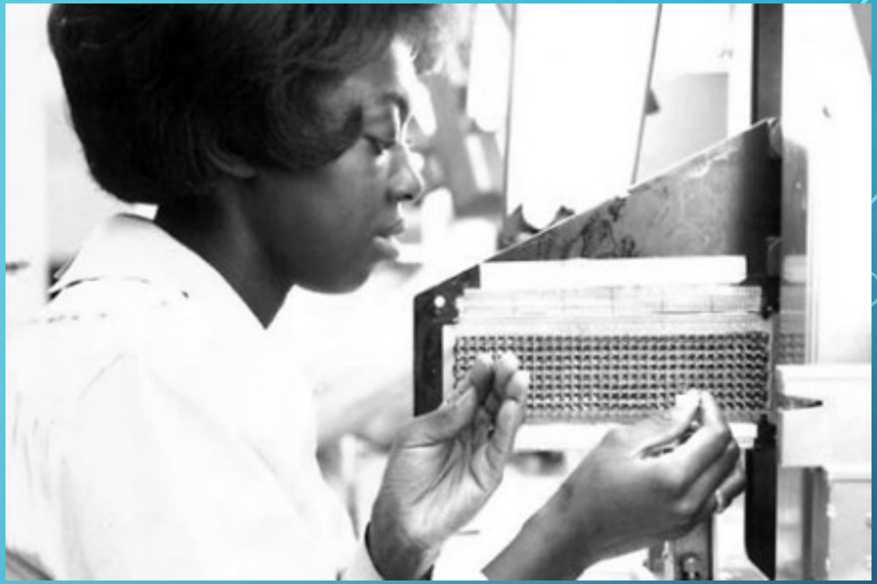
Langley, West Computing Group (1958)



Female Share of Bachelor's Degrees in Computer Science, 1970-2016
40%
35%
30%
25%
20%
15%
10%
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Source: US Department of Education
Carpe Diem

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
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USER INTERFACE

- VERB – NOUN
- 3, 5 char line display
- Indicator Lights
- Two in CM, one in LM one in Huston

VERB LIST

01-05 DISPLAY OCTAL
06 DISPLAY DECIMAL
07 DP DEC DSPLY (≤N38)
11-15 MONITOR OCTAL
16 MONITOR DECIMAL
17 DP DEC MON (≤N38)
21-25 LOAD DATA
27 01 DSPLY FIXED MEMORY
30 EXECUTIVE (PRE/L N26)
31 WAITLIST (PRE/L N26)
32 RECYCLE
33 PROCEED (REQ W/ V21-V23)
34 TERMINATE (EXCEPT N49,60,63,88)
35 TEST LITES (P00)
36 FRESH START
37 CHANGE PROGRAM
40 20 ZERO ICDU'S
40 72 ZERO RR CDU'S
41 20 IMU CRS ALN
41 72 RR CRS ALN
42 GYRO TORQ
43 LOAD FDAI ERROR NEEDLES (P00)
44 TERM RR DESIGNATE
47 INITIALIZE AGS
48 DAP DATA LOAD
49 CREW ATT MNVR (P00)
50 PLEASE PERFORM
52 REQST CURSOR MK
53 REQST SPIRAL MK
54 REQST X OR Y MK
55 INCRMT CLK (H,M,S)
56 TERM TRACKING

NOUN LIST

* - LEGIT LOADABLE NOUN & DATA VALID ANYTIME NOUN CALLED
V - DATA VALID ANYTIME NOUN CALLED
L - LEGIT LOADABLE NOUN
X - LEGIT LOADABLE NOUN (HR, MIN, .01S) (IF LOAD, ENTR R1, R2, R3)

01,02,03 * SPECIFIED OCT ADRS

DSPY	OCT	DEC
N01	[OCT]	[.XXXXX]
N02	[OCT]	[XXXXX.]
N03	[OCT]	[.01°]

04 GRAVITY ERR ∡ [.01°(R1)]
05 SIGHT ∡ DIFF/SV-RR LOS ∡ [.01°(R1)]
06 L OPTION CODE [OCT] (SEE P21, P22, P52, P57)
07 L ADRS/CHNL, BIT ID, ACTION [OCT] (SEE "FLAGWRD/CHNL SET/RESET")
08 V ALARM DATA [OCT] (ALMCADR, "BBCON", ERCOUNT)
09 V ALARM CODES [OCT] (1ST, 2ND, MOST RECENT ALM)
10 * SPECIFIED CHNL [OCT(R1)]
CAN'T READ 34, 35 | CAN'T LOAD 3, 4, 7, 15, 16, 30, 31, 32
IF LOAD CH 33, RESETS BITS 15-11
11 X T CSI OR T APOAPSIS [H, M, .01S] (0,0,0 = COMPUTE T APOAPSIS)
12 L OPTN CODE [OCT (0000X, 0000Y)]

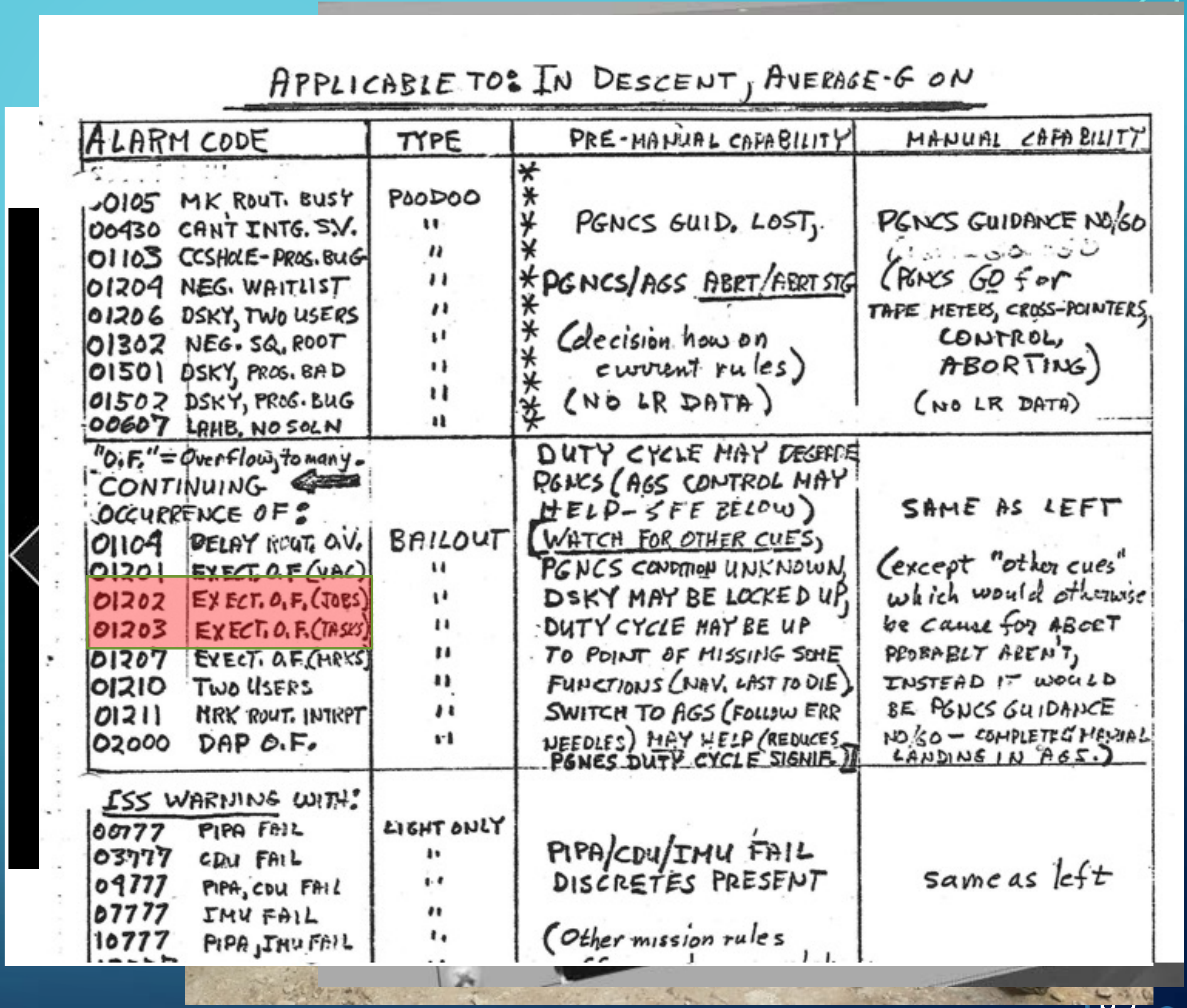
	X (SPFY)	Y=1	Y=2
V82	2 (VEH)	LM	CSM
V89	3 (TK ATT)	+Z	+X
V63	4 (RADAR)	RR	LR
41 72	6 (RR FN)	LOCK	DESIG

13 X T CDH [H, M, .01S]

58
59
60
61
62
63
64
65 V
66 V/
67
68
69 L
70 L
71 L
72
73 L
74
75
76 L
77
78

APOLLO 11

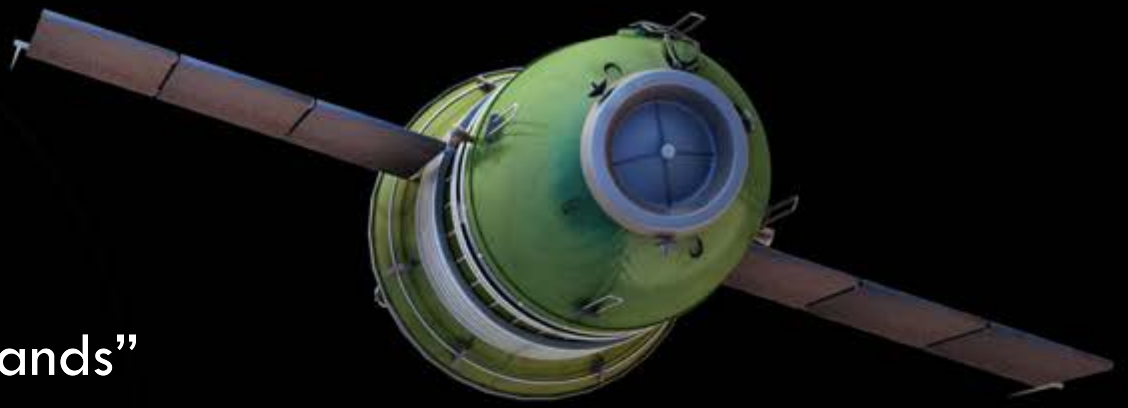
- Russian Luna 15
- Program alarms & restarts
- Hot I/O Device
- Boulder Field & Manual Inputs
- Ascent engine arm CB



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

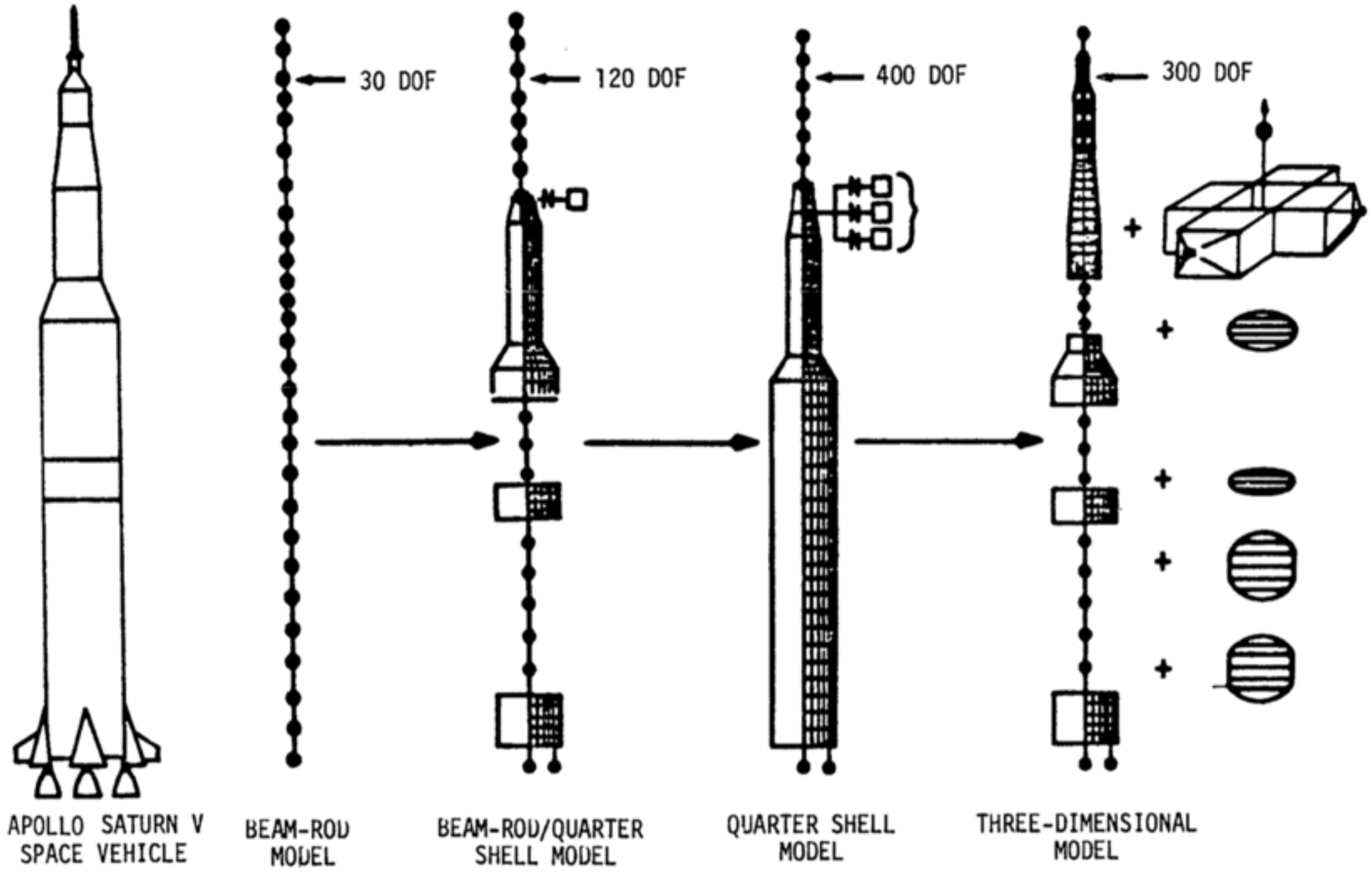


FIGURE 1-7 MATH MODEL EVOLUTION

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 (Netfilx 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