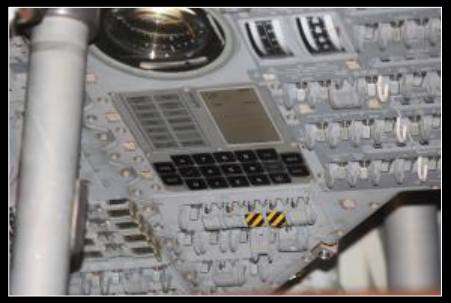


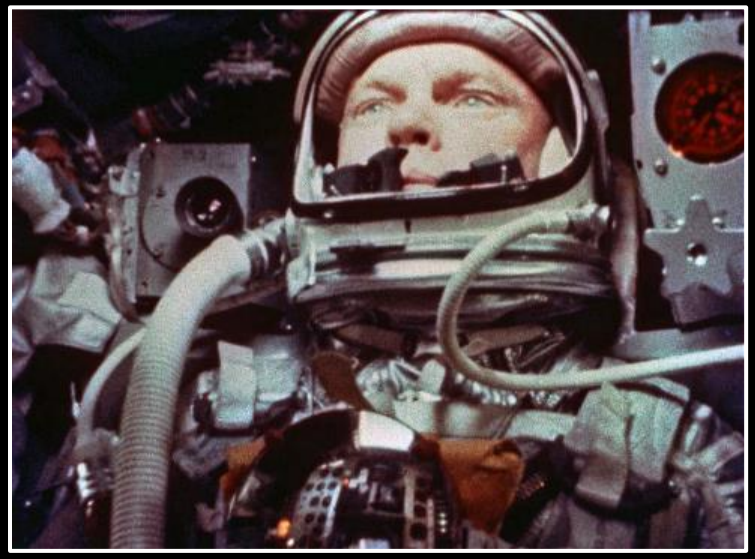
Computers to the Moon

Mark Schulman

SpaceX Crew Dragon

Agenda

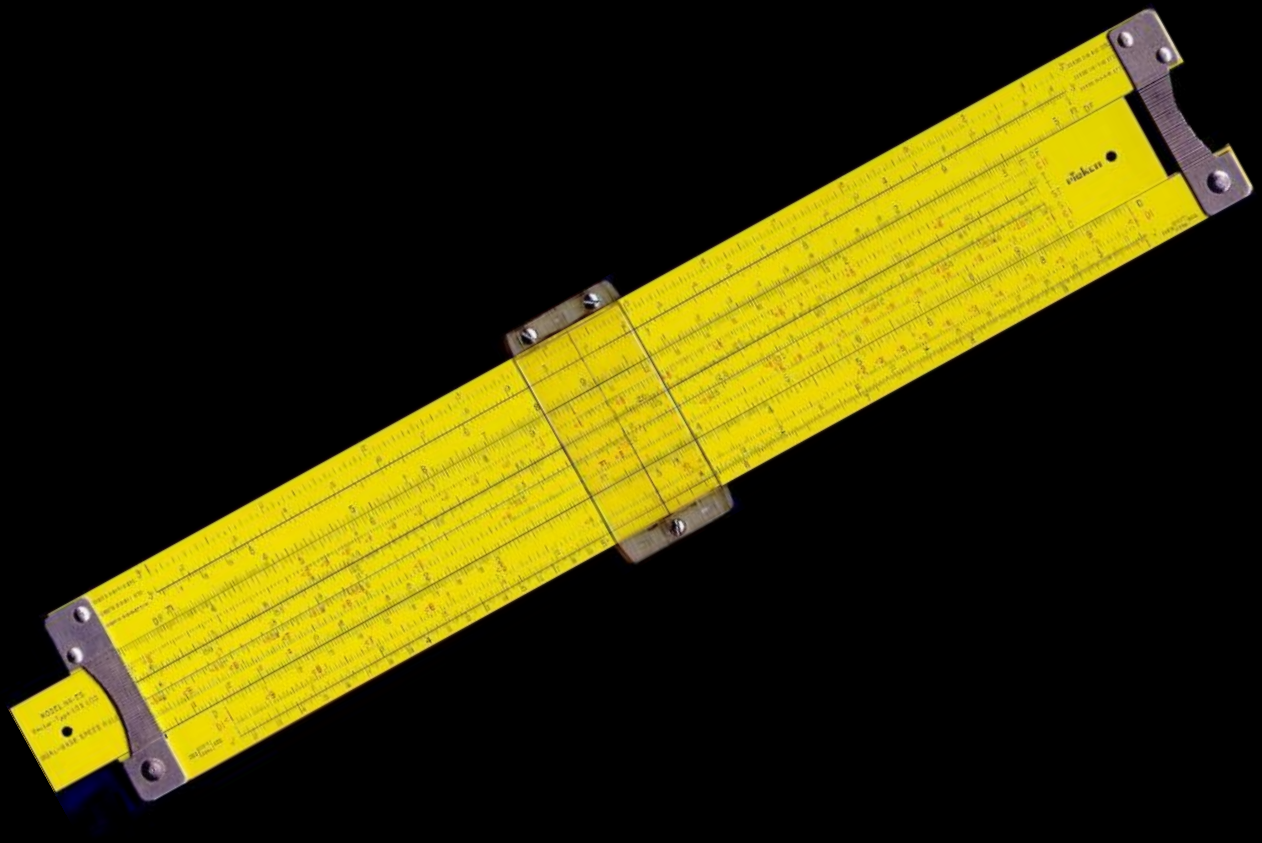
- Talk about the development of computers in the early U.S. space program, and the little-known role of how they got us to the Moon.



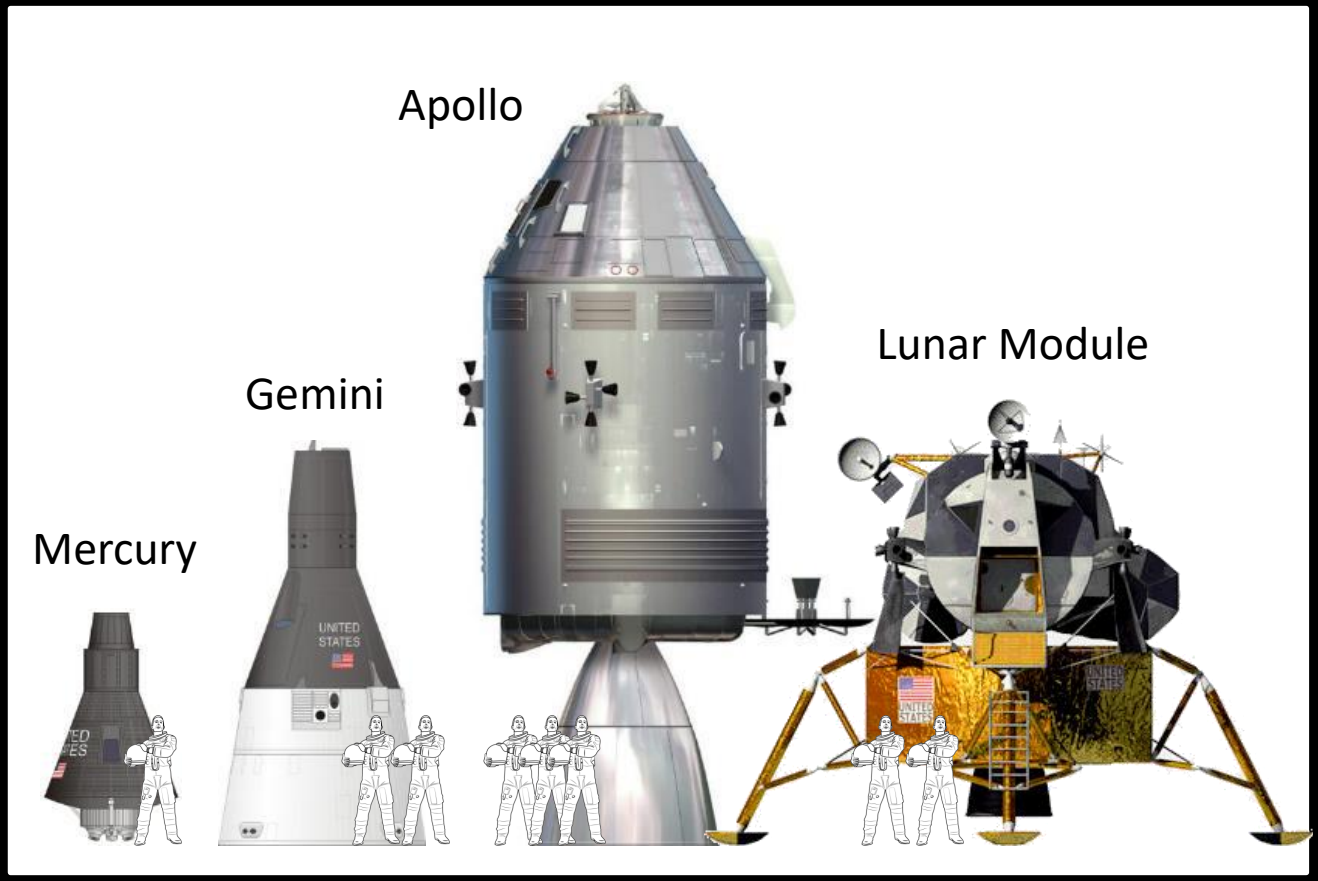
1960s Computing

NASA Real Time Computing Center, 1966

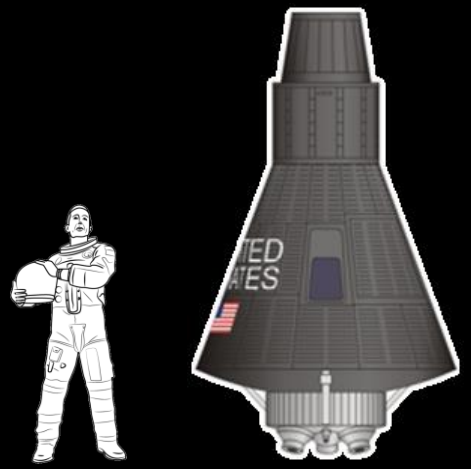
Personal Computers in 1960



Pioneering U.S. Spacecraft



Mercury

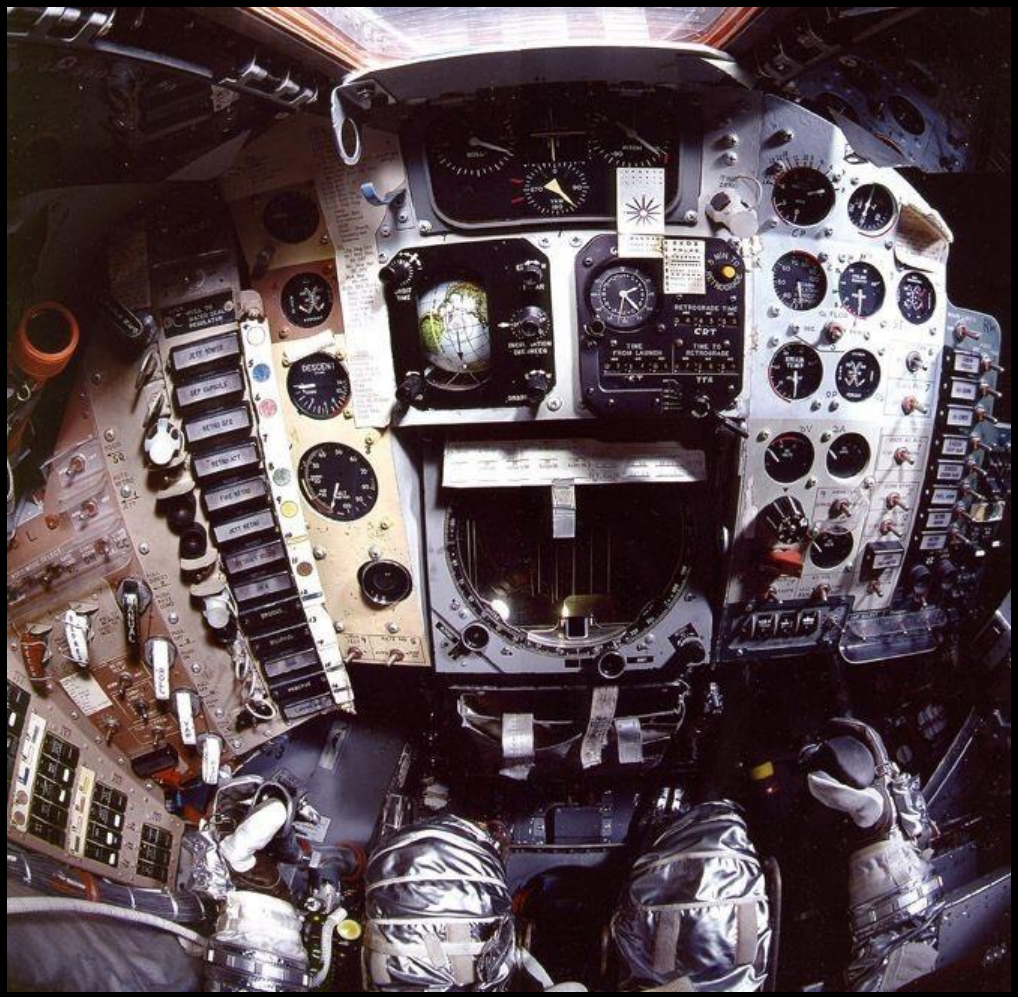


Mercury

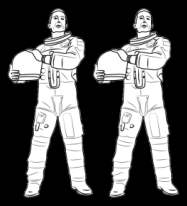
- 1961 - 1963
- 6 flights
- Goal: To put an American into space
- Launched aboard Redstone and Atlas

The Mercury Computer

- There wasn’t one.


RETROGRADE TIME
CDT
TIME FROM LAUNCH
TIME TO RETROGRADE
DESCENT

Gemini



Gemini

- 1965 - 1966
- 10 flights
- Crew of 2 (16 different astronauts)
- Launched aboard Titan II

Gemini Goals

Perfect techniques for getting to the Moon

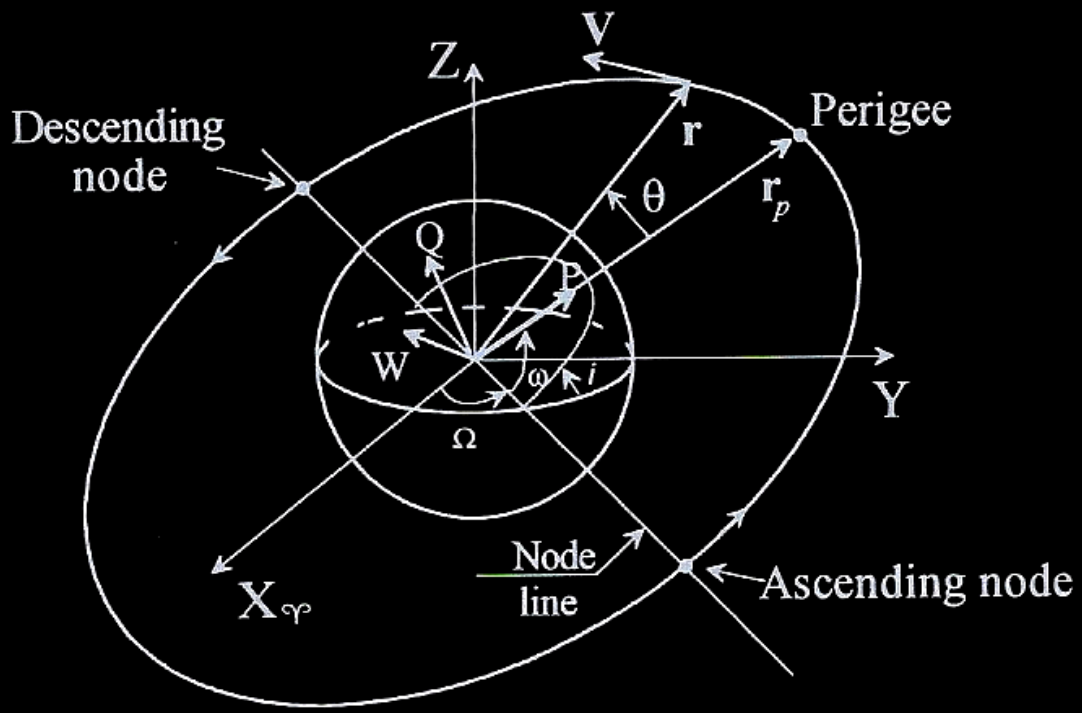
1. Prove that people can work outside the spacecraft
2. Long-duration flights
3. Navigate in space: orbit changes, rendezvous and docking

Gemini Goals

Space walks and long duration don’t require a computer

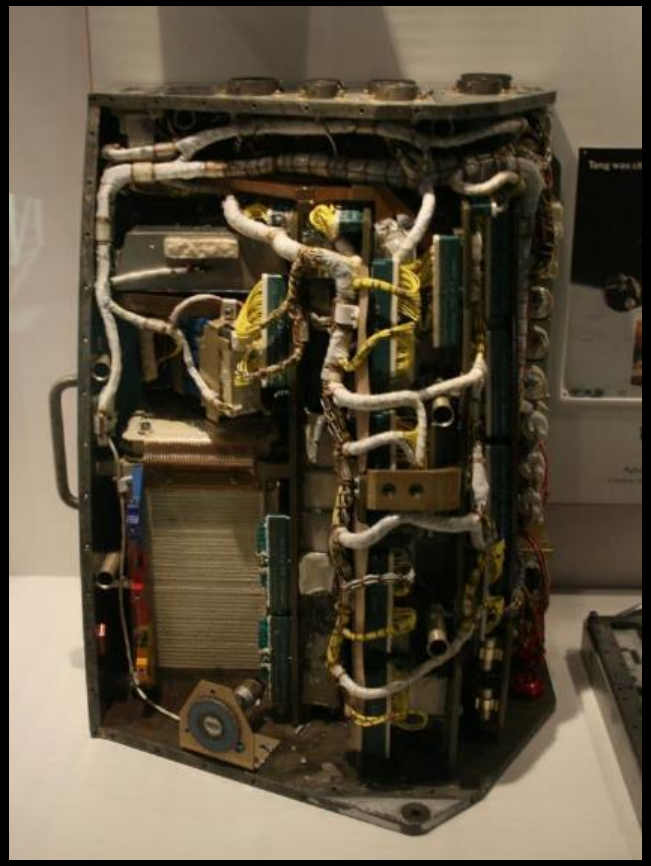
Maneuvering in Space

- There's a reason they call it rocket science

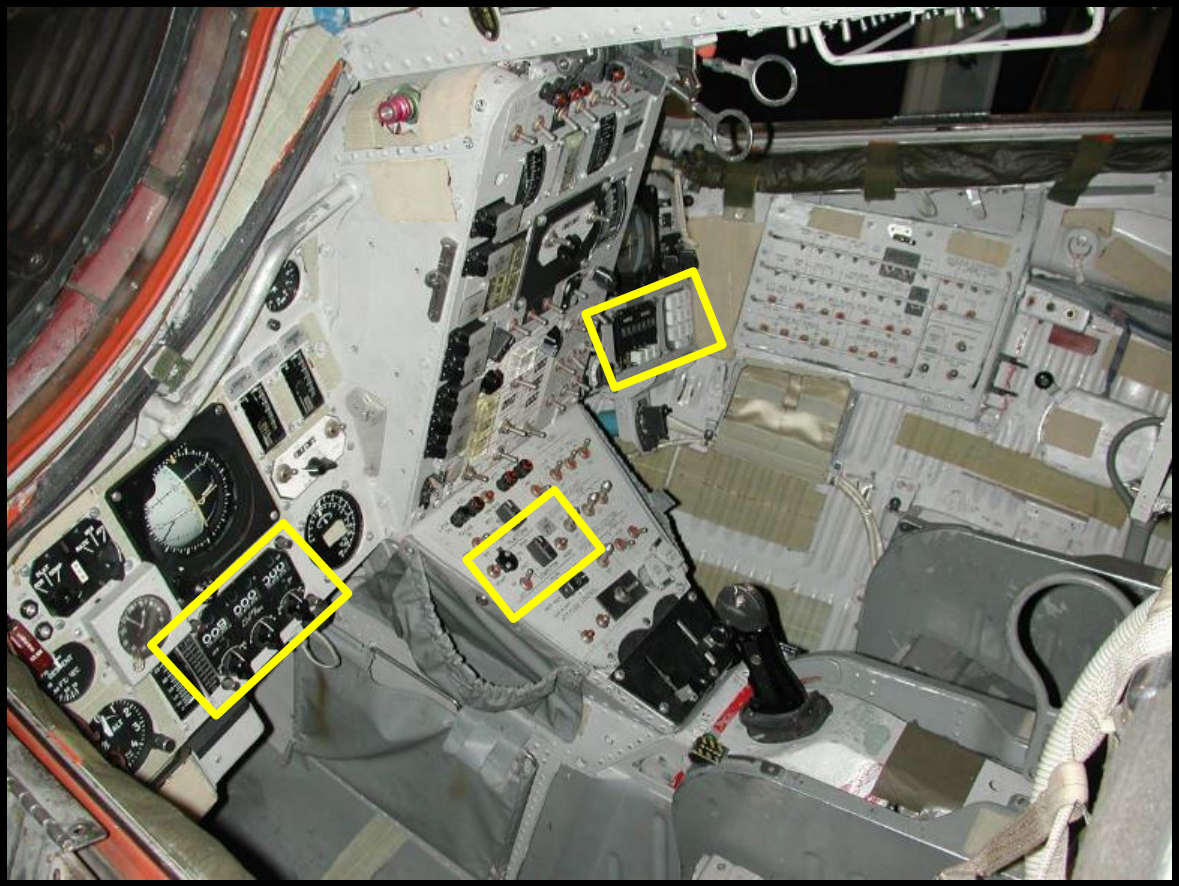


Gemini On-Board Computer (OBC)

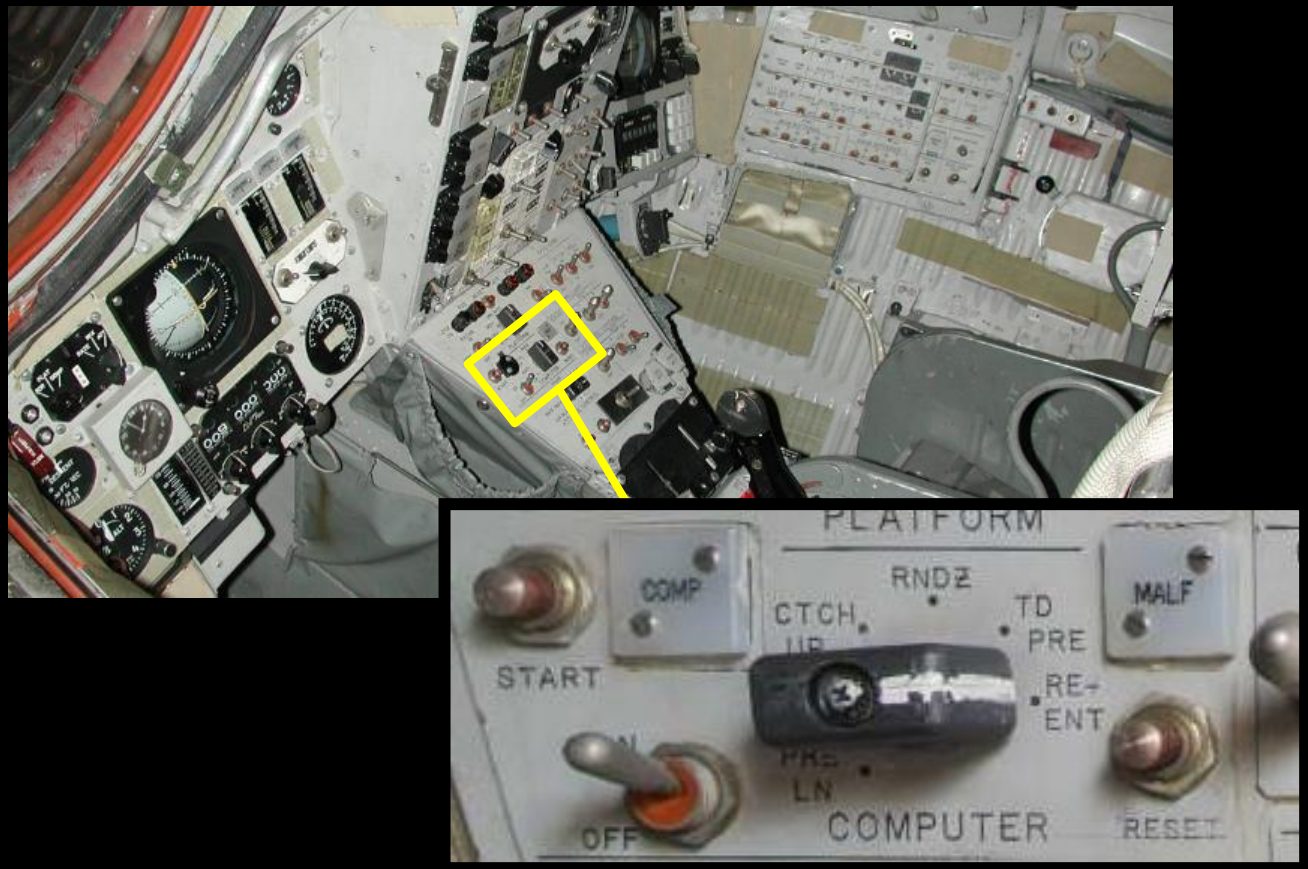
- Built by IBM Federal Systems Division
- True digital computer
- Clock speed: ~7 kHz
- Core memory, 4K words
- Weight: 59 pounds



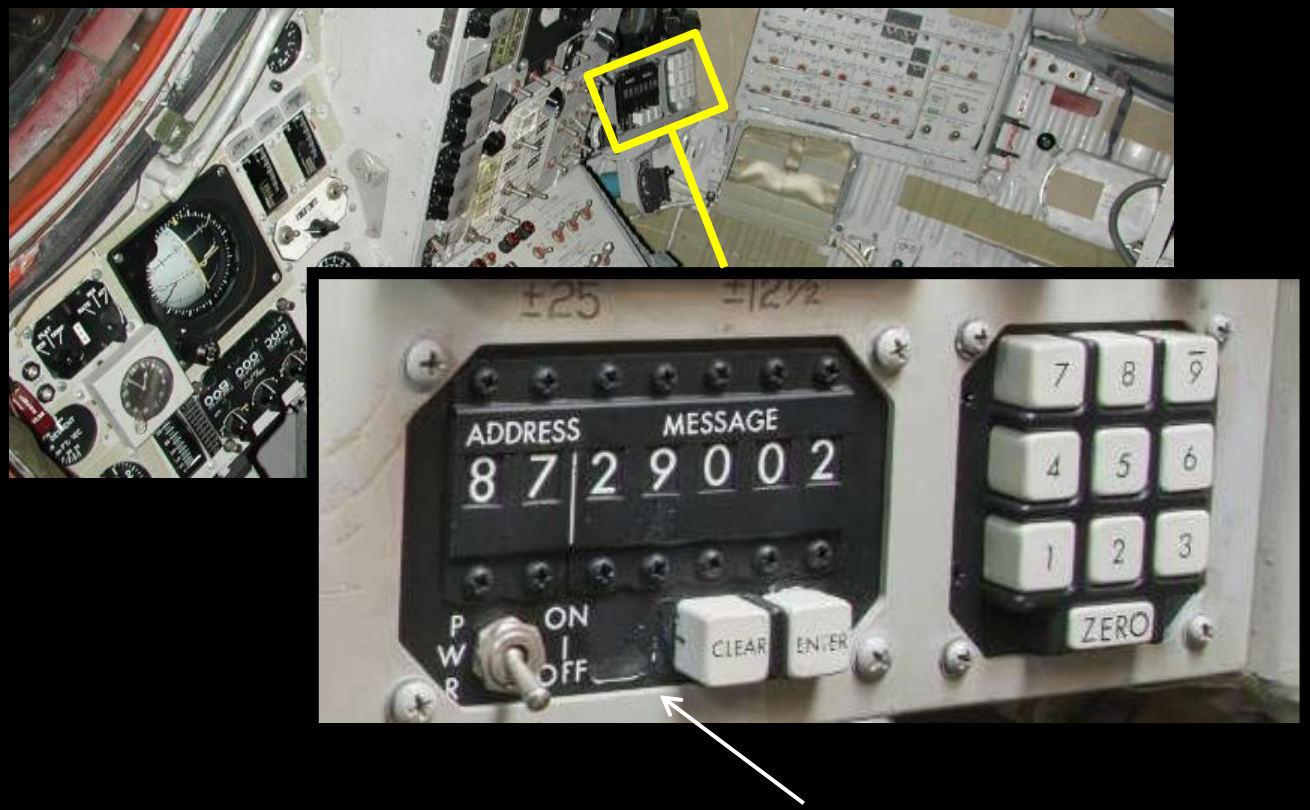
Gemini Control Panel



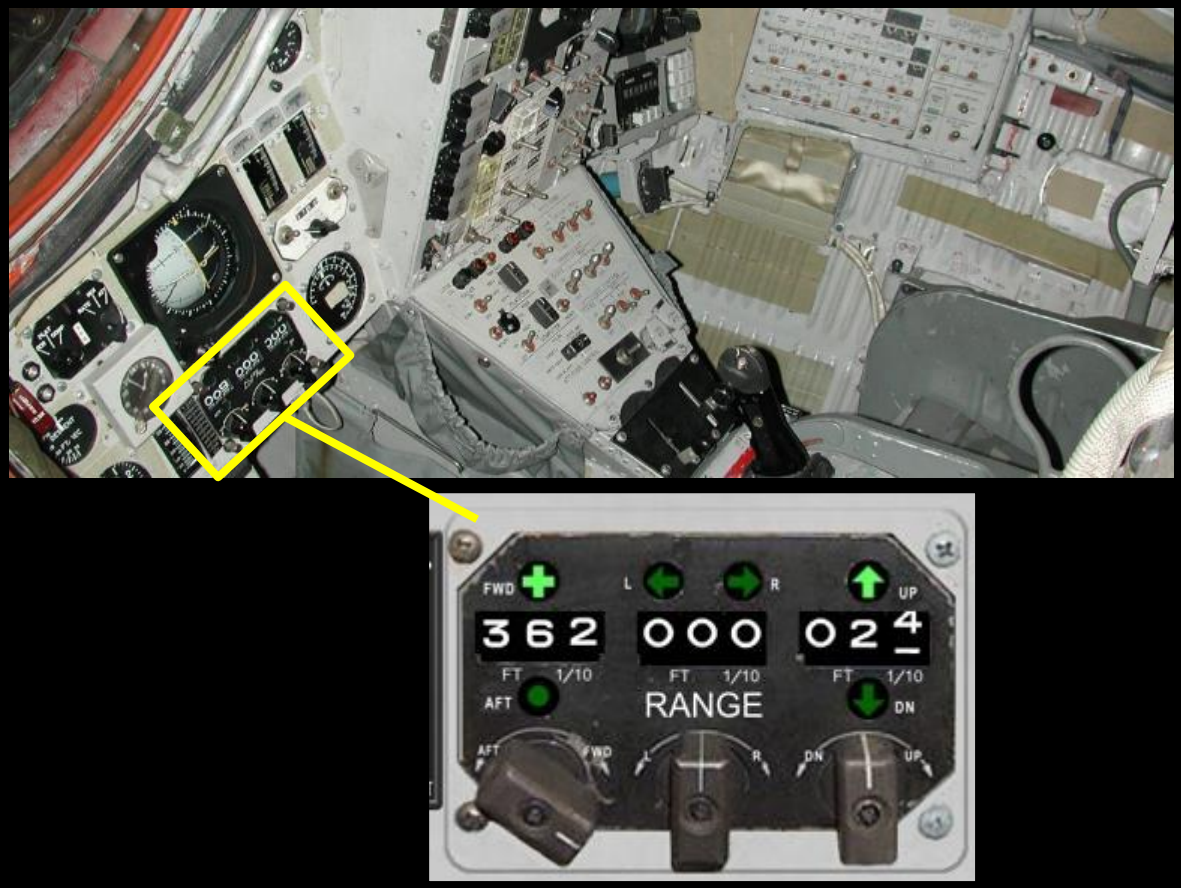
Main Computer Panel



Computer User Interface



Computer User Interface



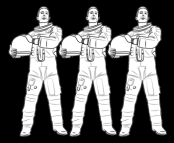
Gemini 6 and 7

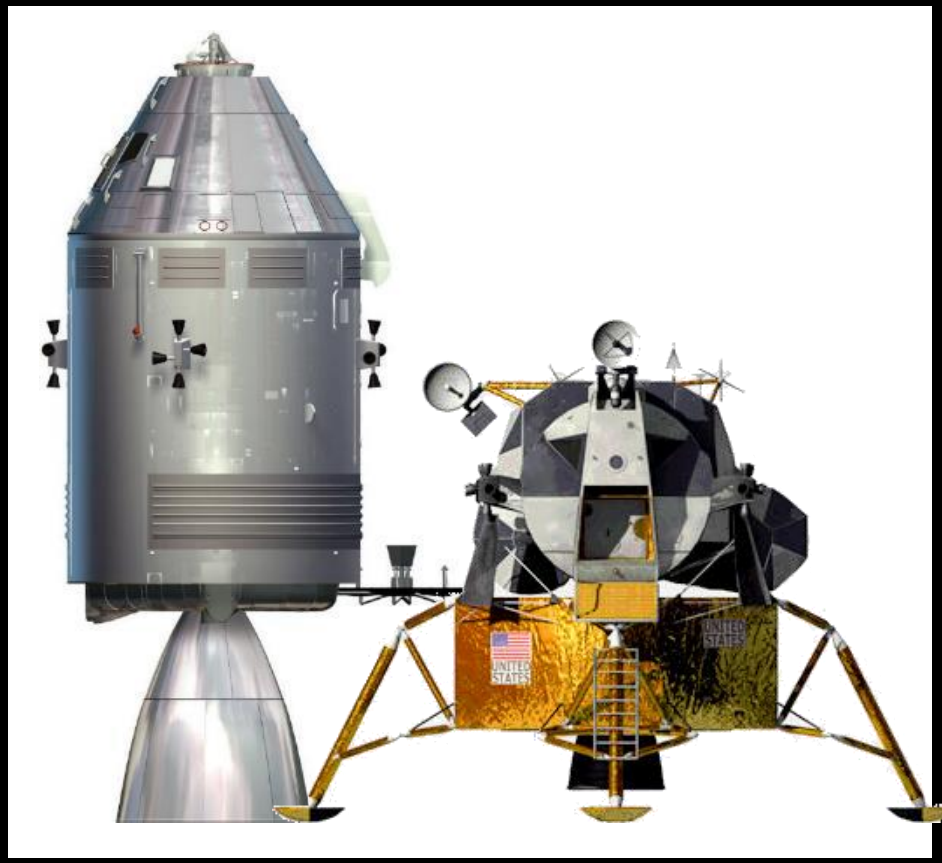
- Dec. 15, 1965

Agena Target Vehicle

- 1966
- Gemini 8, 9, 10, 11, 12

Apollo



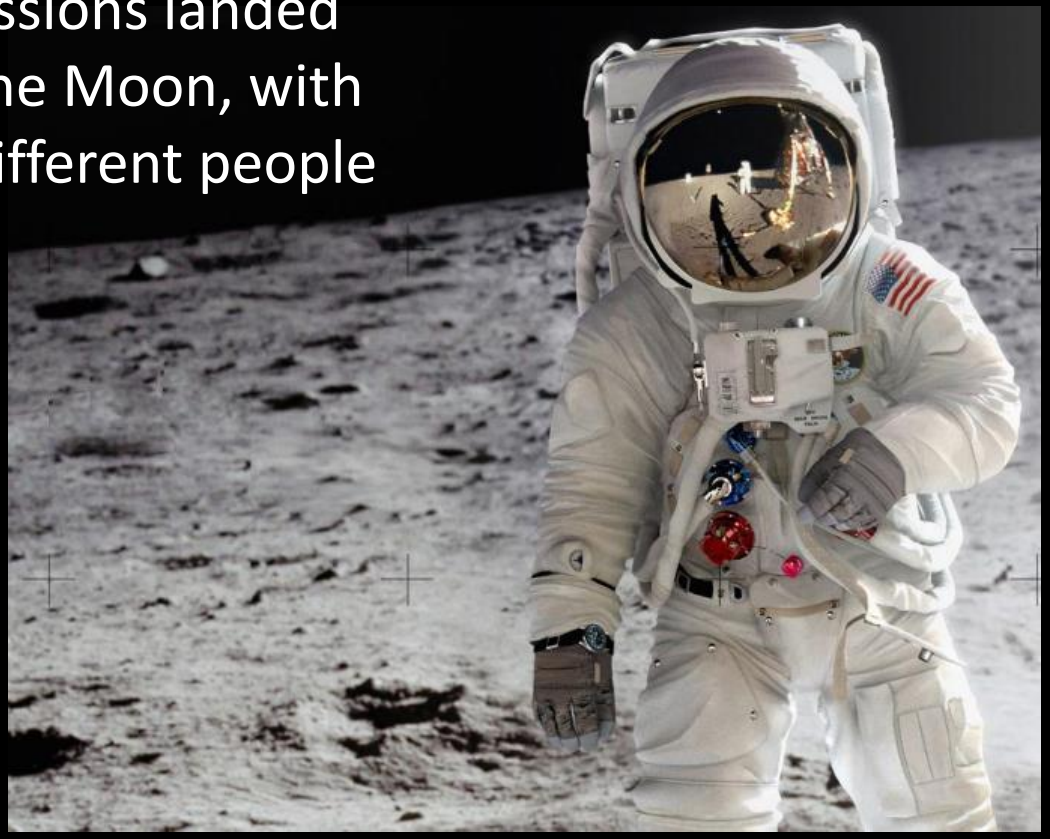


Apollo

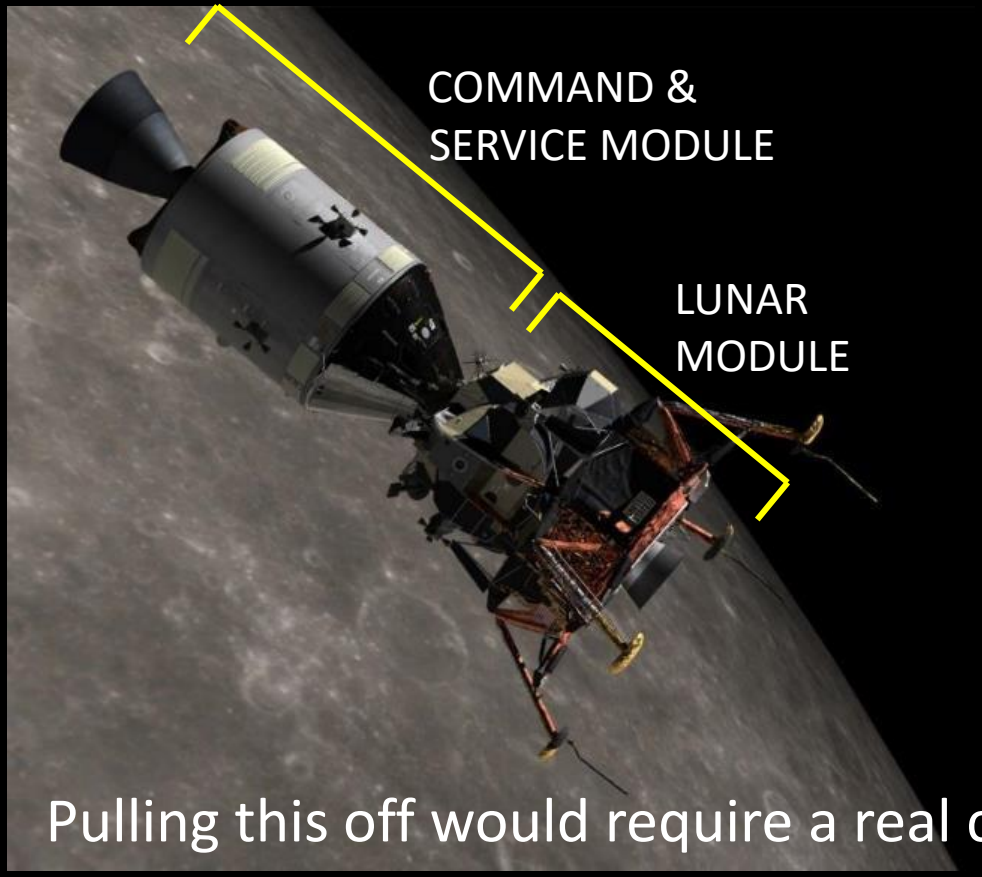
- 1968 - 1972
- 11 flights
- Crew of 3 (29 astronauts)
- Launched aboard Saturn rockets
- Goal: Land people on the Moon

1969 - 1972

6 missions landed on the Moon, with 12 different people



Apollo Spacecraft and Mission



Pulling this off would require a real computer

Computer Requirements

- Navigate from the Earth to the Moon
- Continuously update position and attitude
- Control spacecraft attitude and engines
- Perform all calculations for lunar landing, ascent, rendezvous
- Remote updates from the ground
- Real-time information display

The Apollo Guidance Computer (AGC)

- Developed by MIT
- Manufactured by Raytheon
- Development cost: $26.6 million

AGC Hardware

- 15-bit word (plus a parity bit)
- 36k ROM (core rope)
- 2k RAM
- Clock speed: ~ 40 kHz
- Weight: 70 pounds
- One in the Command Module, one in the Lunar Module

Core Rope Memory

- Wires woven through iron cores

Core Rope – How It Was Made

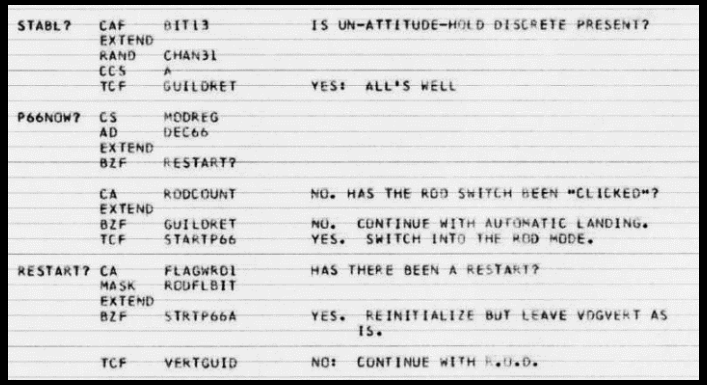
External Storage

Interfaces

- Gyroscopes and accelerometers
- Sextant and telescope
- Radar equipment
- Display and Keyboard
- Engines (main engines, plus control thrusters)
- Flight instruments

Software

- Hardware the same in both spacecraft
- Different software:
  - Command Module: Colossus
  - Lunar Module: Luminary
- 1400-man years of effort, peak workforce of 350



```
STABL?    CAF     BIT13          IS UN-ATTITUDE-HOLD DISCRETE PRESENT?
          EXTEND
          RAND    CHAN31
          CCS     A
          TCF     GUILDRET       YES:  ALL'S WELL

P66NOW?   CS      MODREG
          AD      DEC66
          EXTEND
          BZF     RESTART?

          CA      RODCOUNT       NO.  HAS THE ROD SWITCH BEEN "CLICKED"?
          EXTEND
          BZF     GUILDRET       NO.  CONTINUE WITH AUTOMATIC LANDING.
          TCF     STARTP66       YES.  SWITCH INTO THE ROD MODE.

RESTART?  CA      FLAGWRD1       HAS THERE BEEN A RESTART?
          MASK    RODFLBIT
          EXTEND
          BZF     STRTP66A       YES.  REINITIALIZE BUT LEAVE VDGVERT AS
                                        IS.

          TCF     VERTGUID       NO:  CONTINUE WITH R.O.D.
```

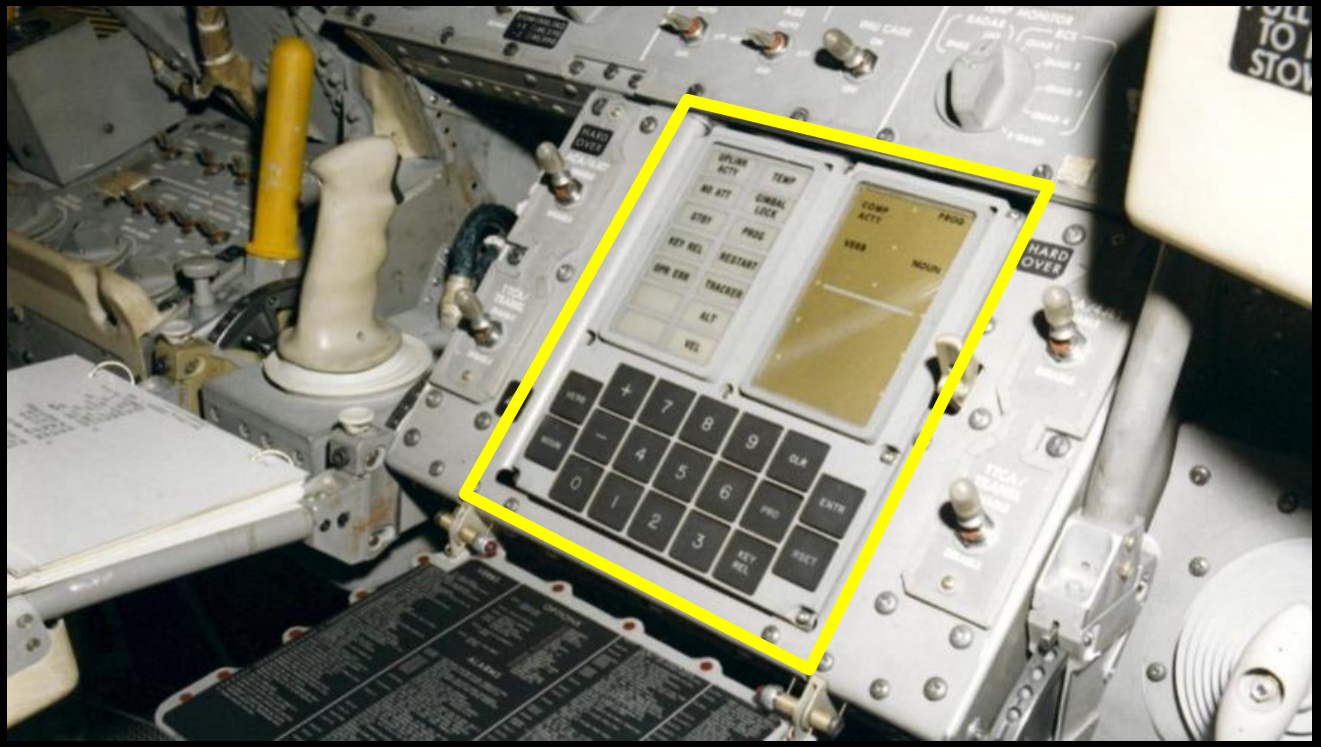
Why the AGC Software was Interesting

- Real-time processing
- Virtual machine interpreter
- Absolutely had to work

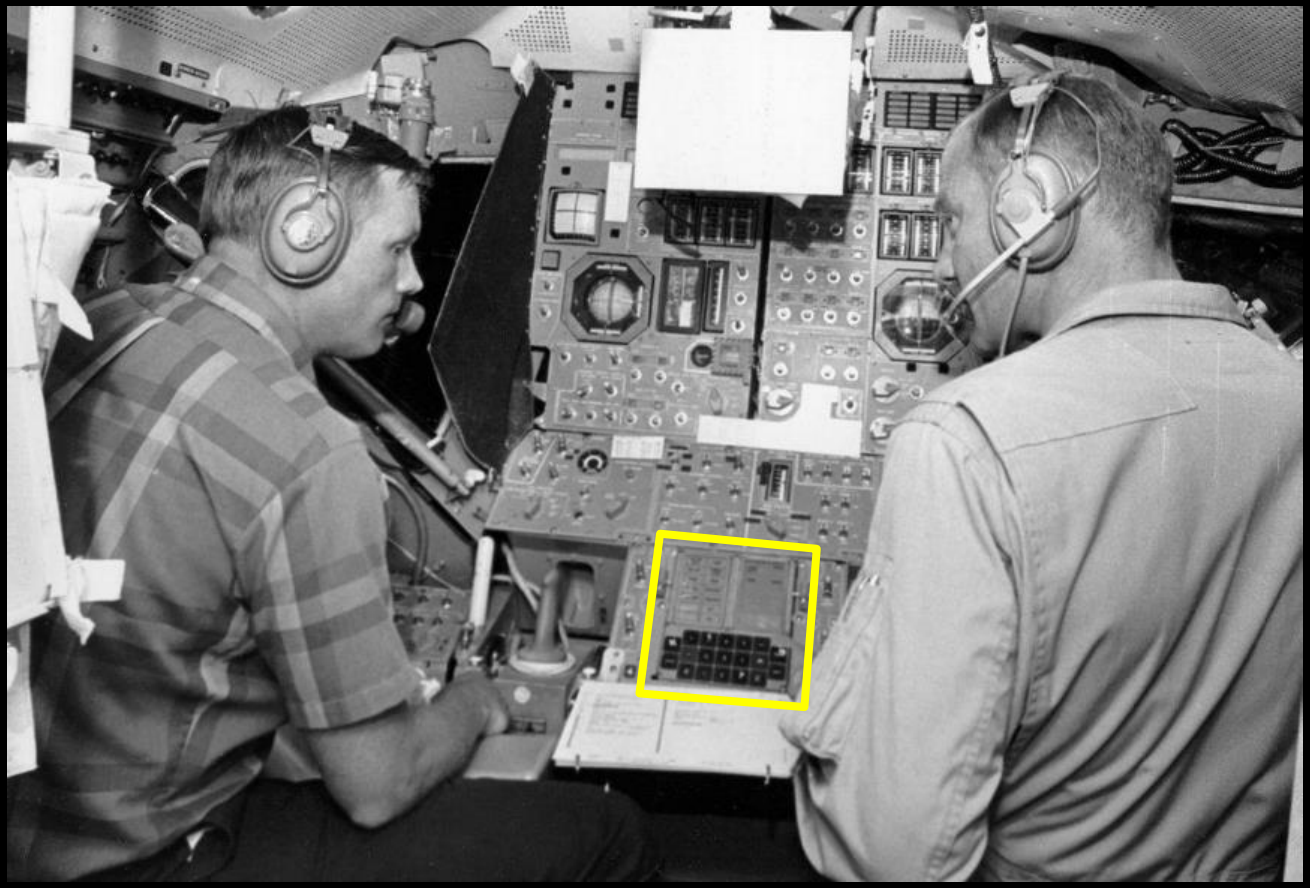
Interface

- So how did the crew interact with the computer?
- Mouse/keyboard/widescreen display?

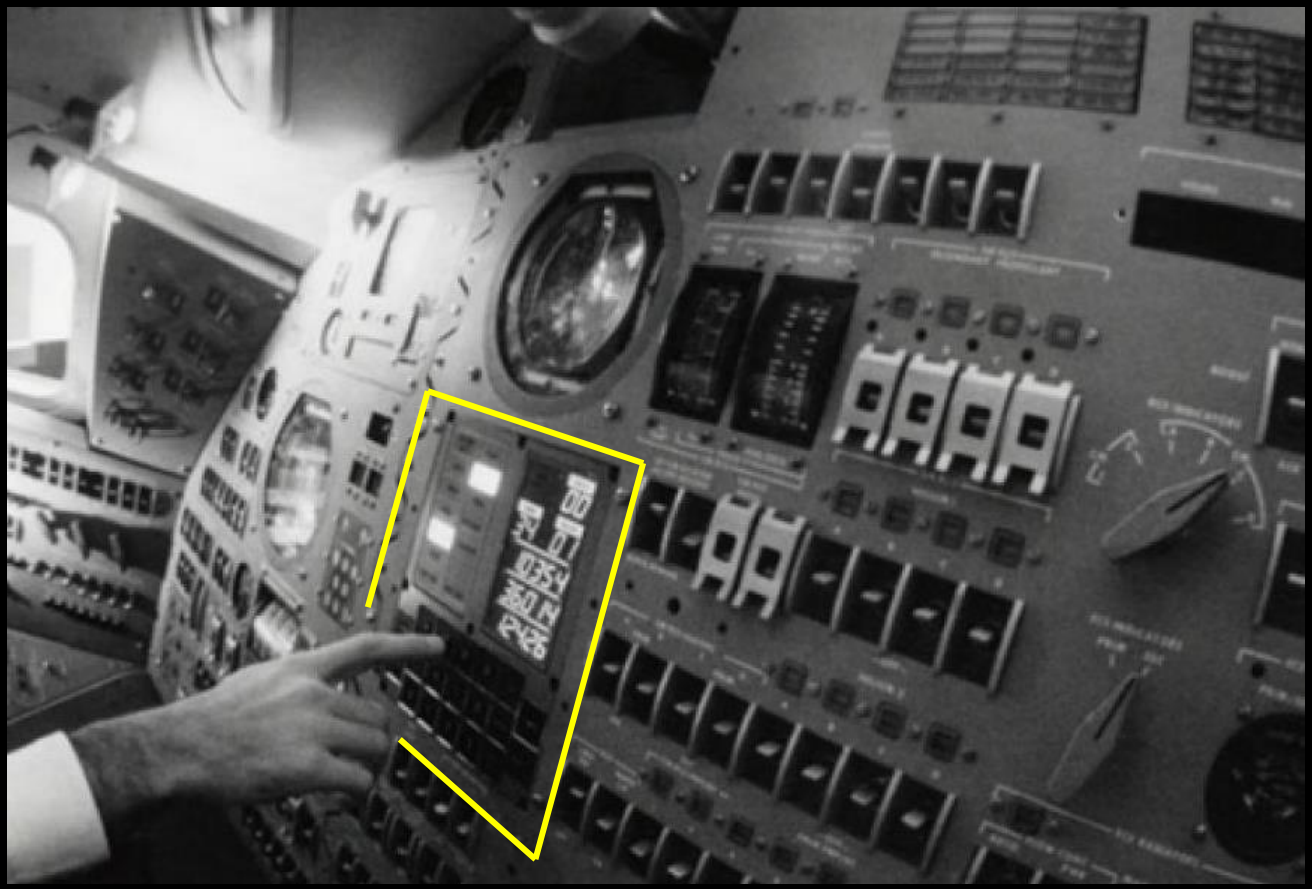
Display/Keyboard (DSKY)



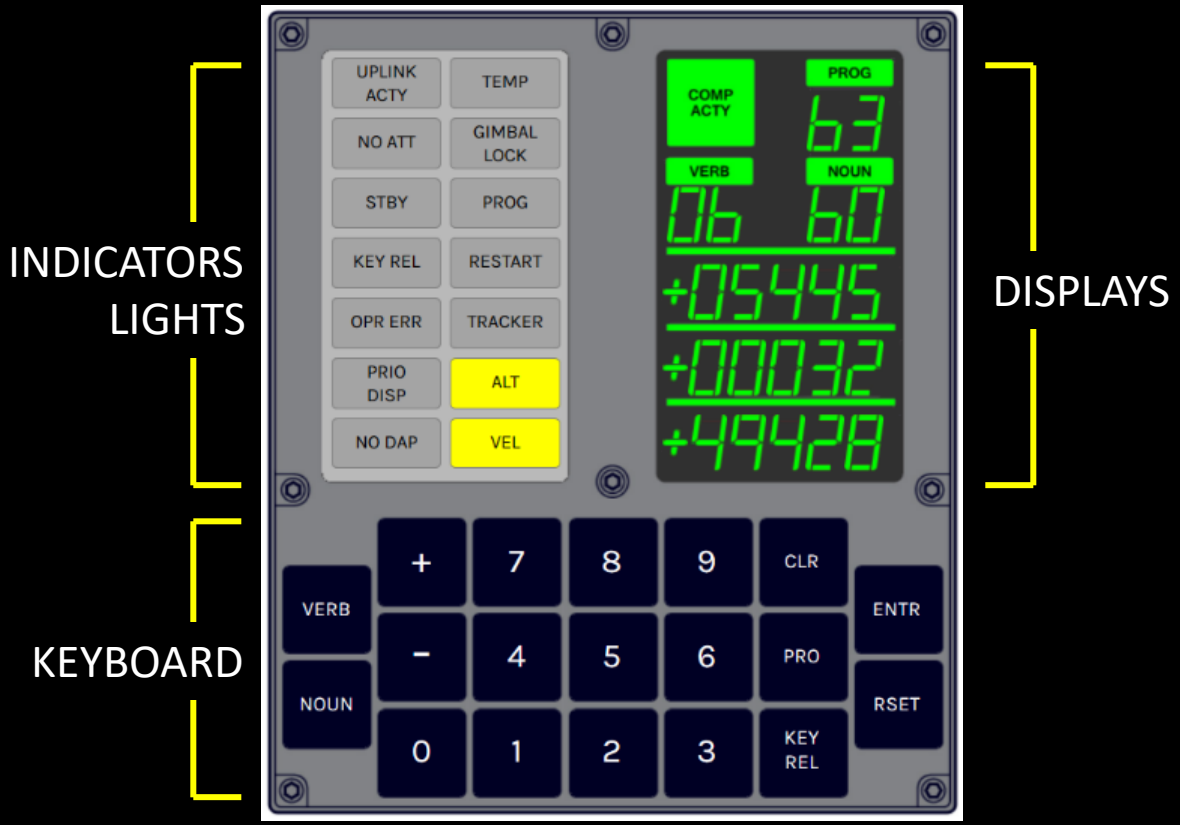
DSKY in the Lunar Module



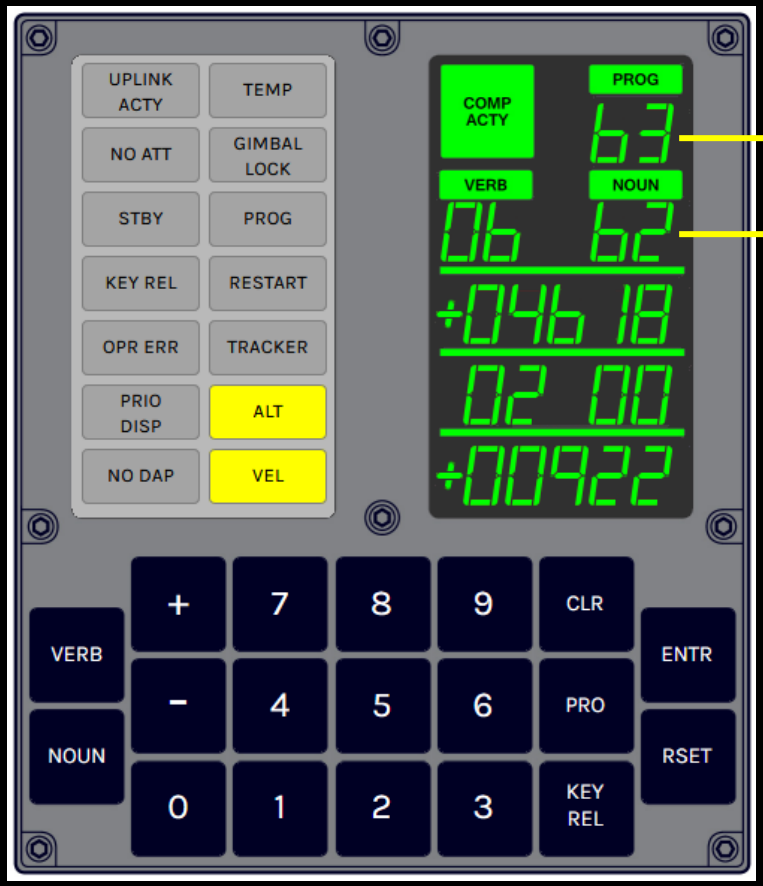
DSKY in the Command Module (1 of 2)



The DSKY (Display and Keyboard)



Communicating with the AGC



Program

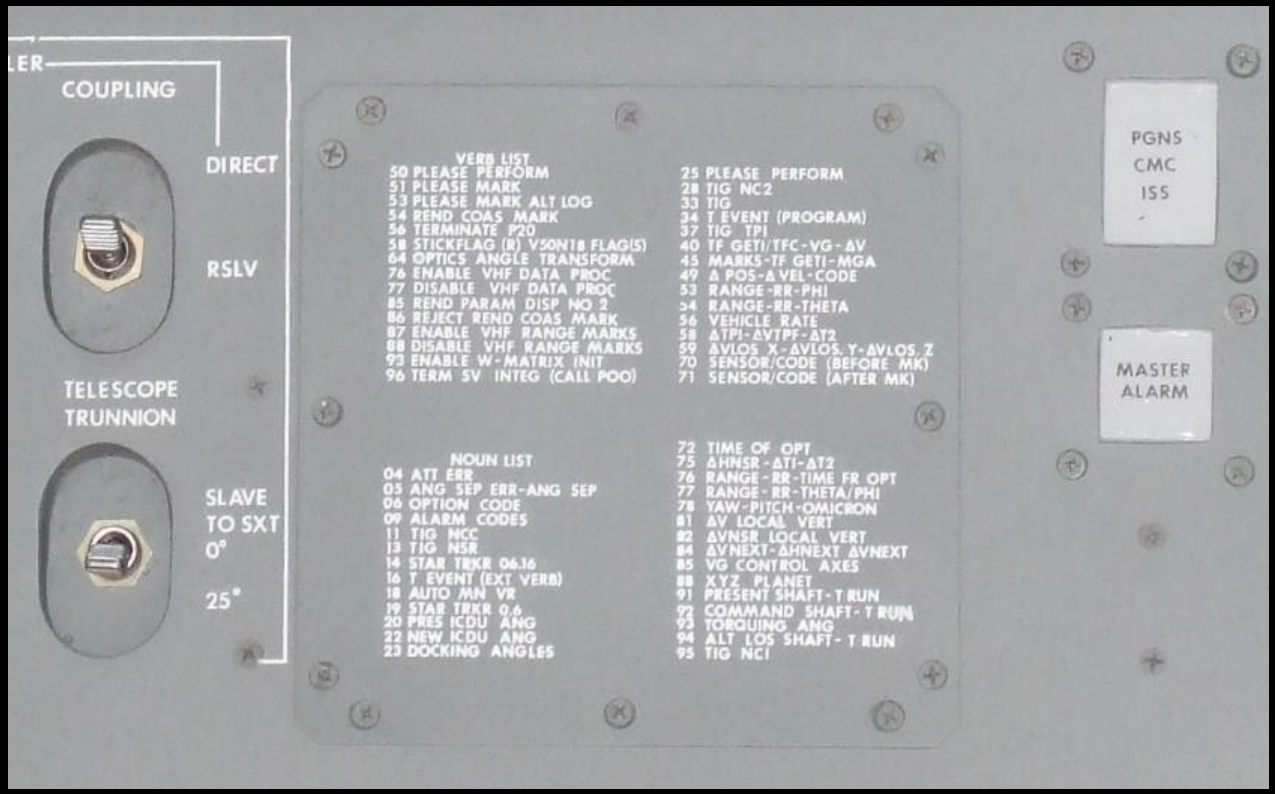
Verb and Noun

Registers

Verbs and Nouns

- Verbs: Command to do something
- Noun: Piece of data to do it with

DSKY Cheat Sheets



FLIGHT PLAN

CDR	LM	LMP	MCC-H
P20 RENDEZVOUS NAVIGATION ACQUIRE AND TRACK CSM MAINTAIN RR TRACKING ATTITUDE SLEW STEERABLE ANT ANT P 58, Y -38		V32 - MARKS = 5 V32 - MARKS = 10 RCS TEMP/PRESS/QTY CK AFT OMNI, PCM LBR	CSM: R 0, P 180/271, Y 0
		FINAL CSI COMPUTATION V90 OUT OF PLANE V47 INITIALIZE AGS (PCM-HI)	
V83 SET ORDEAL P41 RCS THRUSTING		CSI DATA TO CSM (PCM-LO) LOAD AGS ΔV	
	RCS, CSI	TIG: 125:21:19 BT: 45 SEC ΔV: 49.5 FPS	
VERIFY RESIDUALS Z AXIS BORESIGHT		V76, V67, VHF RANGING P33 CDH PRETHRUST V93 MARKS = 4 V32 MARKS = 3 V90 OUT OF PLANE V32 MARKS = 10 P30 EXTERNAL ΔV V90 OUT OF PLANE	LM FDAI: R 0, P 187.8, Y 0
MAINTAIN RR AND VHF TRACKING ATTITUDE P41 RCS THRUSTING		LOAD AGS ΔV	
	RCS, PLANE CHANGE	TIG: 125:50:28 ΔV=NOMINALLY ZERO	
		V76, P33 CDH PRETHRUST	

Sample DSKY Operations

1. Lamp test
2. Display the current mission time
3. Key in weights of both spacecraft

Landing on the Moon

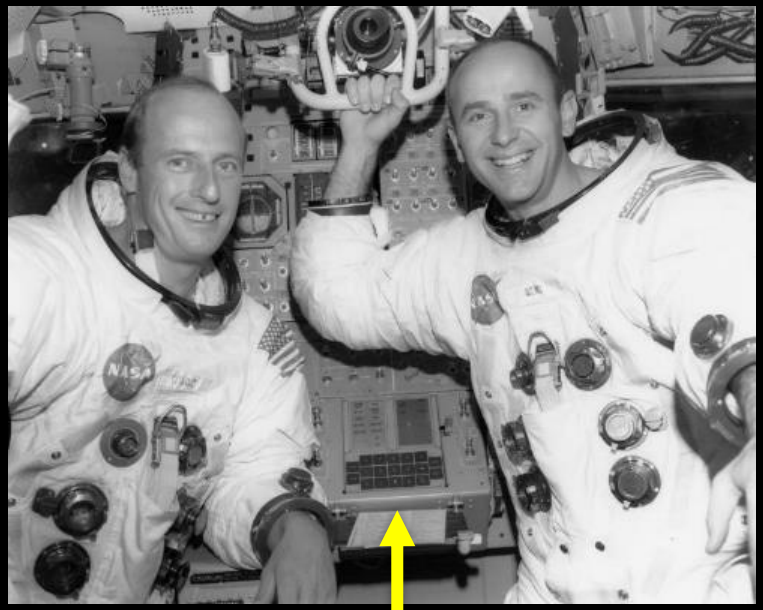
- One attempt, no second chances!
- AGC handles all guidance and control
- Three programs: P63, P64, P66

Apollo 12 Landing

- November 19, 1969 - Ocean of Storms
- Pete Conrad, Dick Gordon, Al Bean
- First precision landing

Apollo 12 Dramatis Personae

"Pete" Conrad
Commander



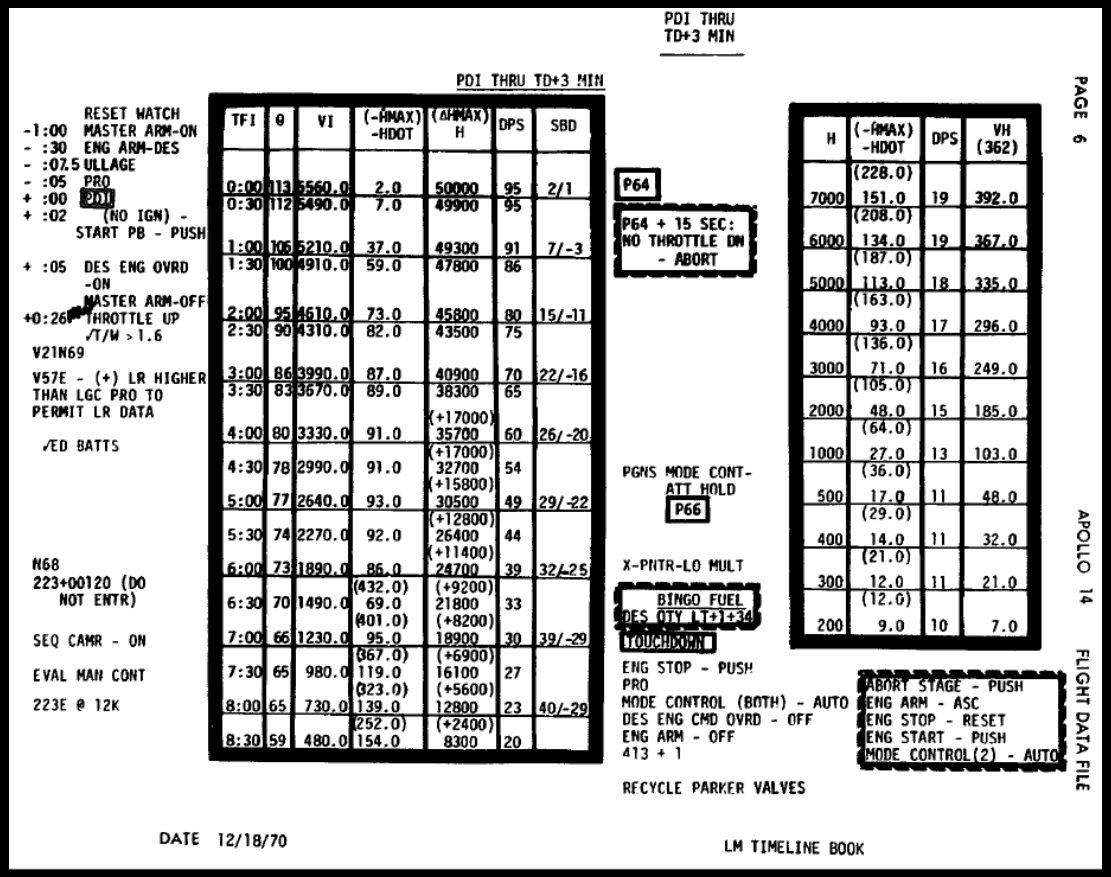
Al Bean
LM Pilot

Apollo
Guidance
Computer

P63 - Braking Phase

- Started 10-20 minutes before descent (PDI)
- Computes landing site targeting
- Ignition begins at ...
  - 50,000 feet altitude
  - 240 miles from site
  - 5,540 feet/sec (3,777 mph)
  - 12 minutes from landing

Landing Cue Cards



PDI THRU TD+3 MIN

PDI THRU TD+3 MIN

RESET WATCH
-1:00 MASTER ARM-ON
- :30 ENG ARM-DES
- :07.5 ULLAGE
- :05 PRO
+ :00 PDI
+ :02 (NO IGN) - START PB - PUSH

+ :05 DES ENG OVRD -ON
MASTER ARM-OFF
+0:26 THROTTLE UP
√T/W > 1.6

V21N69

V57E - (+) LR HIGHER THAN LGC PRO TO PERMIT LR DATA

√ED BATTS

N68
223+00120 (DO NOT ENTR)

SEQ CAMR - ON

EVAL MAN CONT

223E @ 12K

TFI	θ	VI	(-ḣMAX) -HDOT	(ΔḣMAX) 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	
				(+17000)		
4:00	80	3330.0	91.0	35700	60	26/-20
				(+17000)		
4:30	78	2990.0	91.0	32700	54	
				(+15800)		
5:00	77	2640.0	93.0	30500	49	29/-22
				(+12800)		
5:30	74	2270.0	92.0	26400	44	
				(+11400)		
6:00	73	1890.0	86.0	24700	39	32/-25
			(432.0)	(+9200)		
6:30	70	1490.0	69.0	21800	33	
			(401.0)	(+8200)		
7:00	66	1230.0	95.0	18900	30	39/-29
			(367.0)	(+6900)		
7:30	65	980.0	119.0	16100	27	
			(323.0)	(+5600)		
8:00	65	730.0	139.0	12800	23	40/-29
			(252.0)	(+2400)		
8:30	59	480.0	154.0	8300	20	

P64

P64 + 15 SEC: NO THROTTLE DN - ABORT

PGNS MODE CONT-ATT HOLD
P66

X-PNTR-LO MULT

BINGO FUEL
DES QTY LT+1+34
TOUCHDOWN

ENG STOP - PUSH
PRO
MODE CONTROL (BOTH) - AUTO
DES ENG CMD OVRD - OFF
ENG ARM - OFF
413 + 1

RECYCLE PARKER VALVES

H	(-ḣMAX) -HDOT	DPS	VH (362)
	(228.0)		
7000	151.0	19	392.0
	(208.0)		
6000	134.0	19	367.0
	(187.0)		
5000	113.0	18	335.0
	(163.0)		
4000	93.0	17	296.0
	(136.0)		
3000	71.0	16	249.0
	(105.0)		
2000	48.0	15	185.0
	(64.0)		
1000	27.0	13	103.0
	(36.0)		
500	17.0	11	48.0
	(29.0)		
400	14.0	11	32.0
	(21.0)		
300	12.0	11	21.0
	(12.0)		
200	9.0	10	7.0

ABORT STAGE - PUSH
ENG ARM - ASC
ENG STOP - RESET
ENG START - PUSH
MODE CONTROL(2) - AUTO

PAGE 6

APOLLO 14 FLIGHT DATA FILE

DATE 12/18/70

LM TIMELINE BOOK

P64 - Approach Phase

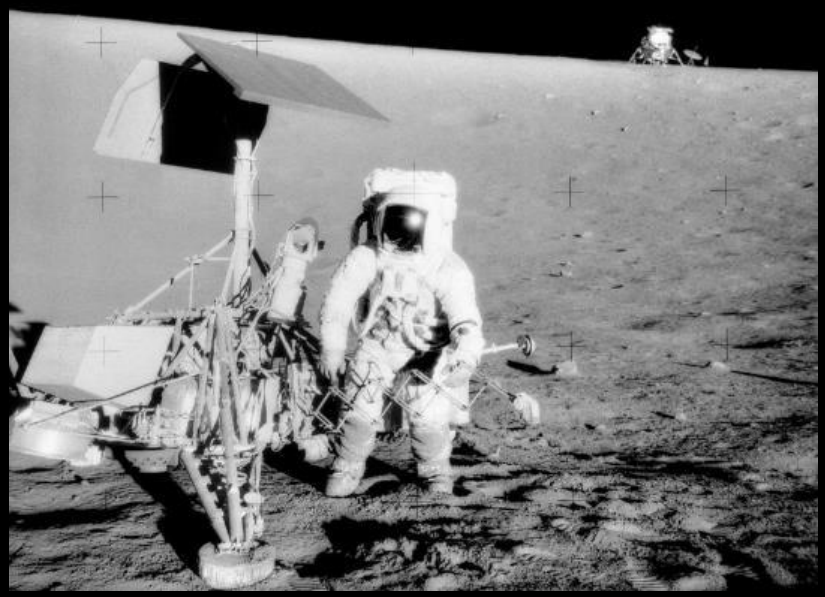
- Computer runs P64 automatically ...
  - 7,000 feet altitude
  - 700 feet/second (477 mph)
  - 2 miles from landing site
- First view of landing site

P66 - Landing Phase

- Computer runs P66 when crew flips a switch ...
  - 300 feet altitude
  - ~6 feet/second (4 mph)
- Seconds until landing
- Computer no longer targeting

Apollo 12 and Surveyor 3

- One of the goals: retrieve parts from Surveyor 3, landed 2.5 years before

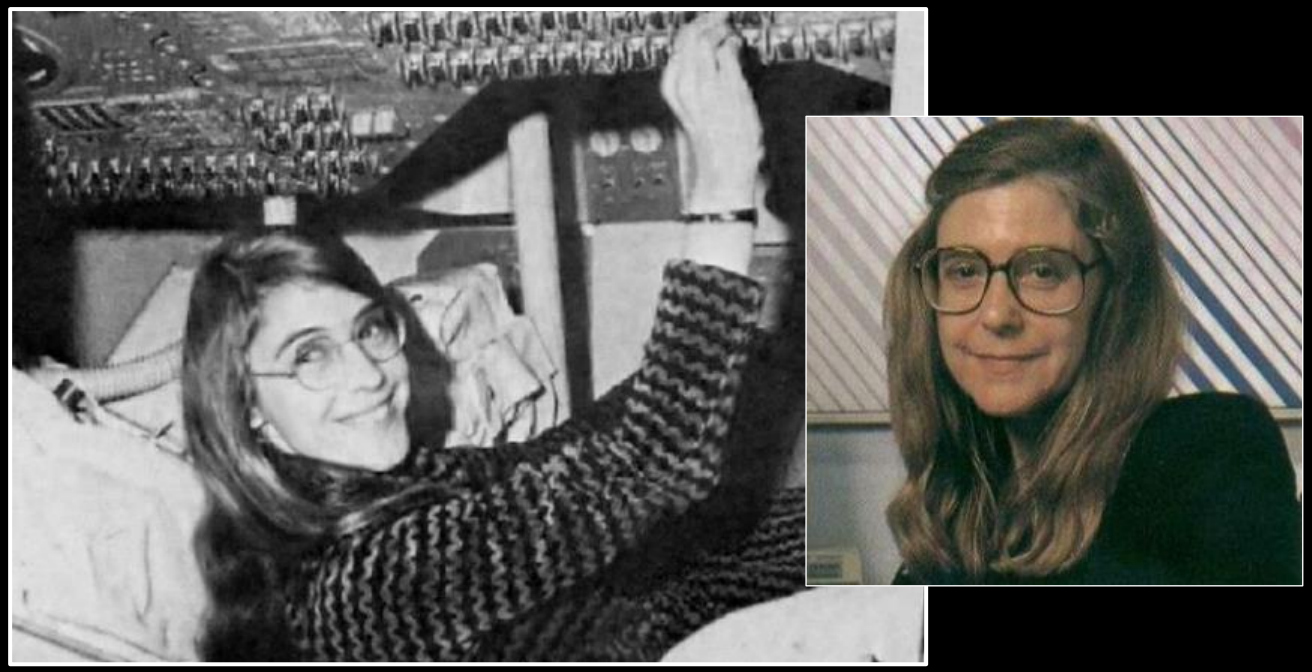


A Few Pioneering Things

- Logic built entirely with integrated circuits
- Priority multitasking
- Digital fly-by-wire
- Digital autopilot
- Discipline of software engineering ♦

Margaret Hamilton

- Director of Software Engineering Division of MIT's Instrumentation Lab

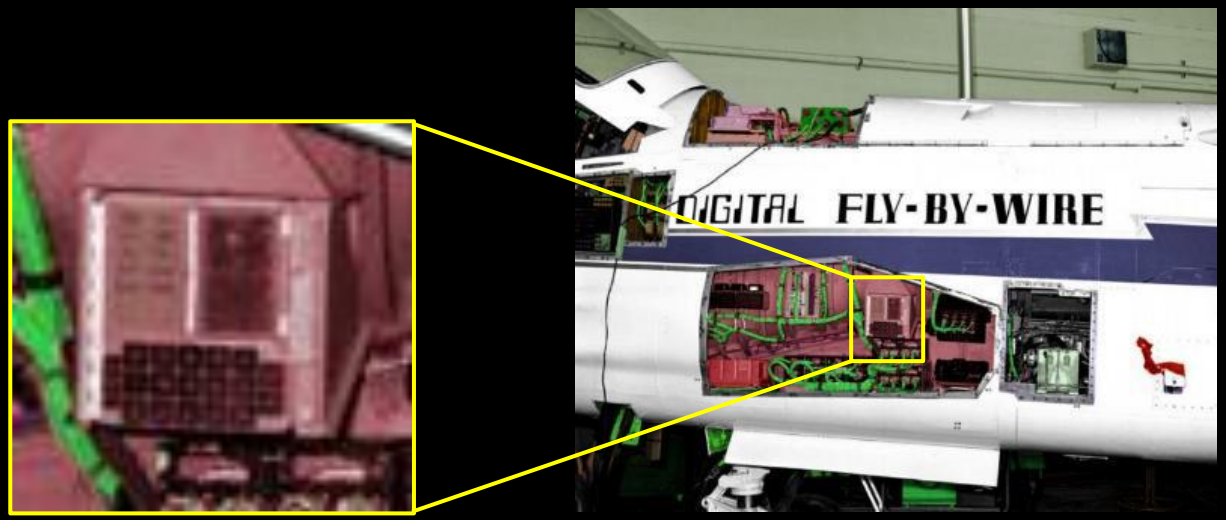


Margaret Hamilton

Presidential Medal of Freedom, 2016

Legacy of the AGC

- Already “bleeding edge” by the end of the Apollo program



Abort Guidance Systems

- Simple backup computer
- Pronounced “ags”

The AGC in Popular Culture

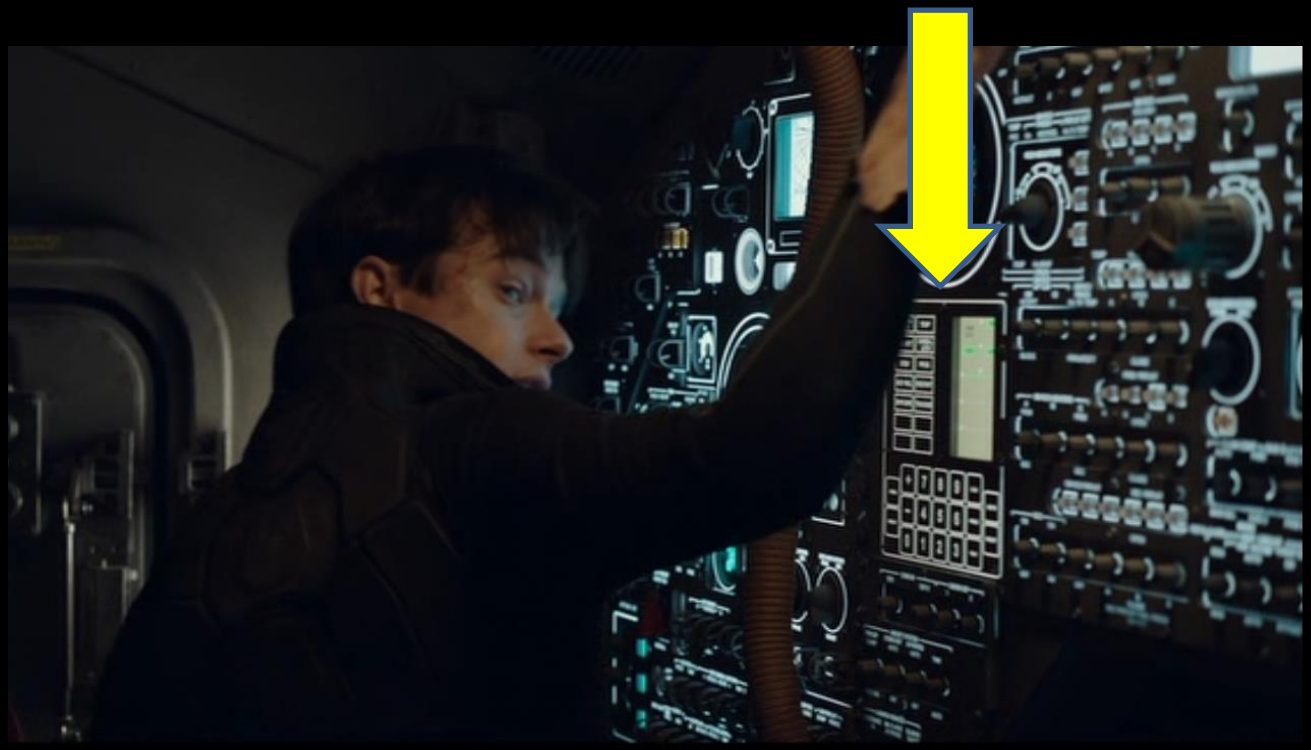
Apollo 13

1995

Valerian and the City of a Thousand Planets

2017

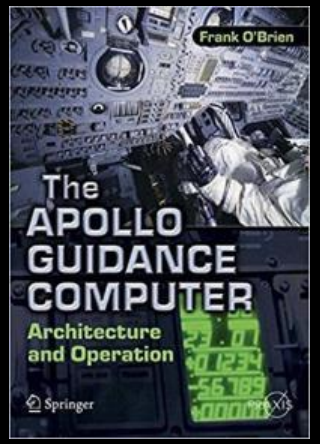
Valerian and the City of a Thousand Planets



Reproductions

Explore More

- *The Apollo Guidance Computer*, by Frank O'Brien
- Virtual AGC
  `http://www.ibiblio.org/apollo`
- AGC source code
  `https://github.com/chrislgarry/Apollo-11`
- YouTube: CuriousMarc



Questions?

Computers to the Moon

Mark Schulman
Central Florida Computer Society

marks@schulmans.com

apcug
An International Association of Technology & Computer User Groups