The Apollo Guidance Computer

Architecture and Operation

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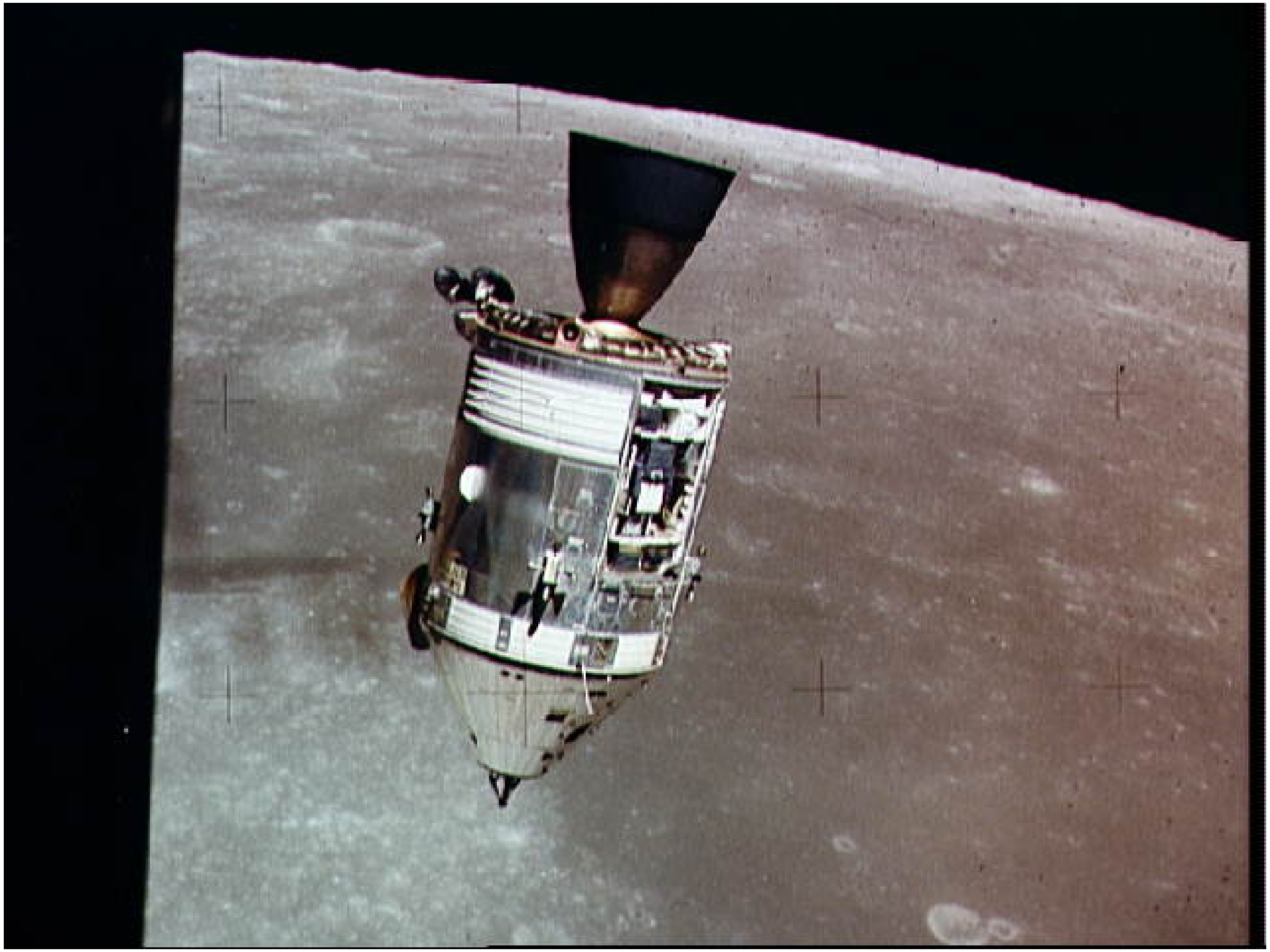
Infoage Science/History
Learning Center

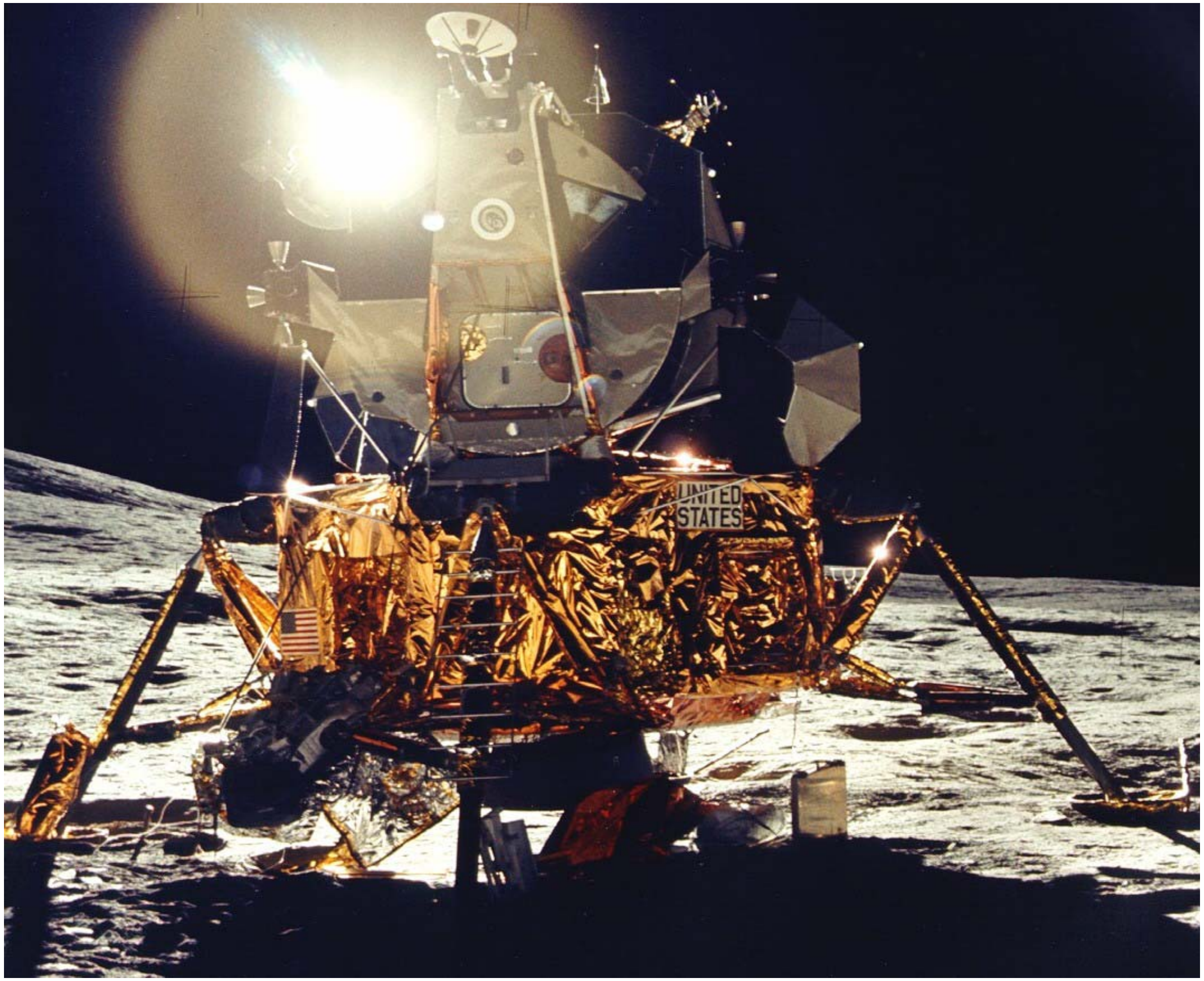
What we hope to accomplish

- AGC Origins and Requirements
- Hardware overview
- Software overview
- User interface
- “How to land on the Moon”!

Command and Service Modules



Lunar Module



AGC Origins

- NASA contracted MIT to develop AGC
  - Now Charles Stark Draper Laboratory
- Early work done on Polaris ballistic missile
- Vigorous debate on the interaction of man, spacecraft and computer
- As Apollo requirements grew, computer requirement grew even more!

Early Design Issues

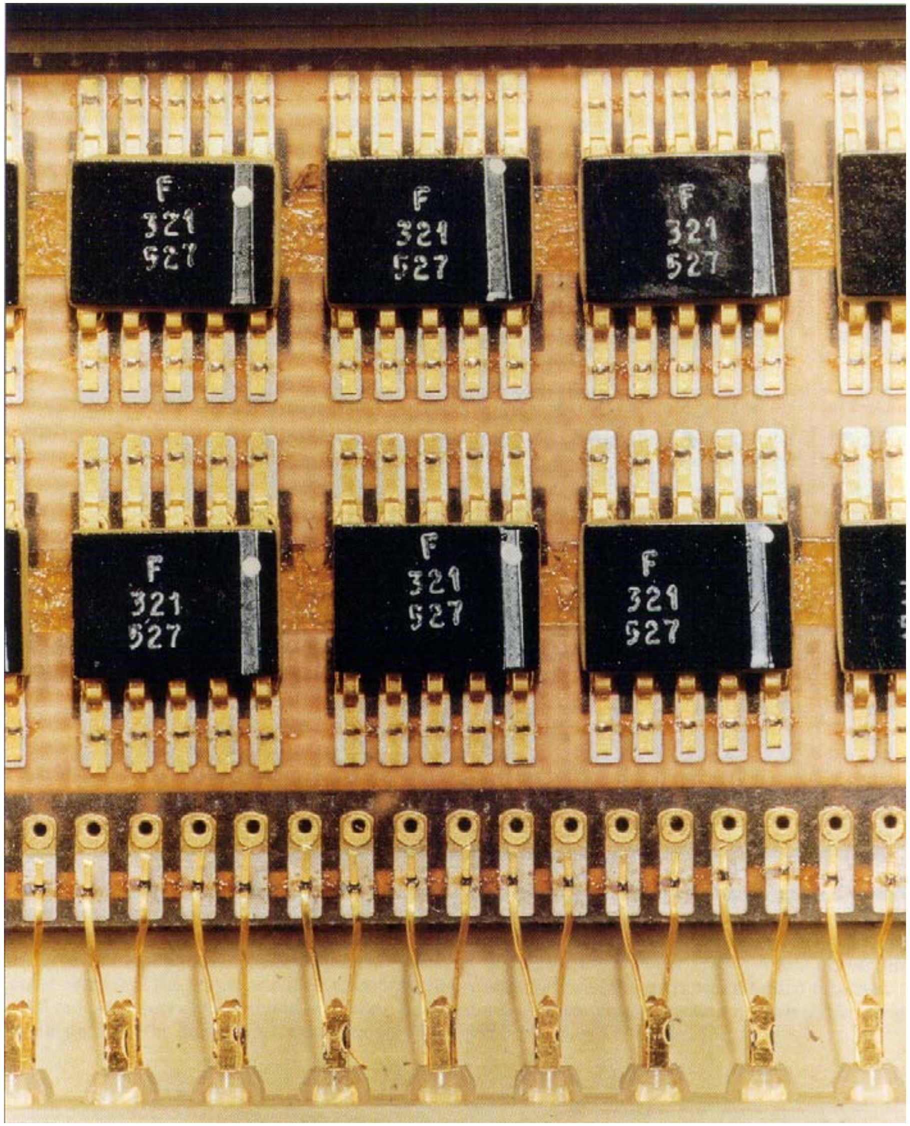
- What systems will it interface with?
- How much computing capacity?
- What type of circuit technology?
- Reliability and/or in-flight maintenance?
- What do we *need* a computer to do?
- What does a human interface look like?

AGC Requirements

- Autonomously navigate from the Earth to the Moon
- Continuously integrate State Vector
- Compute navigation fixes using stars, sun and planets
- Attitude control via digital autopilot
- Lunar landing, ascent, rendezvous
- Manually take over Saturn V booster in emergency
- Remote updates from the ground
- Real-time information display
- Multiprogramming
- Event timing at centisecond resolution
- Multiple user interfaces (“terminals”)

Logic Chips

- Fairchild introduced the “Micrologic” chip
- Two triple-input NOR gates per chip
  - Resistor-Transistor Logic
- Virtually all logic implemented using the Micrologic chips
  - Single component greatly simplifies design, testing
  - Greater production quantities -> better yields and higher quality
  - Several hundred thousand chips procured (!)

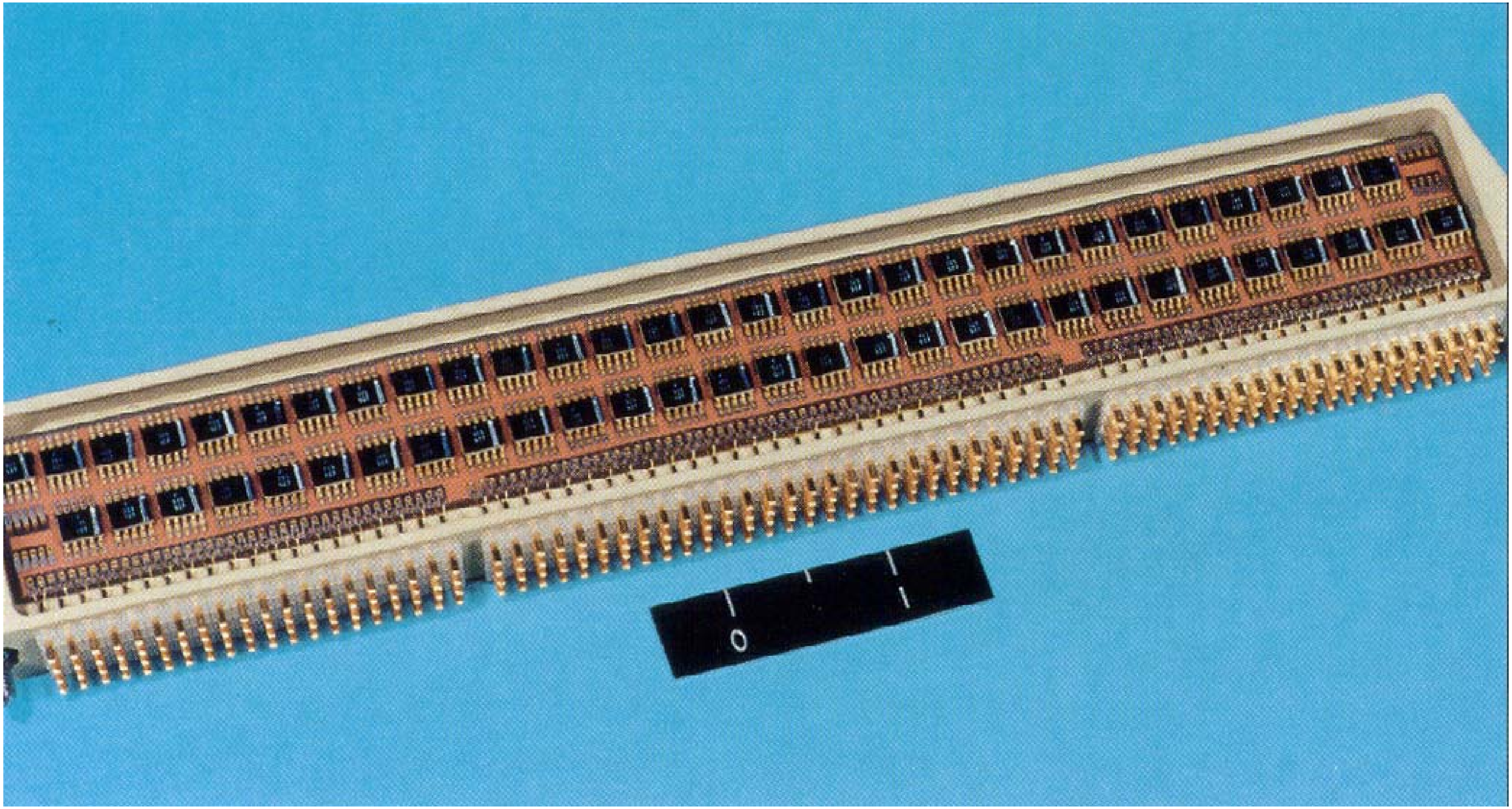


Micrologic chips installed on “Logic Stick”

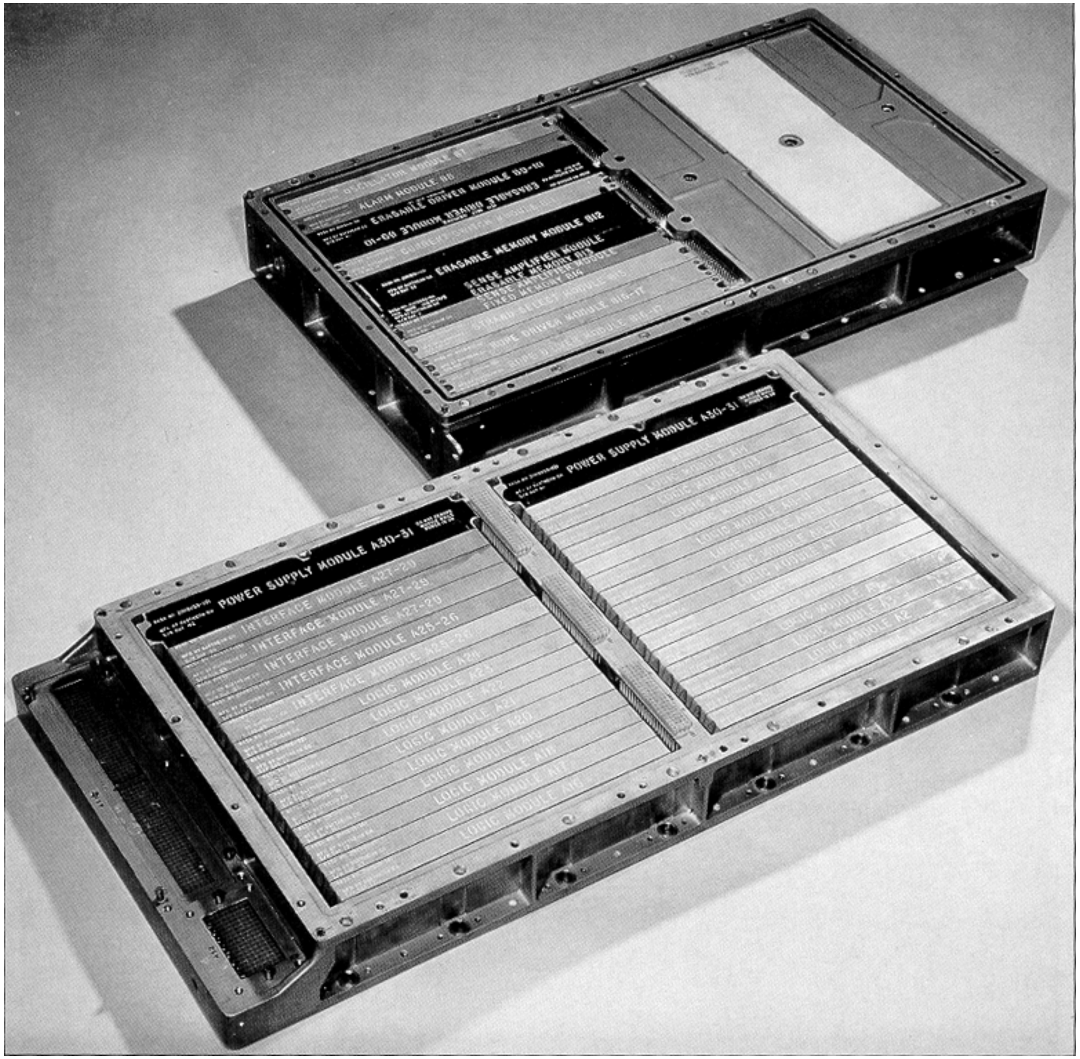
Logic Assemblies

- Subassemblies (sticks) contain 120 chips (240 gates)
- Chips welded to multilayer boards
- Logic boards essentially identical
- Traditional circuit boards could not produce the necessary logic density
- Interconnections made through wire-wraps in the underside of the “logic tray”

Completed “Logic stick”



AGC upper and lower trays



Upper tray: Core Rope and Erasable memory

Lower tray: Logic and interface modules

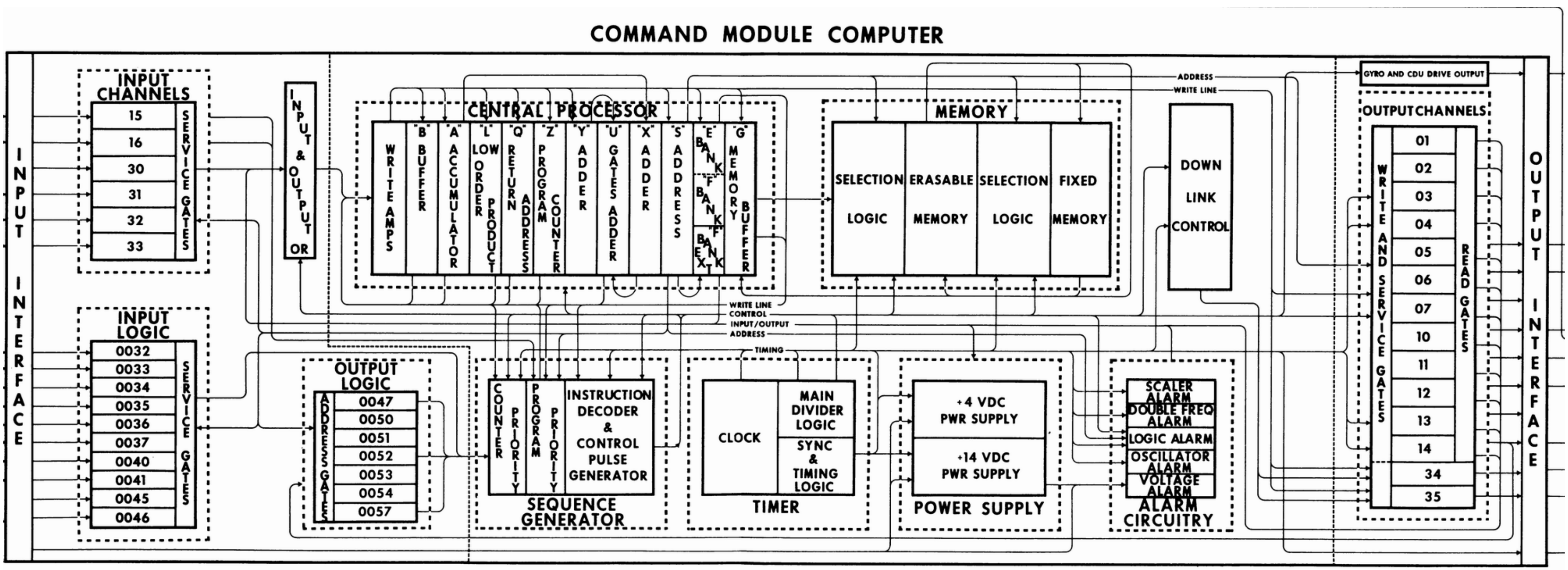
AGC Hardware

- 36K (16-bit) words ROM (core rope)
- 2k (16-bit) words core RAM
- Instructions average 12-85 microseconds
- 1 cu.ft, 70 pounds, 55 watts
- 37 “Normal” instructions
- 10 “Involuntary” instructions
- 8 I/O instructions

AGC Internal Architecture

- Registers
  - The usual suspects: Accumulator, program counter, memory bank, return address, etc.
- Input/output channels
- Data uplink / downlink
- No index register or serialization instructions (!)
- Interrupt logic and program alarms
- One’s complement, “fractional” representation

Logical overview (Spaghetti diagram)



Instruction Set

- The usual suspects – 37 instructions
  - 3 bit opcode, plus (sometimes) two bit "quarter code", plus "Extend" mode, plus….
- "Interpreted" instructions
  - Coded in Polish Notation
  - Similar to "p-code"
  - Trigonometric, matrix, double/triple precision
  - *Huge* coding efficiency

Instruction Set

- 8 I/O – read/write instructions to I/O channels
- 10 Involuntary instructions - counters
  - Example: Update from Inertial Measurement Unit
    - Counters represent accelerometer and gimbal changes
  - No context switch!
    - Currently running program *NOT* interrupted
  - Counters updated directly by hardware
  - Processing resumes after involuntary instruction (counter update) finishes
  - Processing delayed only about 20 microseconds

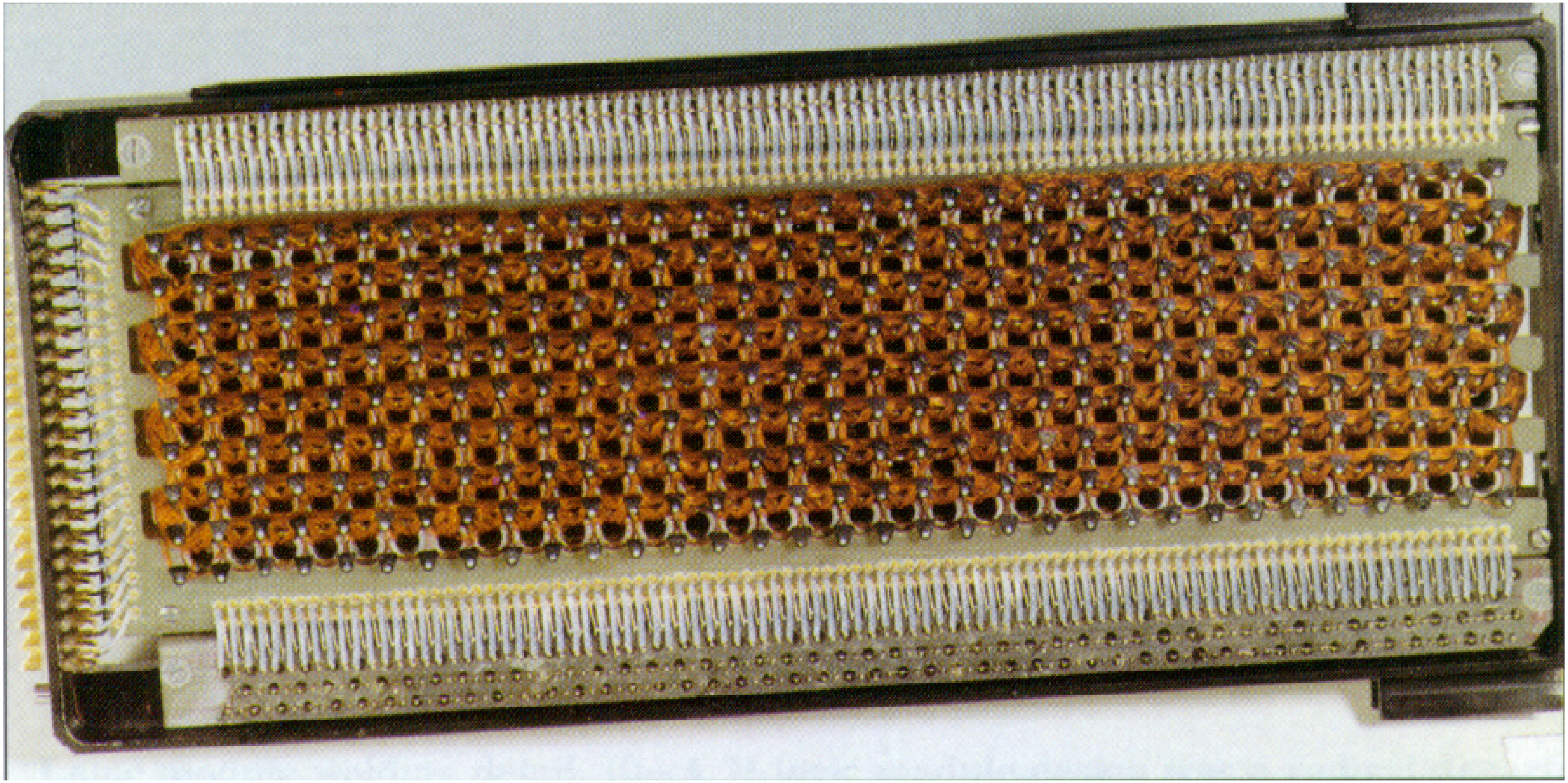
Memory Architecture

- All memory 16 bit words
  - 14 bits data, 1 bit sign, 1 bit parity
  - Not byte addressable
- Read/Write memory
  - Conventional coincident-current core memory
  - 2K words
- Read Only Core "Ropes"
  - 36K Read-only storage
  - Contained all programming and some data

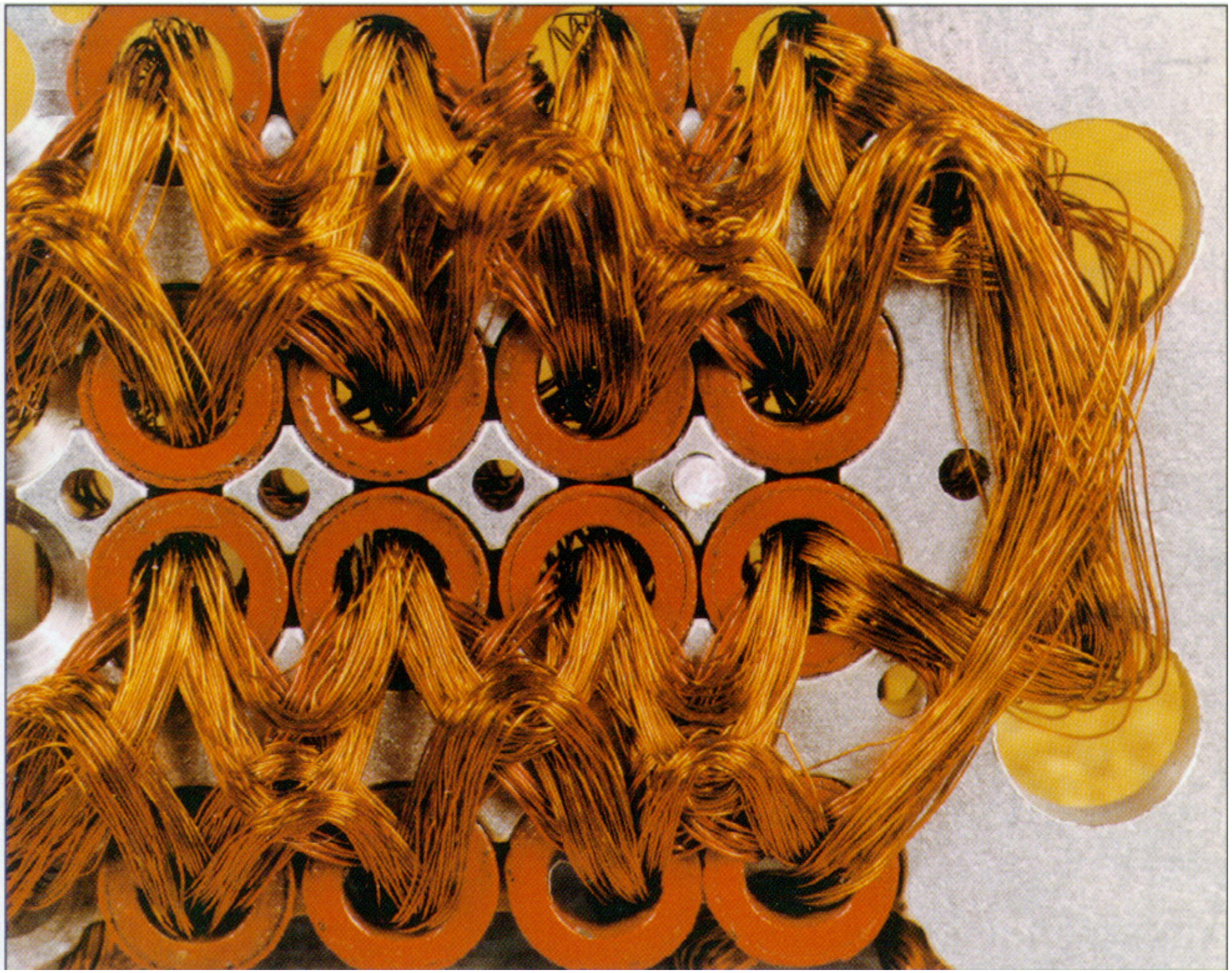
Memory Architecture

- Core "Ropes"
  - Read-only storage
  - One "core" reused 24 times for each bit (!)
  - High storage density
  - Software "manufactured" into the ropes
    - Software frozen 10 months before launch!
    - Ropes installed in spacecraft 3-4 months prior to launch
  - 6 rope modules, each 6K of memory
  - Rope modules easily replaced in computer

Core Rope Module



Core Rope Wiring Detail



Addressing memory

- Instruction has 8 to 12 bits for addressing
- Need to address 36K for instructions, 2K for data
- Not enough bits! (need at least 16 bits -> 64k)
- Torturous memory bank addressing
  - "Banks" are either 1K or 256 bytes
  - Three banking registers required to address a specific memory location
  - Lots of extra code needed to manage memory banks

Interfaces (“I/O Devices”)

- **Gyroscopes and accelerometers**
  - Collectively known as the “IMU” (Inertial Measurement Unit)
- **Optics**
  - Sextants and telescopes used for navigations sightings
- **Radars and ranging equipment**
  - 2 radars on LM, VHF ranging on CSM
- **Display and Keyboards (DSKY’s); 2 in CM, 1 in LM**
- **Engines**
  - CSM: SPS, LM: DPS, APS
  - Both have 16 attitude control thrusters, CM has additional 12 for reentry
- **Analog Displays**
  - “8-Balls”, altitude, range, rate displays
- **Abort buttons (!)**

I/O Channels

- Mapped as memory addresses in low core
- Accessible only by I/O instructions
- All 16 bits wide
- 7 input channels
- 14 output channels
- Most are single bit status flags

Man-Machine Interactions

- Hasn't changed in 50+ years
- Machine instructions
  - Opcode - Operands
- Command line interface
  - Command - Options
- Even WIMP's use similar philosophy!
- All define an object, and the action to be performed on that object

Using the DSKY interface

- DSKY – Display and Keyboard
- Specialized keys assigned for each function
- Three “registers” displayed data
- Commands entered in “Verb-Noun” format
  - “Verb”: Action to be taken
    - Display/update data, change program, alter a function
  - “Noun”: Data that Verbs acts upon
    - Velocities, angles, times, rates

DSKY – Display Keyboard

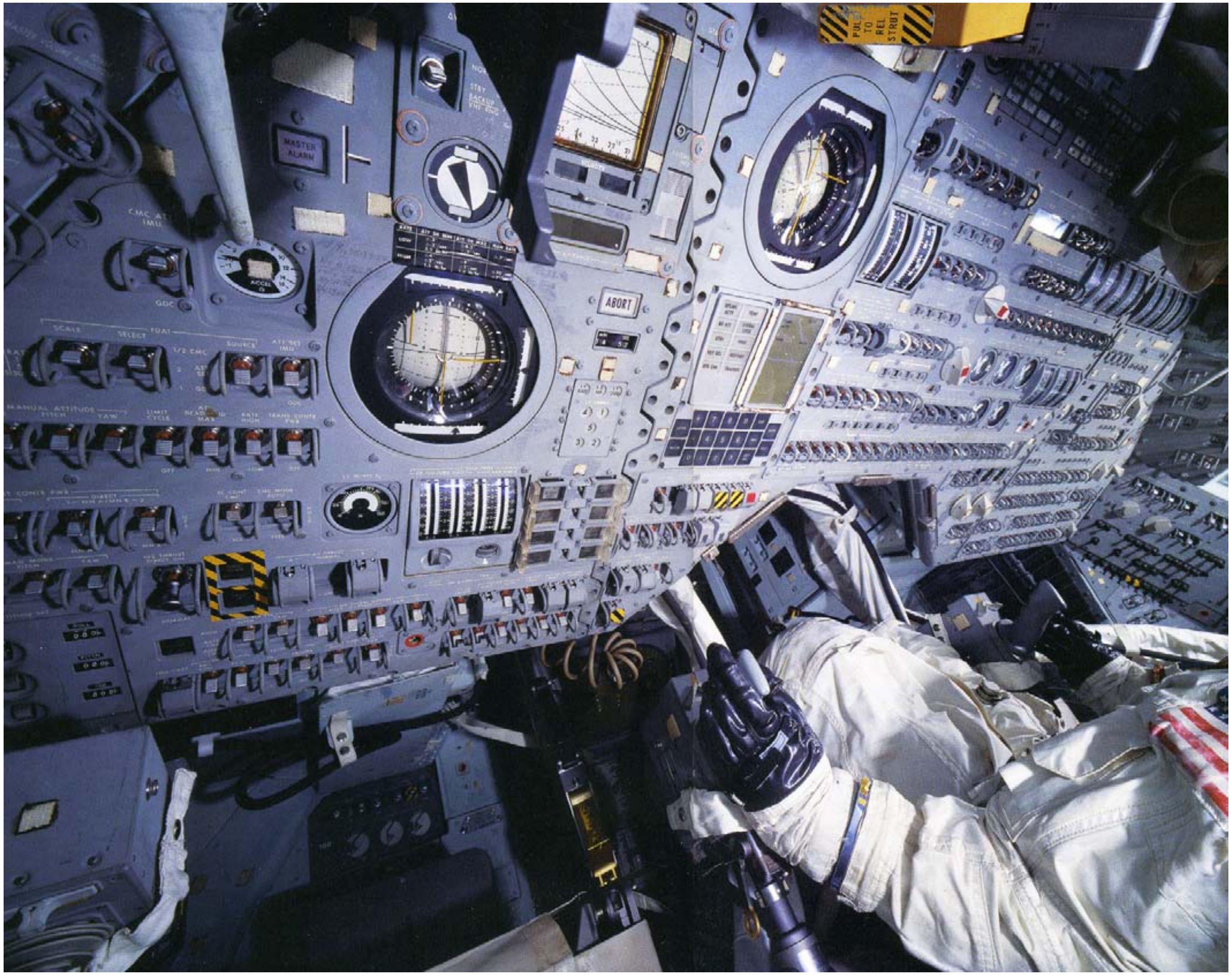
DSKY Components

- Electroluminescent digits (not LED/LCD)
- 2 digit displays for Program number, Verb, Noun
- 3, 5-digit displays for data, +/- signs
  - No decimal points!
- Keyboard
- Warning lights
- DSKY separate from computer

Using the DSKY interface

- “PRO”: Proceed with the data as offered by computer
- “Enter”, “Clear”: – self explanatory
- “Key Rel”: Releases control of the DSKY to computer (upon computer request)
- “Reset”: resets program alarm

DSKY in the Command Module



DSKY in the Lunar Module

Sample DSKY Query

- Programs, Verbs and Nouns referred to by their “number”
- Lots to remember:
  - ~45 Programs, 80 verbs, 90 Nouns
- Example: Display time of the next engine burn
- Enter Verb, 06, Noun, 33, Enter
  - Verb 06: Display Decimal Data
  - Noun 33: Time of Ignition
  - End with pressing Enter
- Notation: V06N33E

Sample DSKY Query: Time of Engine Ignition

Verb 06, Noun 33: Display Time of Ignition

Verb 06: Display values

Program number – P63

Noun 33: Time of Ignition

Hours

Minutes

Seconds . hundredths

Time of Ignition: 104:30:10.94 (Mission time)

AGC Executive

- Multiprogramming, priority scheduled, interrupt driven, real-time operating system
- Several jobs running at one time
  - Up to 7 “long running” jobs
  - Up to 7 short, time dependent jobs
- Only one program has control of the DSKY

Scheduling a New Job

- Starting a program requires temporary storage be allocated
- Two types of storage areas available
  - CORE SET: 12 words
    - Priority, return address and temp storage
    - Always required
  - VAC Area: 44 words
    - Larger temp storage
    - Requested if vector arithmetic is used
- 7 CORE SET's and 7 VAC Areas available

Scheduling a New Job

- All work assigned a priority
- Executive selects job with highest priority to run
  - DSKY always the highest priority
  - In exceptional situations, jobs can change priority
- Every 20 milliseconds:
  - Job queue checked for highest priority task
  - Highest priority job allowed to execute
- Jobs are expected to run quickly, and then finish
  - "Night Watchman" verifies job is not looping, and new work is being scheduled (every 1.2 seconds)
  - Restart forced if a job is hung up

Error Messages

- Errors need to be communicated to crew directly
  - Software might encounter errors or crash
  - Crew may give computer bad data or task
- “Program Alarm” issued, w/error light on
  - Verb and Noun code indicate type of error
- Depending on severity of error, may have to force a computer restart

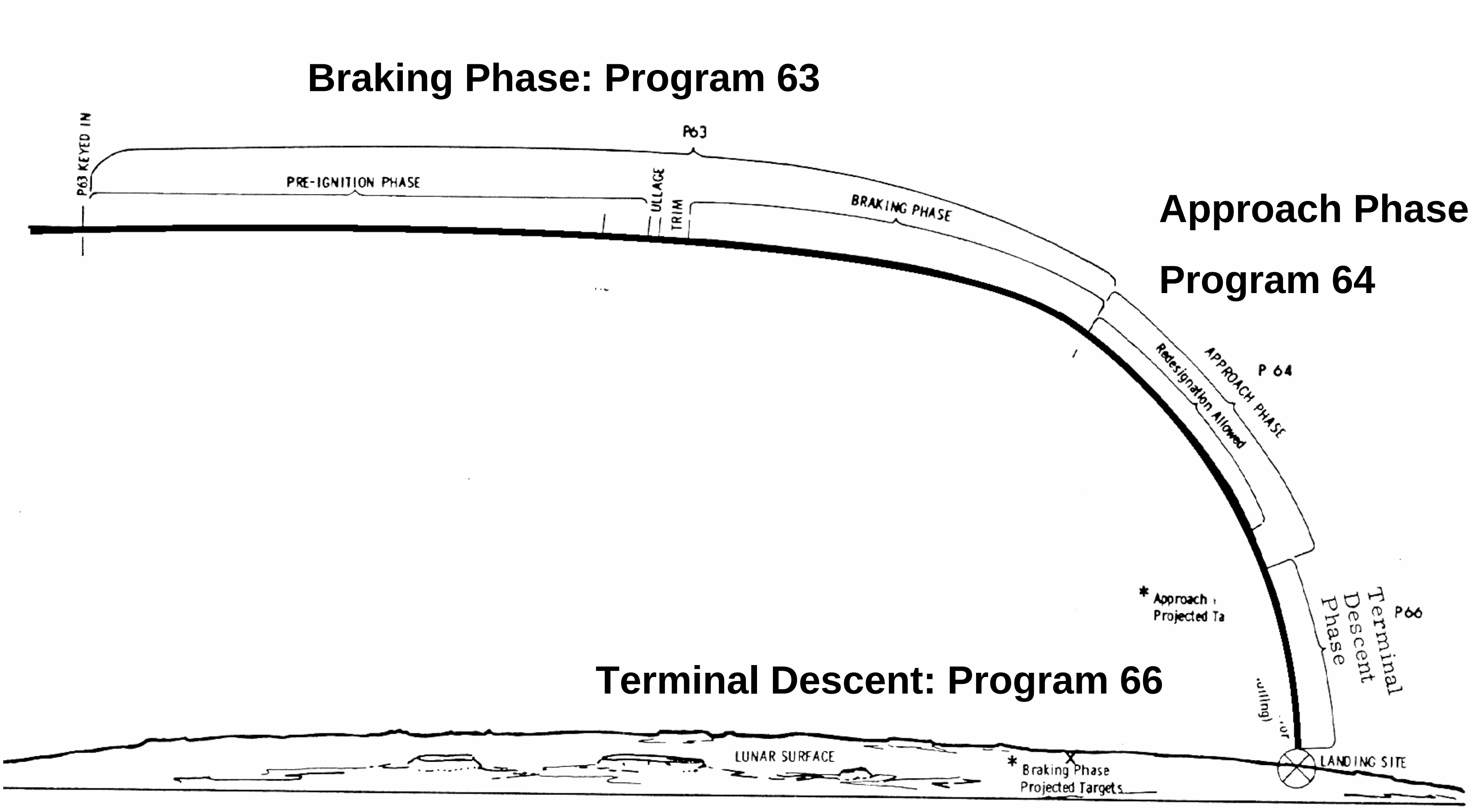
Error Recovery

- All programs resister a restart address
  - Program errors, hung jobs, resource shortages can all force a computer restart
- A “restart” is the preferred recovery
  - NOT the same as rebooting
  - All critical data is saved, jobs terminated
  - All engines and thrusters are turned off (most cases)
  - Hardware is reinitialized
  - Programs are reentered at predefined restart point
- Process takes only a few seconds!

Landing on the moon

- One attempt, no second approaches!
- AGC handles all guidance and control
- Three phases
  - Braking (Program 63)
    - Started ~240 nm uprange at 50K feet
  - Approach (Program 64)
    - 2-3 nm uprange, begins at ~7K feet
  - Final Descent (Program 66)
    - Manual descent, started between 1000 to 500 feet

Lunar Module Descent Profile



Program 63: Lunar descent

- Started 10-20 minutes before descent
- Computes landing site targeting
- Started with V37E63E
- Response V06N61
  - Time until end of P63
  - Time from ignition
  - Crossrange distance

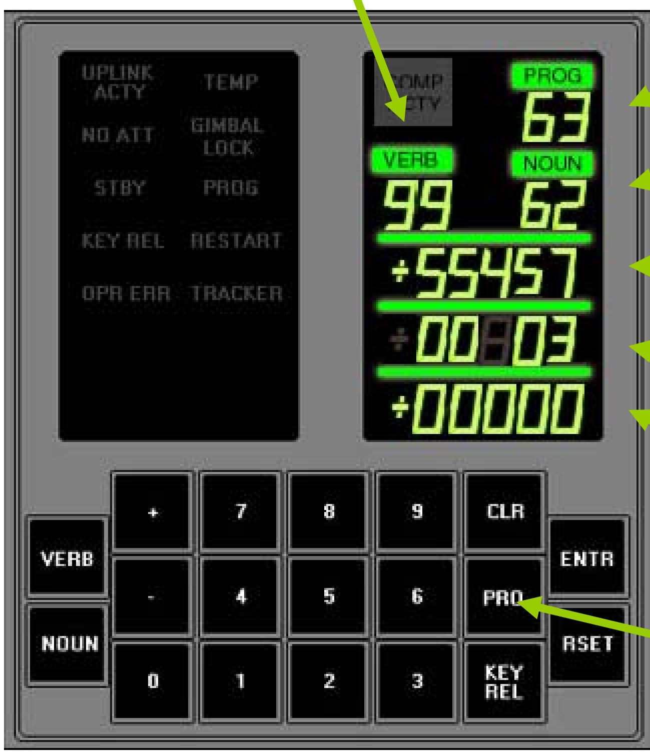
P63 Overview

- Verb 06, Noun 33: time of Ignition
  - Hours, minutes, seconds
  - 104:30:10.94
- Verb 06, Noun 62: Velocity info
- Flashing Verb 99: Permission to go?
  - Key PRO! Ignition!
- P63 displays Verb 06, Noun 63
  - Delta altitude, altitude rate, computed altitude

P63 – Braking phase (Confirm Engine Ignition)

T-35 Seconds, DSKY Blanks for 5 seconds, at T-5, Flashing Verb 99 displayed

Verb 99: Please enable Engine Ignition



Program number – P63

Noun 62: Pre-ignition monitor

Current Velocity

Time to ignition (min, sec)

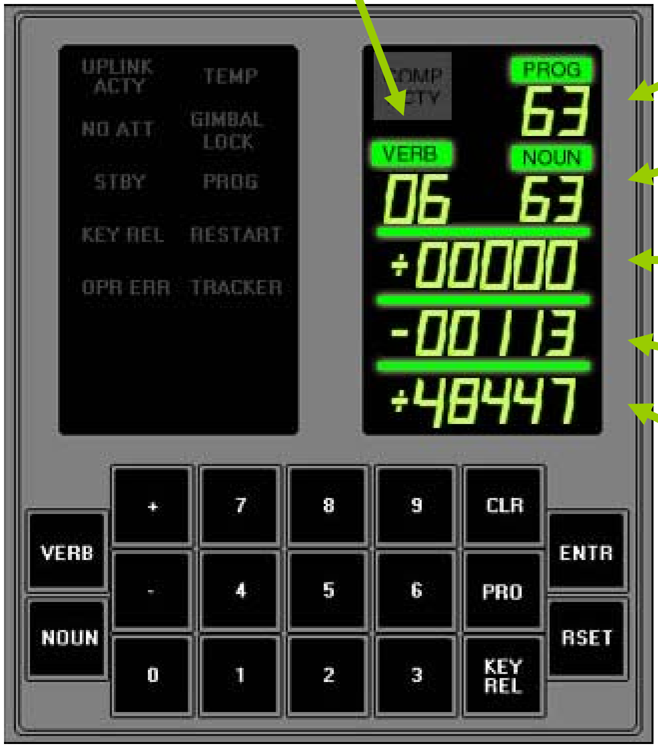
Delta V accumulated

3 seconds until ignition! Press PRO[ceed]

P63 – Braking phase (post-ignition)

Verb 06, Noun 63: Monitor braking phase of descent

Verb 06: Display values



Program number – P63

Noun 63: Descent monitor

Radar altitude - computed altitude (not valid yet)

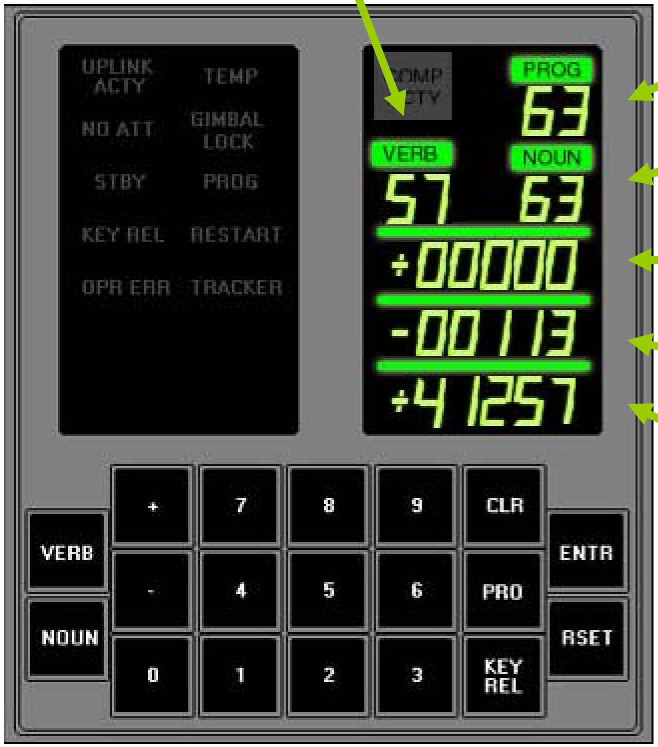
Altitude rate

Altitude

P63 – Accept landing radar updates

Verb 57, Enter

Verb 57: Accept Radar Updates



Program number – P63

Noun 63: Descent monitor

Radar altitude - computed altitude (not valid yet)

Altitude rate

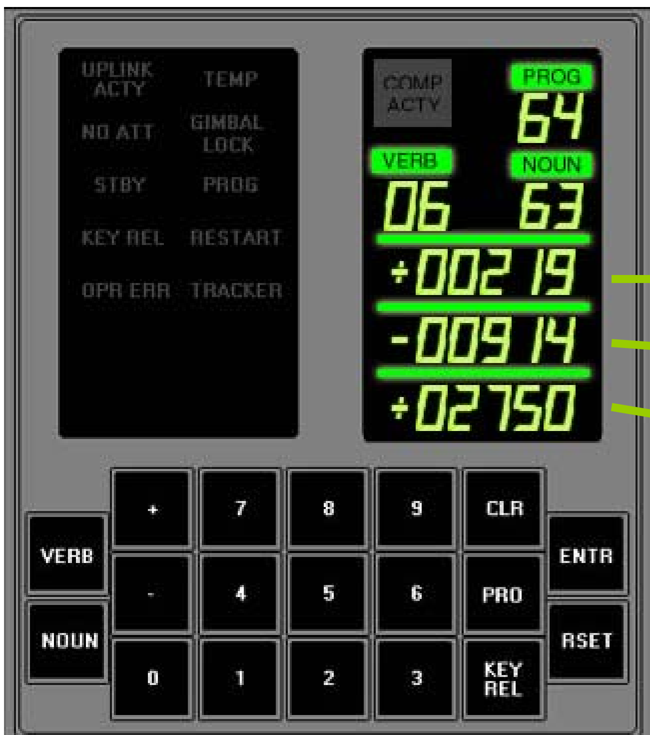
Altitude

P63 – Monitoring the descent

Computer displays were compared against a "cheat sheet" Velcro'd onto the instrument panel

Antenna angle
% Fuel

Time from Ignition
LM Pitch angle



TFI	θ	VI	(-ḢMAX) -HDOT	(ΔHMAX) H	DPS	SBD
0:00	113	5560.0	2.0	50000	95	2/1
0:30	112	5490.0	7.0	49900	95	
1:00	106	5210.0	37.0	49300	91	7/-3
1:30	100	4910.0	59.0	47800	86	
2:00	95	4610.0	73.0	45800	80	15/-11
2:30	90	4310.0	82.0	43500	75	
3:00	86	3990.0	87.0	40900	70	22/-16
3:30	83	3670.0	89.0	38300	65	
4:00	80	3330.0	91.0	(17000) 35700	60	26/-20
4:30	78	2990.0	91.0	(17000) 32700	54	
5:00	77	2640.0	93.0	(15800) 30500	49	29/-22
5:30	74	2270.0	92.0	(12800) 26400	44	
6:00	[illegible]	1890.0	86.0	(11400) 24700	39	32/-25
6:30	70	1490.0	(432.0) 69.0	(9200) 21800	33	
7:00	66	1230.0	(401.0) 95.0	(8200) 18900	30	39/-29
7:30	65	980.0	(367.0) 119.0	(6900) 16100	27	
8:00	65	730.0	(323.0) 139.0	(5600) 12800	23	40/-29

Approach – P64!

- Pitch over the LM to see the landing site
- Program 64 automatically selected by P63
- ~7,000 feet high, 2 miles from landing site
- Key PRO to accept and continue!
- P64 displays V06, Noun 64
  - Time to go, Descent angle, rate, altitude
  - Another cheat sheet velcro'ed to the panel

P64 – Approach phase of landing

Program 64 automatically entered from P63

Verb 06: Display values

Program number – P64

Noun 64: Descent monitor

Seconds until end of P64, and Landing point targeting angle

Altitude rate

Altitude

P66: Terminal Descent

- Final phase – only hundreds of feet high
- Less than one minute to landing
- Computer no longer providing targeting
  - Maintains attitude set by Commander
- Commanders attention is focused "outside" the spacecraft
  - Other astronaut reads off DSKY displays

P66 – Terminal Descent Phase (manual control)

Program 66 entered using usually through cockpit switches

Verb 06: Display values

Program number – P66

Noun 60: Terminal Descent monitor

Forward Velocity

Altitude rate

Altitude

Apollo 11 Alarms During Landing

- During landing, several program alarms occurred
- Aborting the landing was a real possibility!
- Handling “hot I/O” put CPU to 100% utilization
  - Unexpected counter interrupts from rendezvous radar
  - Jobs could not complete in time and free up temporary storage
- “1201”, “1202” alarms: No more CORE SET or VAC areas -> Restart!
- Guidance, navigation and targeting data preserved
- Restart completed within seconds
- Computer functioned exactly as it was designed!

Abort! (A bad day at work….)

Pressing the Abort button automatically switches software to Abort program

Apollo 14 Abort Switch

- Loose solder ball in Abort switch
  - If set, will abort landing attempt when lunar descent is begun
- Detected shortly before descent was to begin
- Need to ignore switch, but still maintain full abort capability
- Patch developed to bypass abort switch
  - Diagnosed, written, keyed in by hand and tested in less than two hours !!

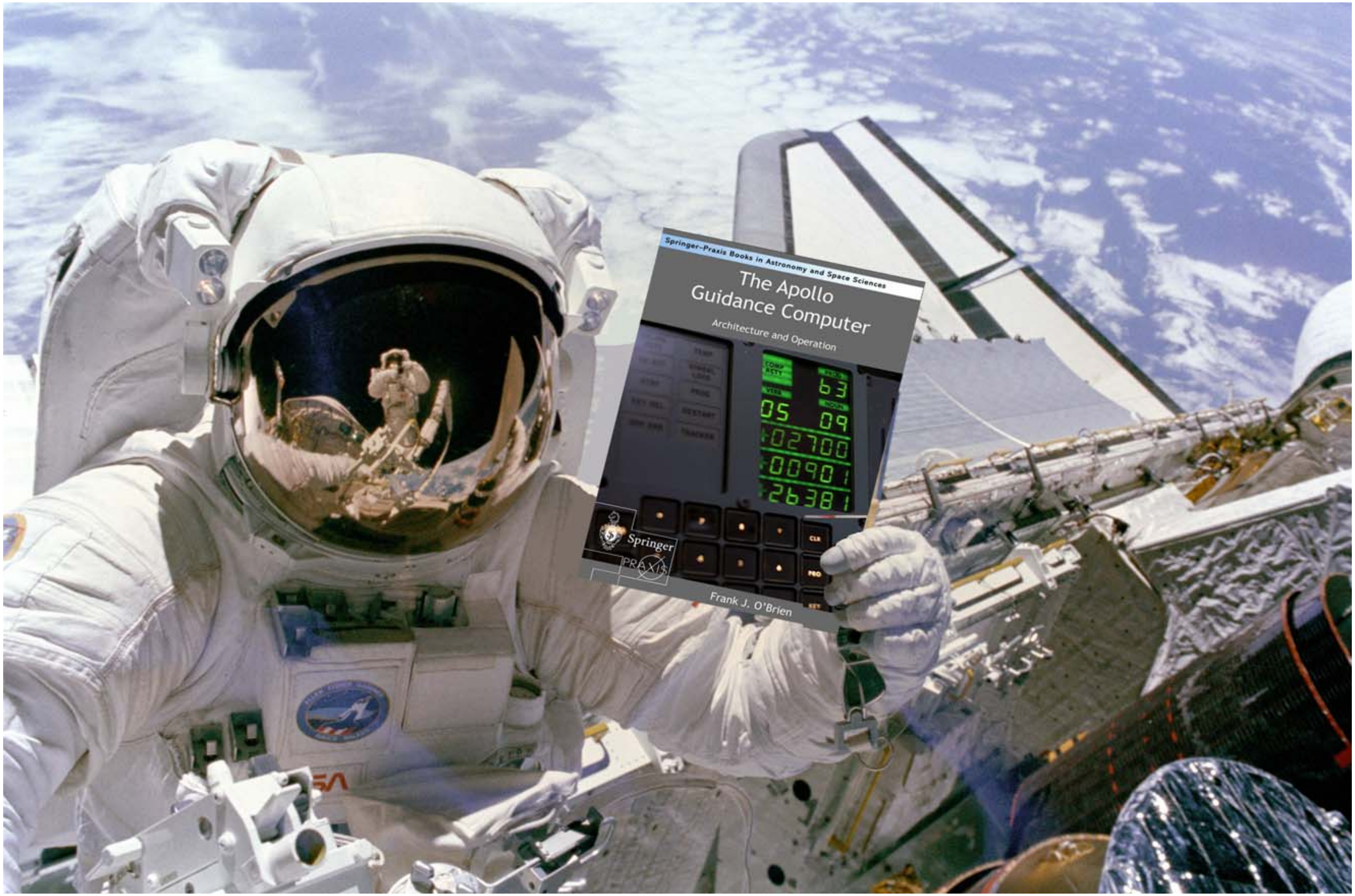
Epilogue

- AGC was “bleeding edge” technology
  - By the end of Apollo, hopelessly outdated!
  - Still, it never failed

- Moral #1: You can never, ever test enough
- Moral #2: Requirements will always grow
- Moral #3: Always design for the future!

Shameless Endorsements

- The Apollo Lunar Surface Journal
  - www.hq.nasa.gov/alsj
- The Apollo Flight Journal
  - www.hq.nasa.gov/pao/History/ap15fj/index.htm
- Journey to the Moon, Eldon Hall, AIAA Press
- Cradle of Aviation Museum
  - Uniondale, Long Island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