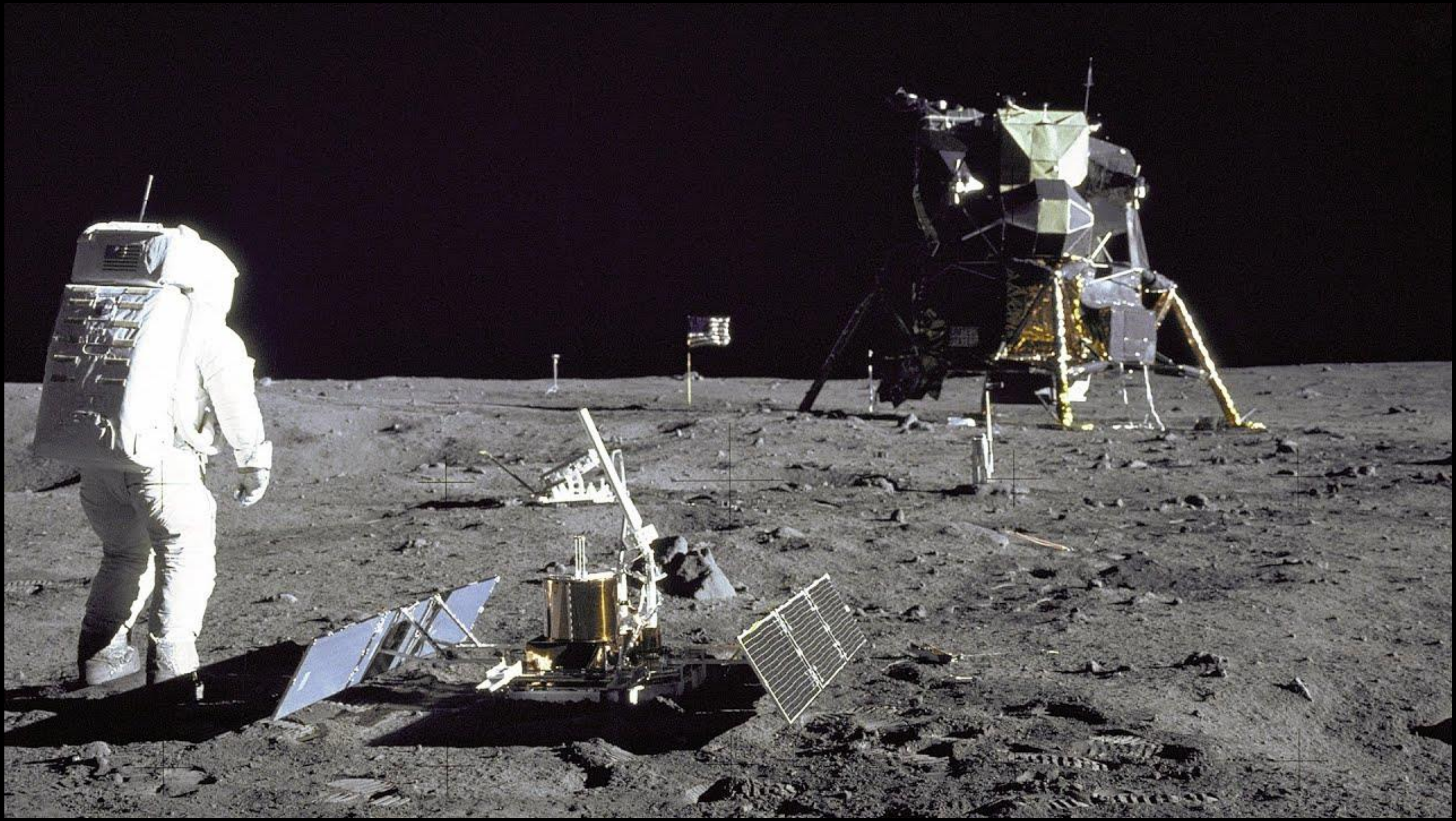
Computers to the Moon

Mark Schulman

Agenda

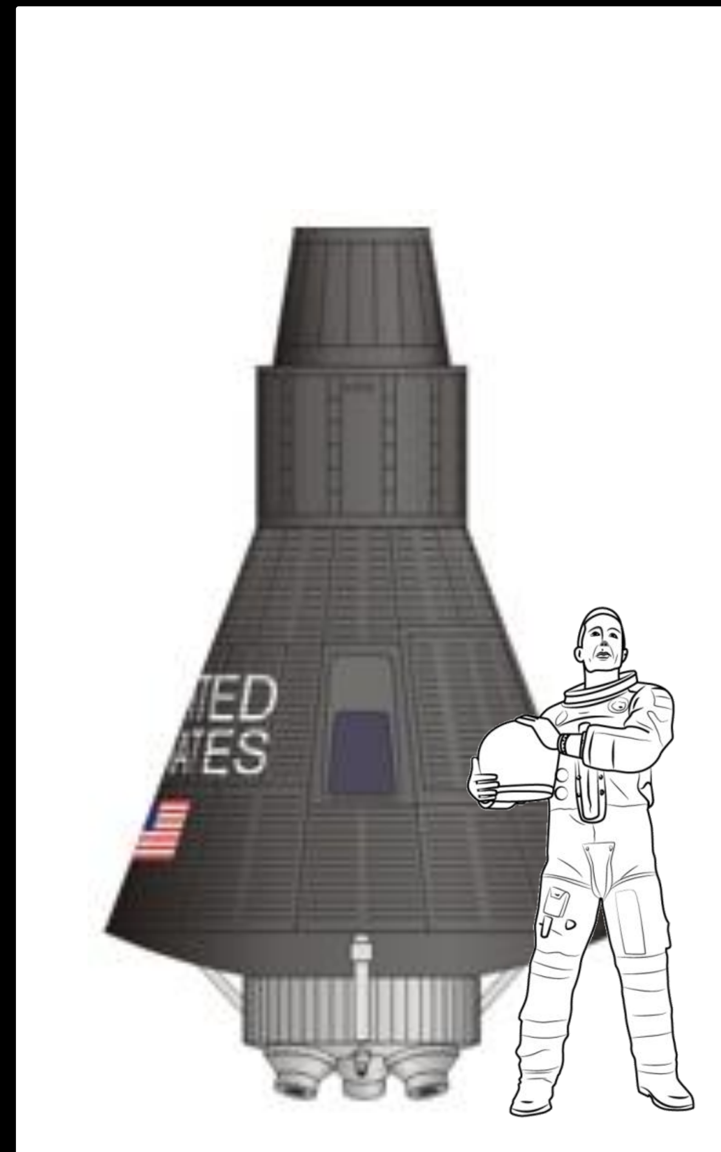
Talk about the little-known role of the computer that got us to the Moon and learn how it worked.



Dawn of the Space Age

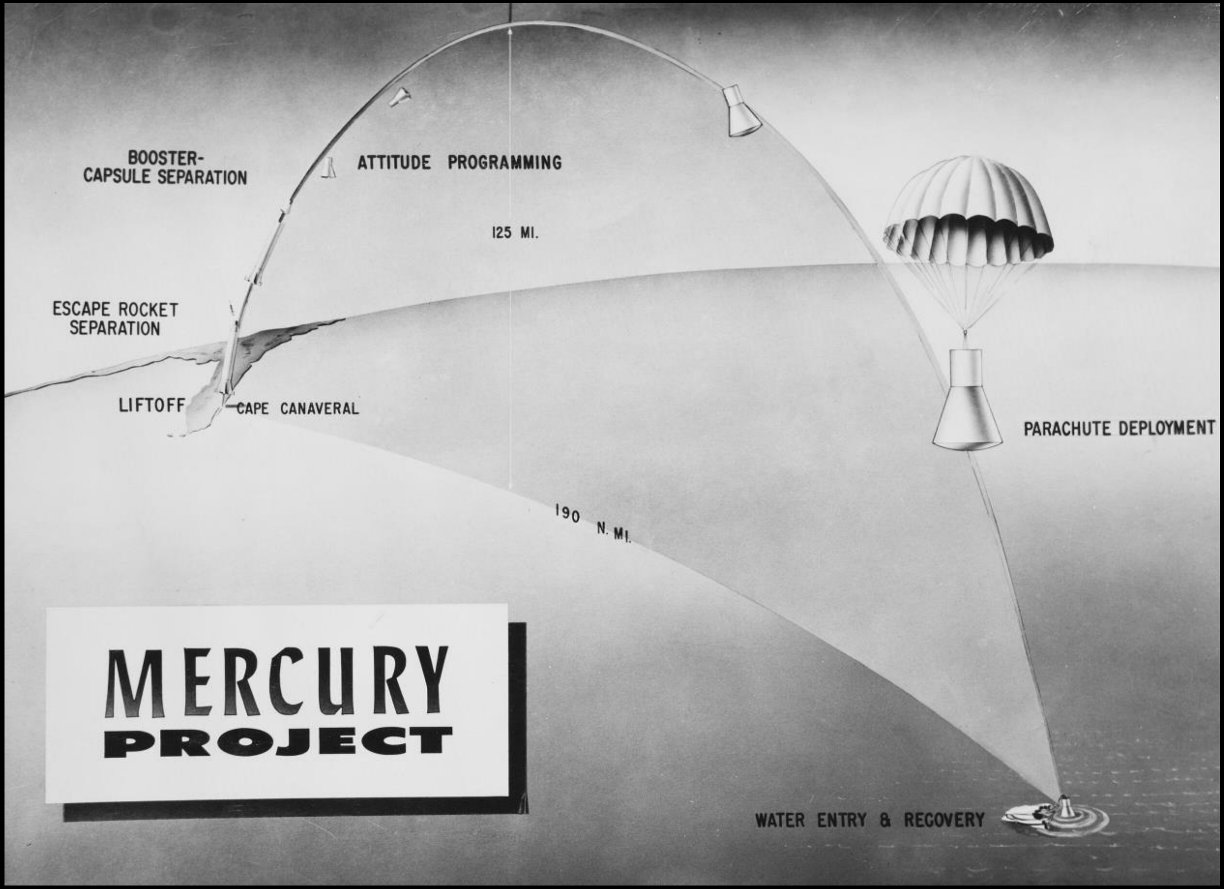
May 5, 1961 – Freedom 7

- Mercury capsule launch aboard a Redstone rocket
- Astronaut Alan Shepard
- First American in space

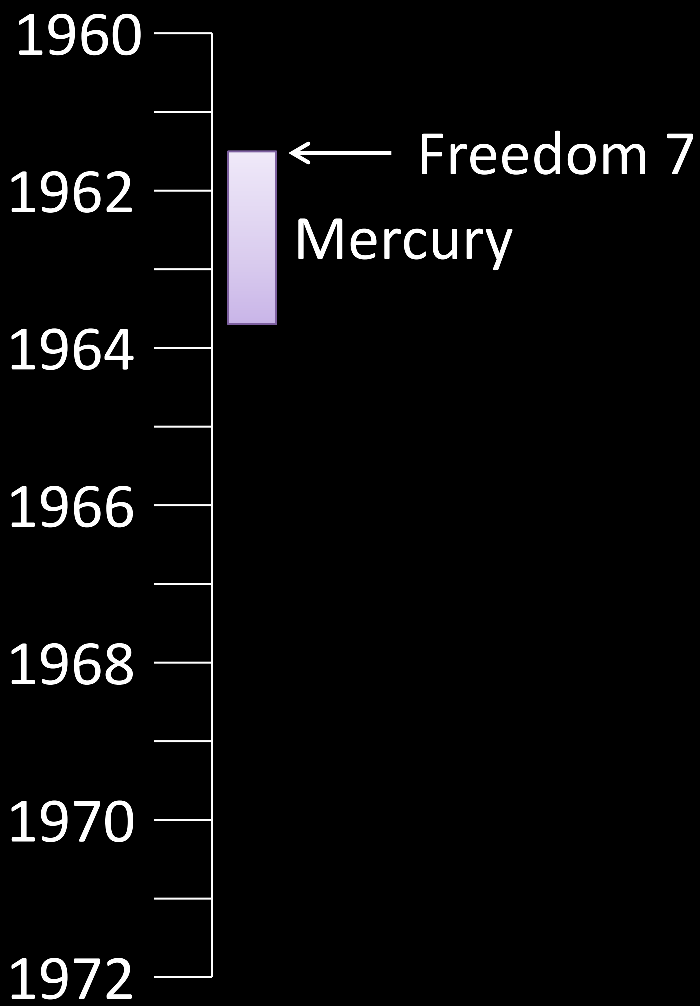


Freedom 7


UNITED STATES
UNITED


BOOSTER-CAPSULE SEPARATION
ATTITUDE PROGRAMMING
125 MI.
ESCAPE ROCKET SEPARATION
LIFTOFF
CAPE CANAVERAL
PARACHUTE DEPLOYMENT
190 N. MI.
MERCURY
PROJECT
WATER ENTRY & RECOVERY

Mercury - First Steps Into Space



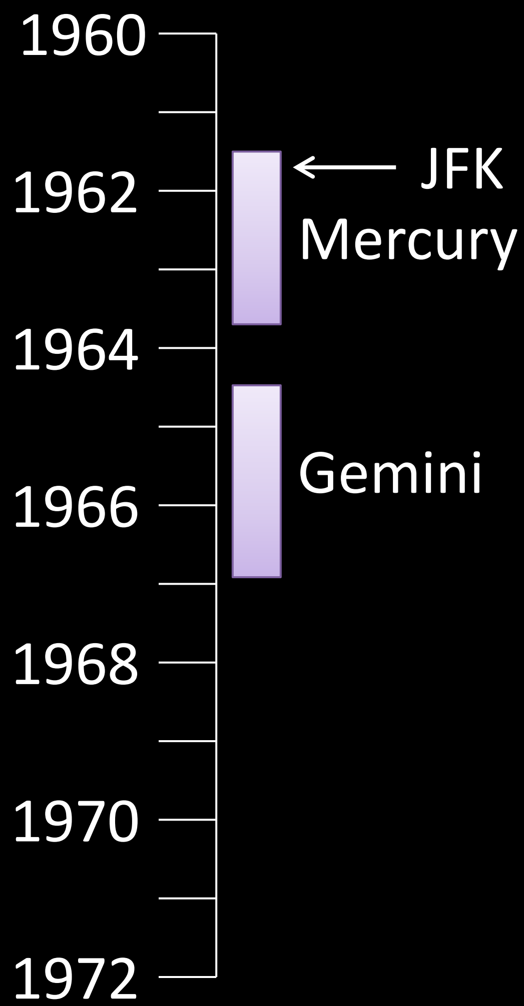
Game Changer

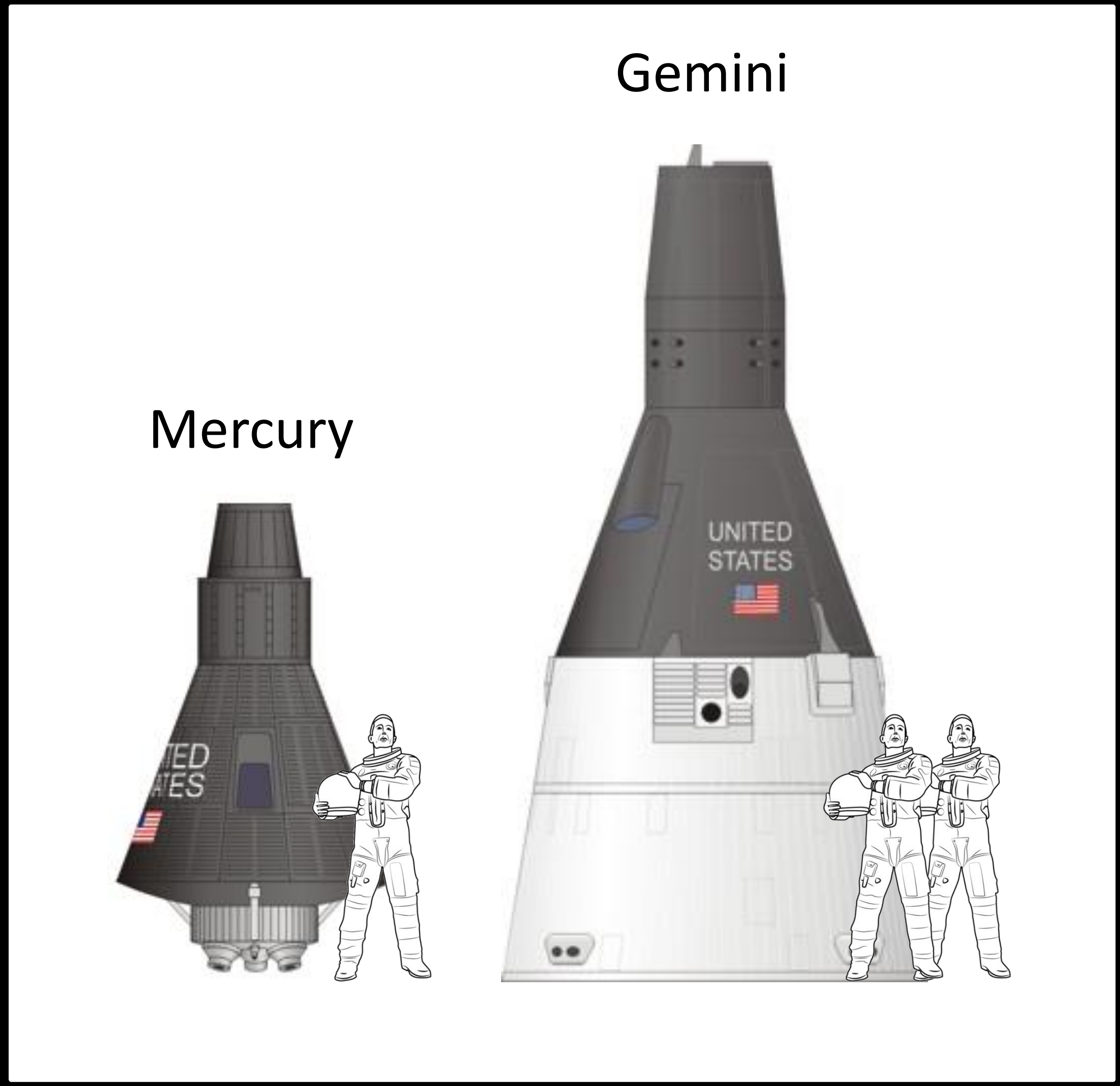
"I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the earth."

-- JFK, May 25, 1961

Frenzy of Research and Development

Gemini - Preparing to Go to the Moon

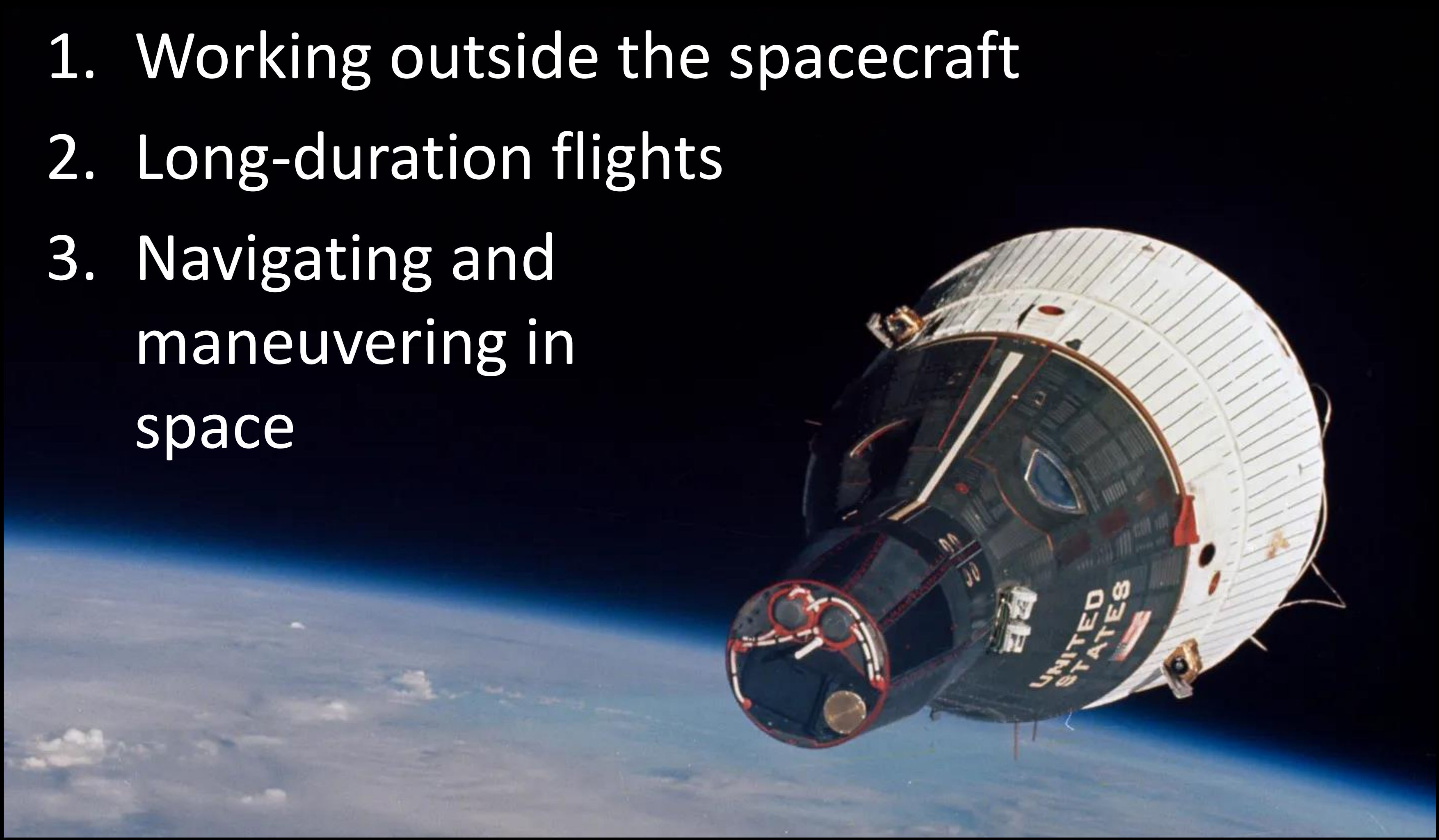




Gemini - Preparing to Go to the Moon

Skills we would need:

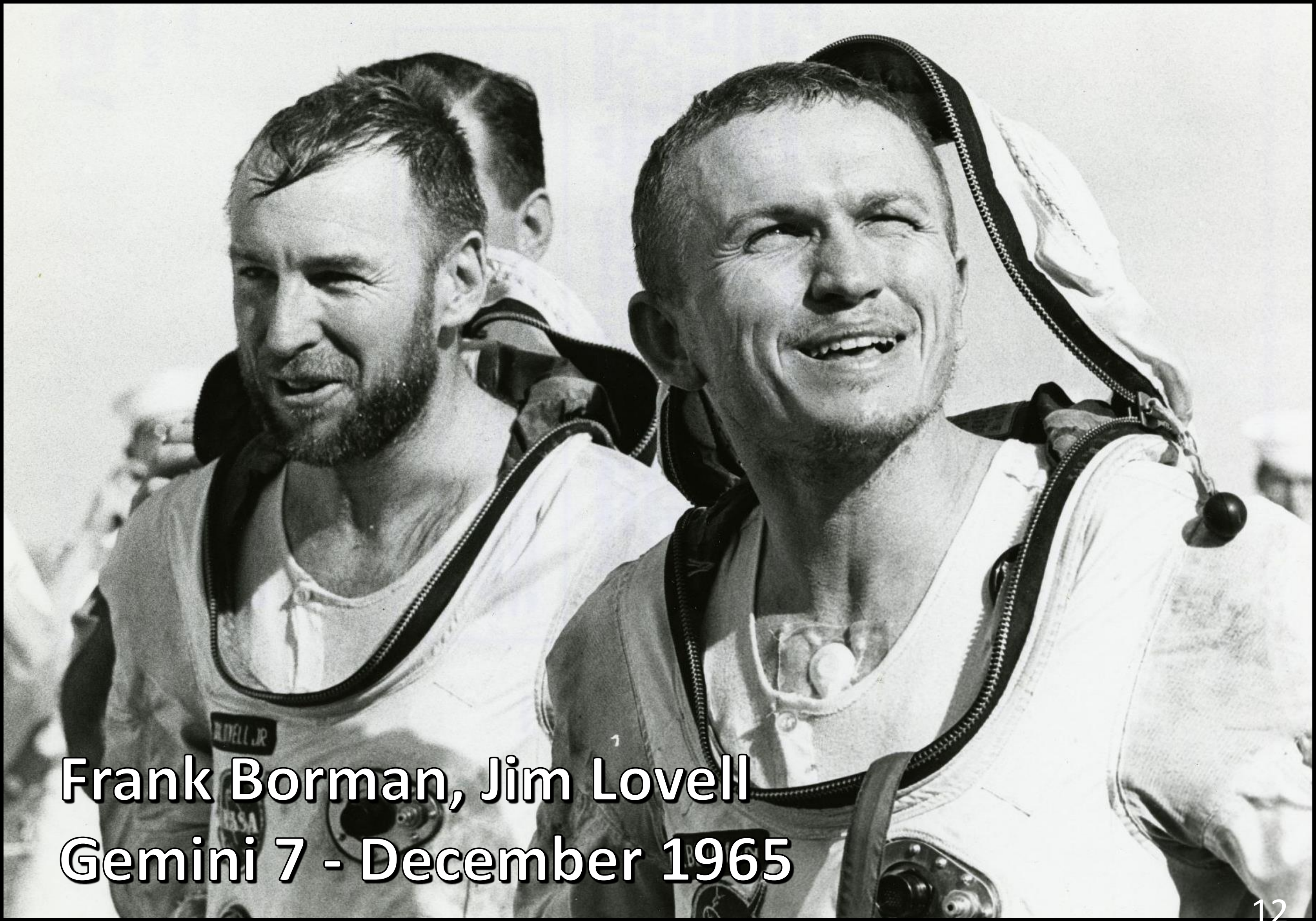
1. Working outside the spacecraft
2. Long-duration flights
3. Navigating and maneuvering in space



Working Outside the Spacecraft

Ed White
Gemini 4
June 1965

Long-Duration Flights

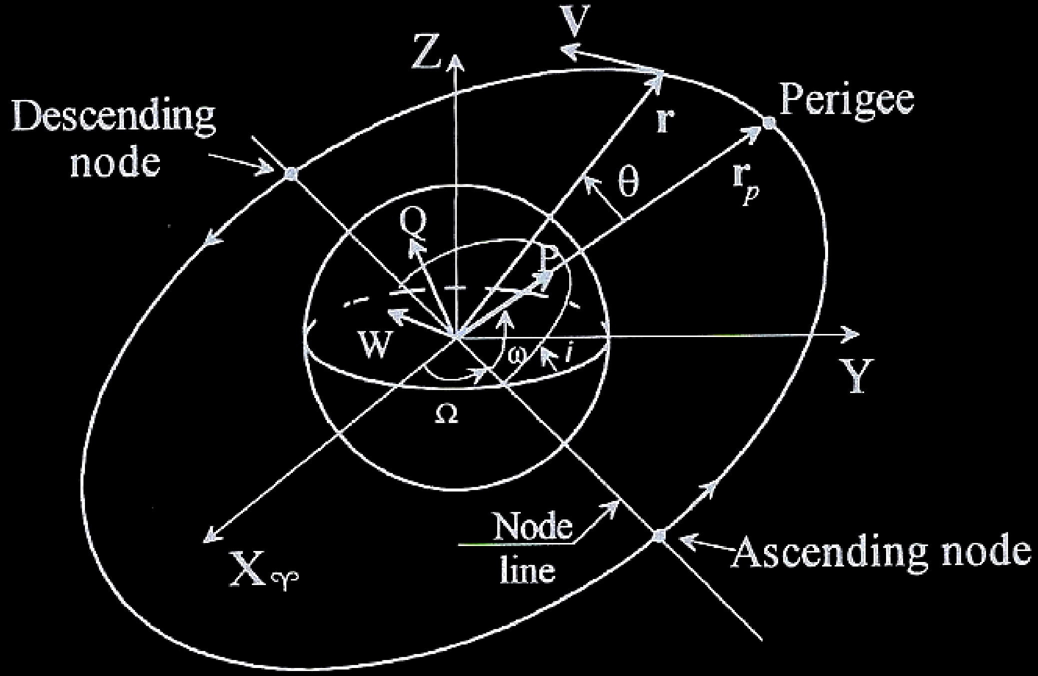


Frank Borman, Jim Lovell
Gemini 7 - December 1965

Maneuvering in Space

- Highly mathematical
- Completely non-intuitive
- There's a reason they call it rocket science

- Just about impossible without a computer



Translunar Injection (TLI)

On the side of the Earth exactly opposite the Moon …

... while traveling at 17,500 mph

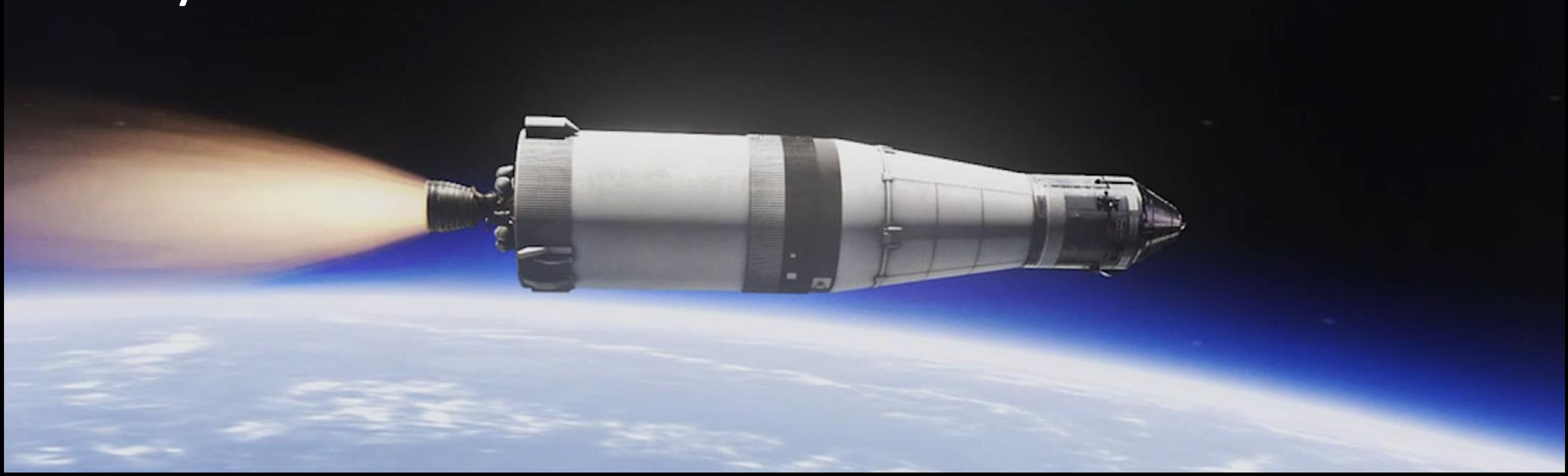
… but with no sensation of speed

… add exactly the right amount of speed (about 7,500 mph)

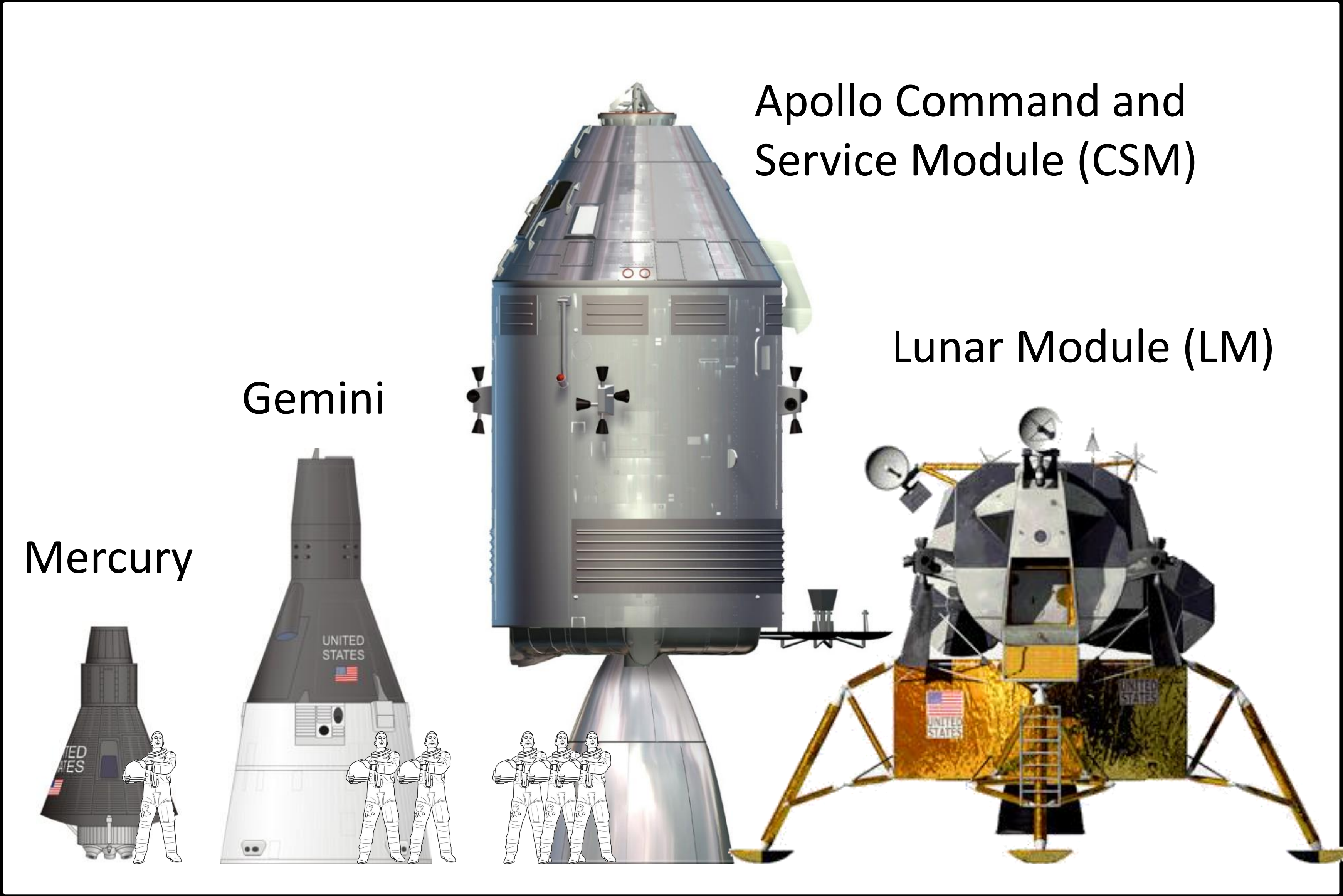
... while pointing toward a precise point in empty space

… so that 3 days later you arrive at a point in space

… exactly 70 miles ahead of where the moon will be then.



Apollo – Going to the Moon



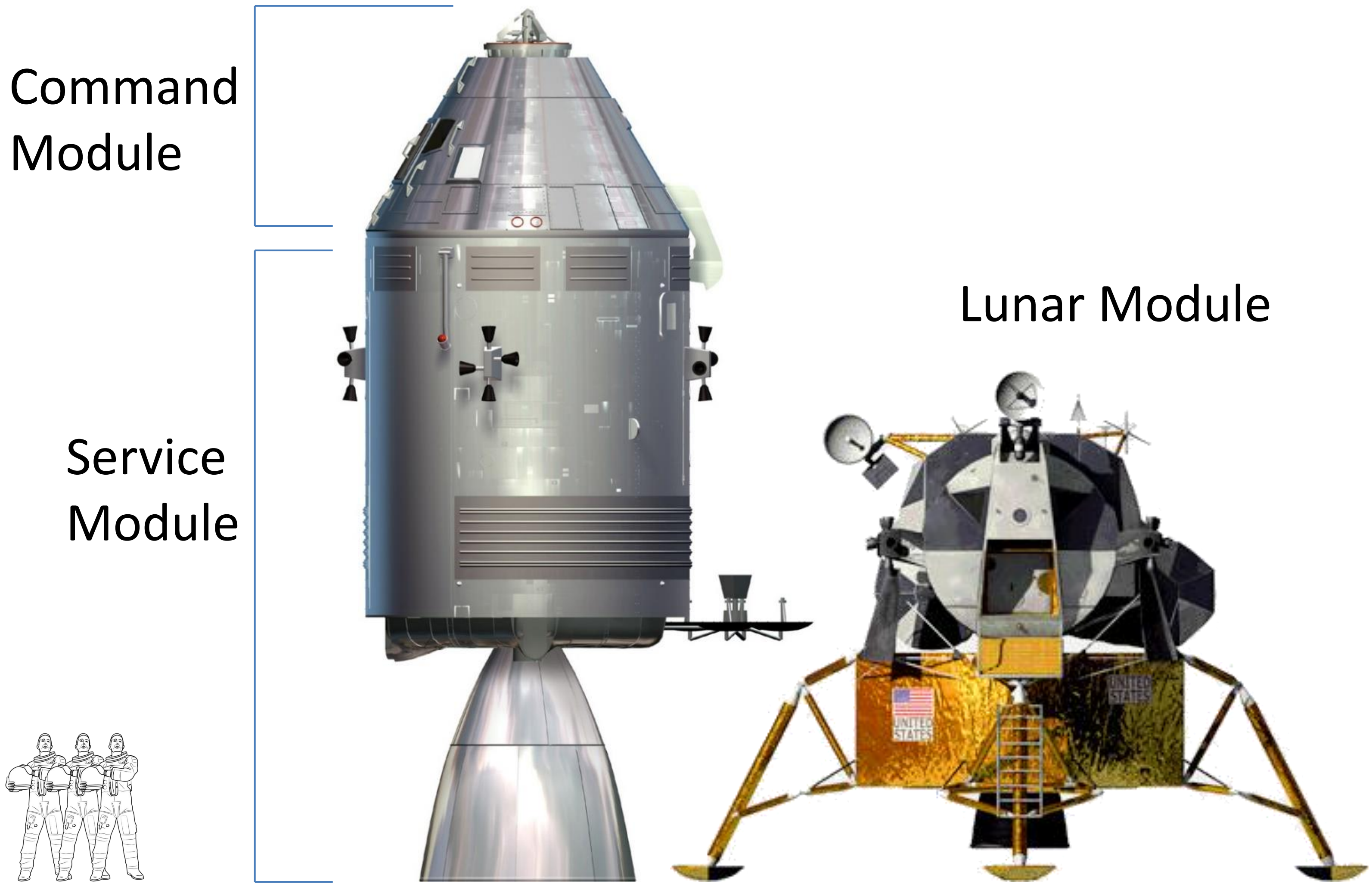
Apollo – Going to the Moon

1960
1962
1964
1966
1968
1970
1972

← JFK
Mercury
Gemini
Apollo

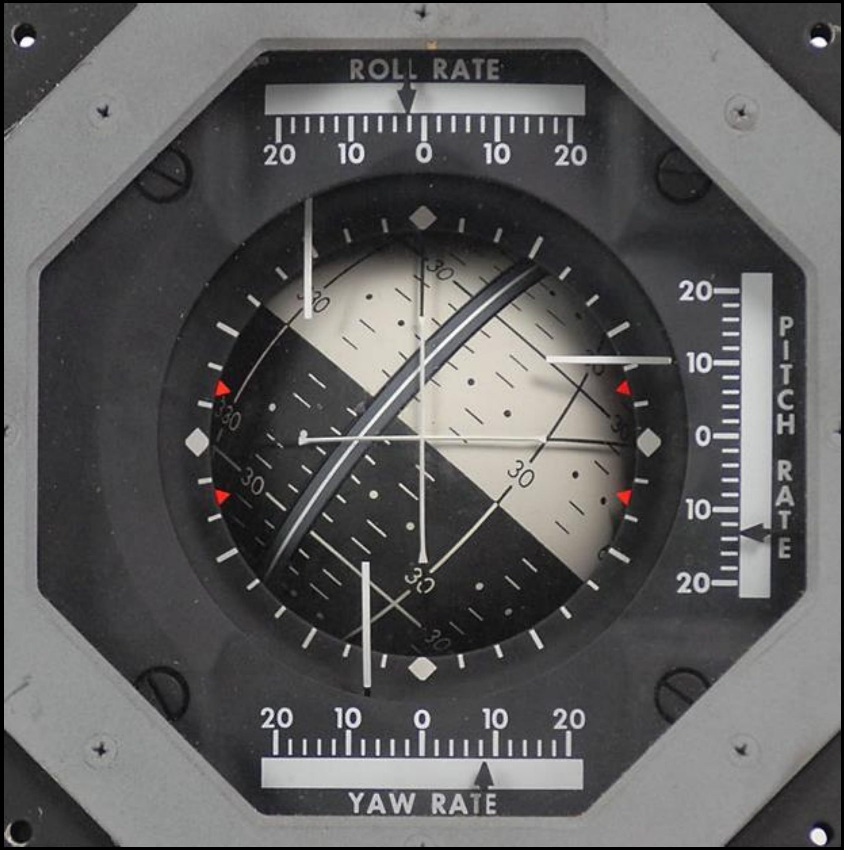
A Computer for Apollo

Apollo – Going to the Moon



Computer Requirements

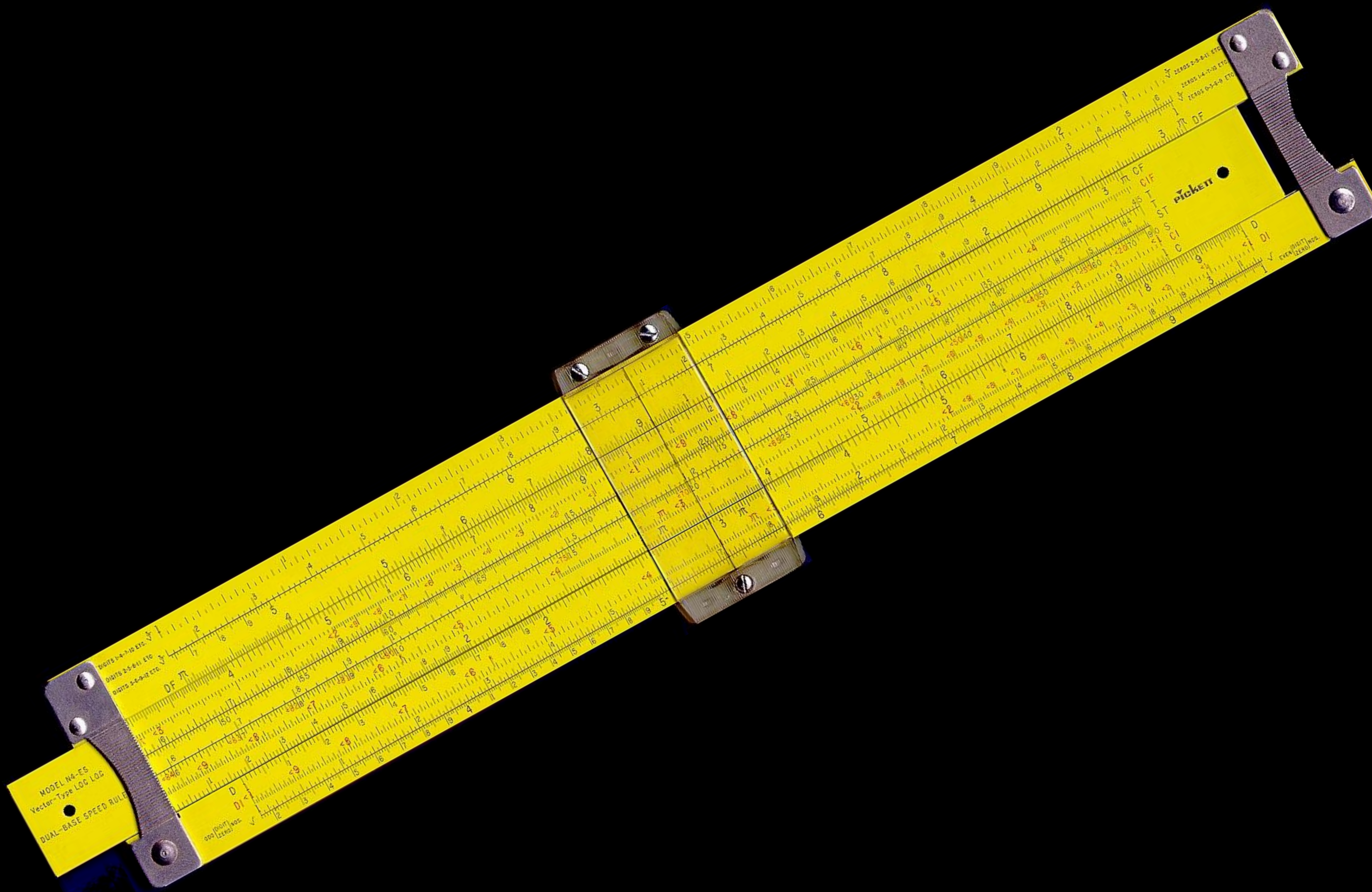
- Execute trajectories between the Earth and the Moon
- Keep track of the spacecraft position and attitude
- Control equipment such as radars, engines, and thrusters
- Display flight data
- Receive updates from the ground



1960s Computing

NASA Real Time Computing Center, 1966

Personal Computers in 1960



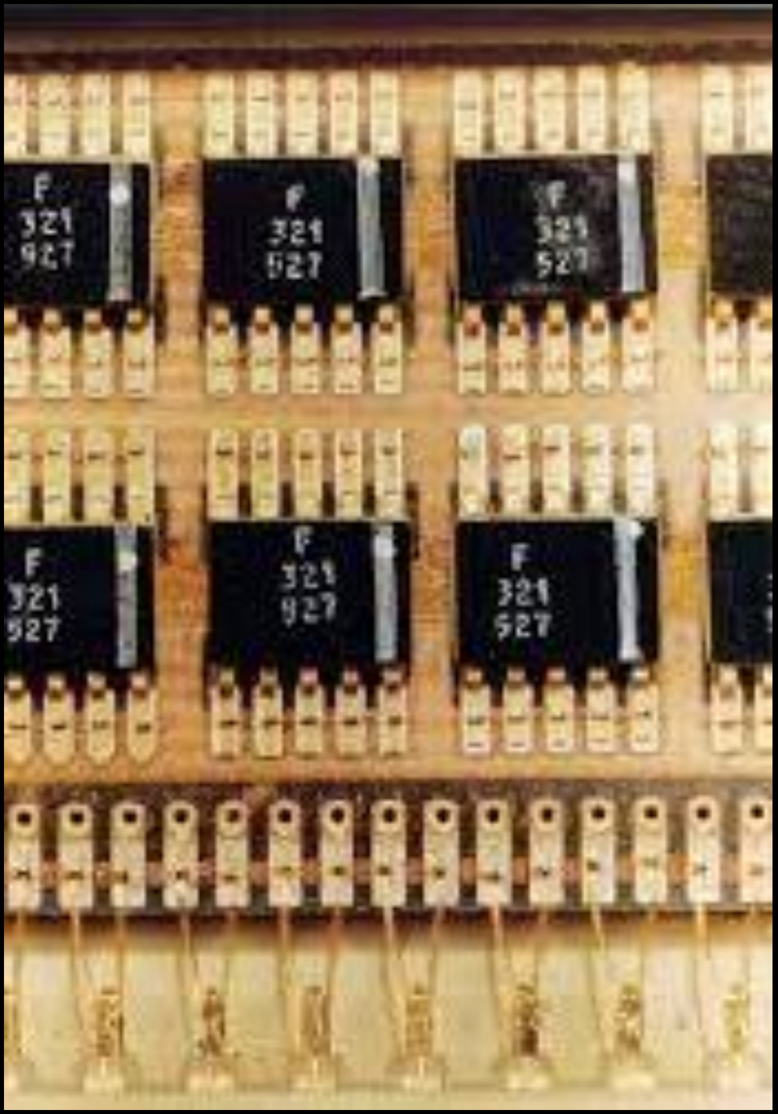
Charles Stark “Doc” Draper

- Head of the MIT Instrumentation Lab
- Believed his team could build a digital computer for a moon mission
- Most serious constraint: weight
- Next most serious constraint: power

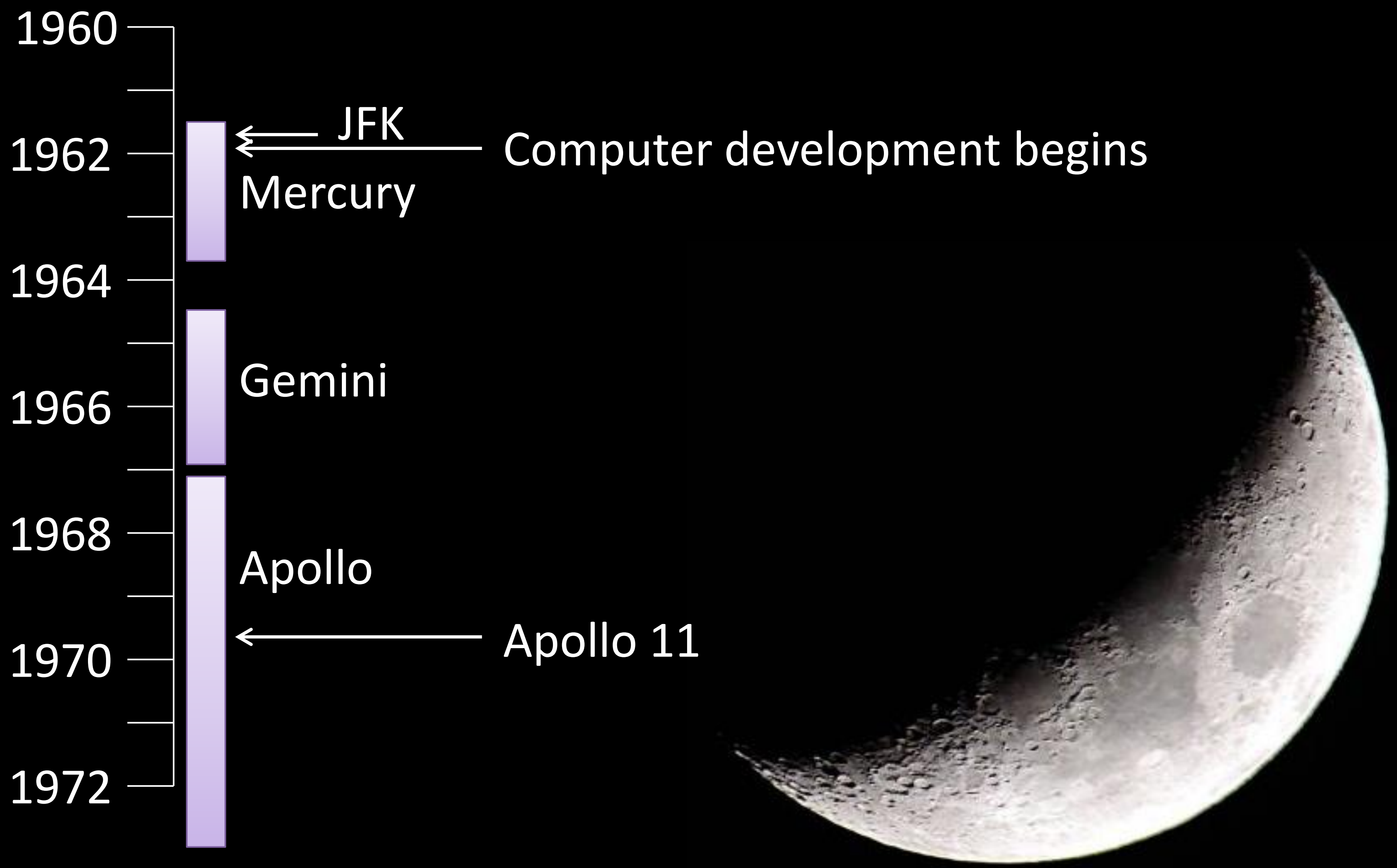
Crucial Decisions

1. Computer would be digital
2. Save weight and power by using integrated circuits
3. Simplify by using identical integrated circuits

Work began in 1961

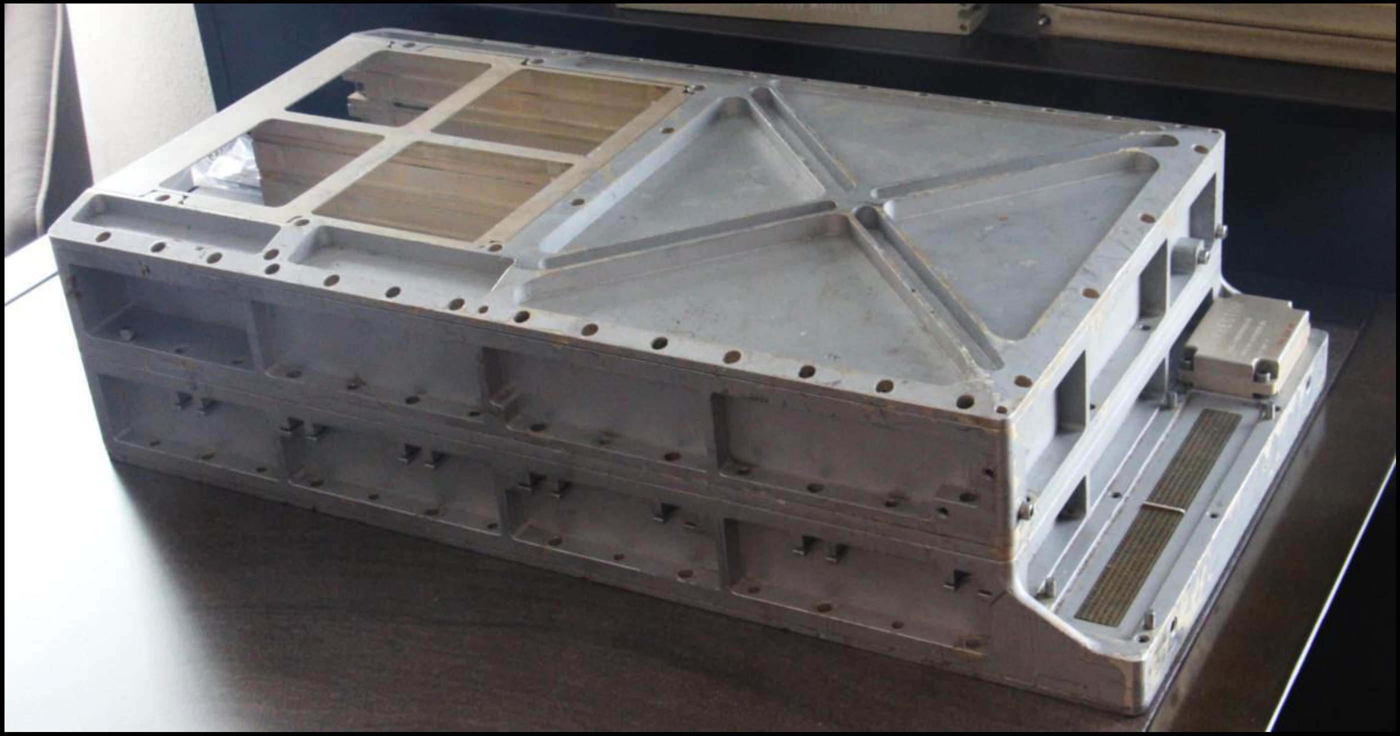


Apollo – Going to the Moon



The Apollo Guidance Computer (AGC)

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



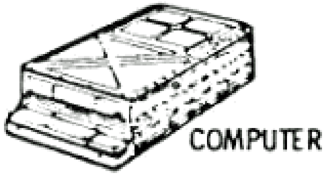
AGC Hardware

- 15-bit word (plus a parity bit)
- 36k words of read-only memory (ROM)
- 2k words of read/write memory (RAM)
- Weight: 70 pounds
- Power usage:
  70 watts peak

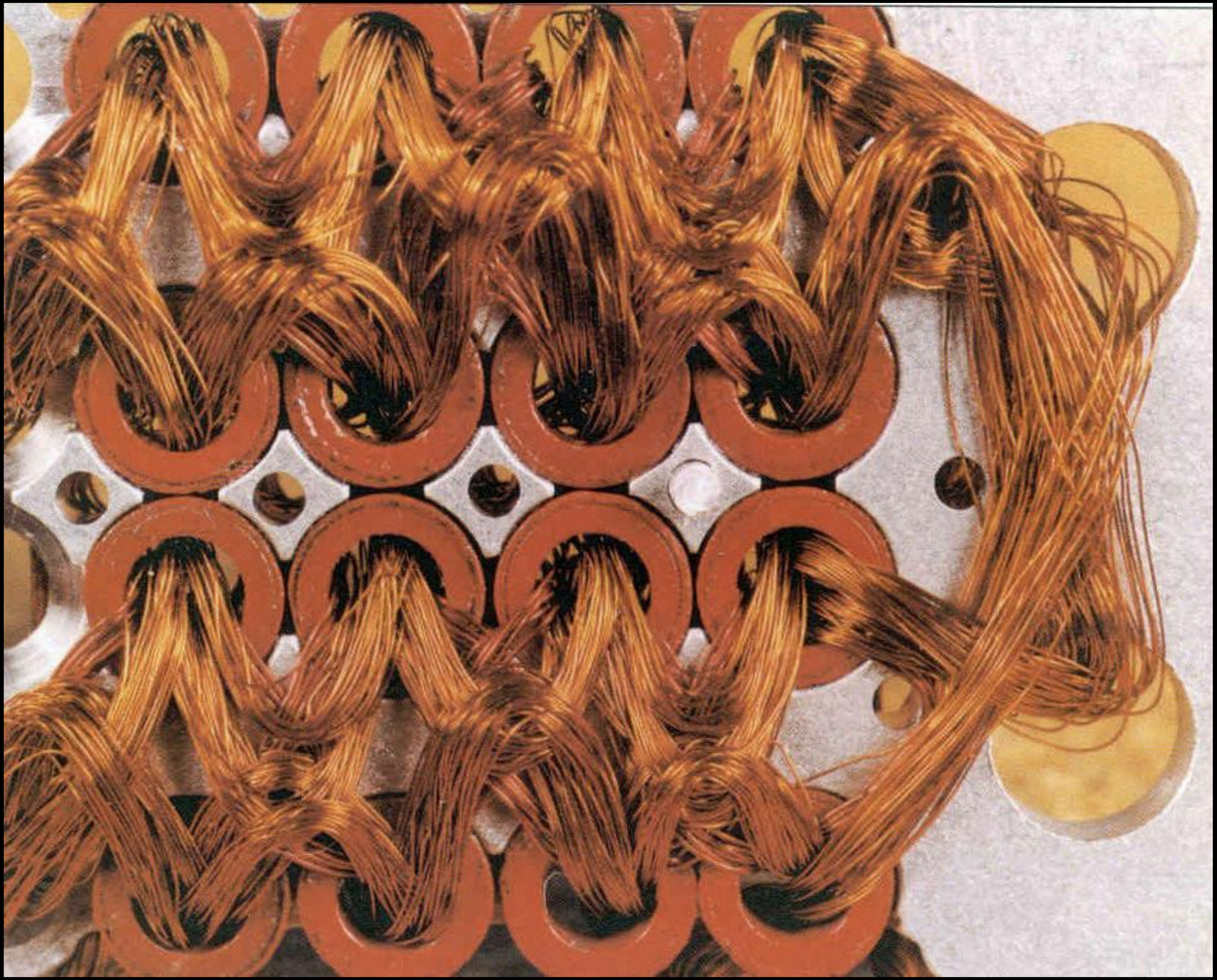
The Innards


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
ALARM MODULE B8
NON-FLYABLE
ERASABLE DRIVER MODULE B9-10
ERASABLE DRIVER MODULE B9-10
CURRENT SWITCH MODULE B11
SENSE AMPLIFIER MODULE B13-14
SENSE AMPLIFIER MODULE B13-14
STRAND SELECT MODULE B15
ROPE DRIVER MODULE B16-17
ROPE DRIVER MODULE B16-17

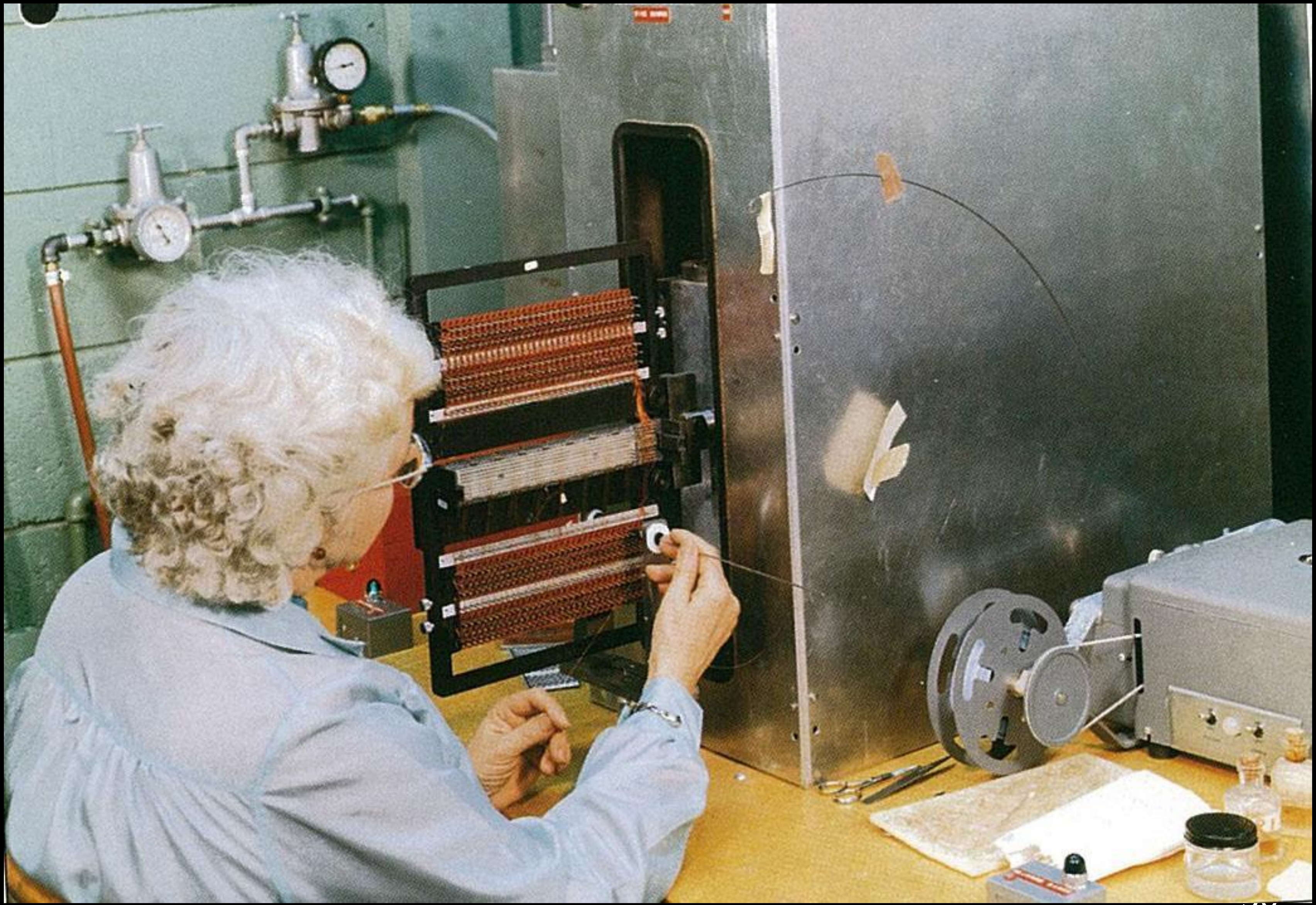
What Did the AGC Actually Do?



Core Rope Memory

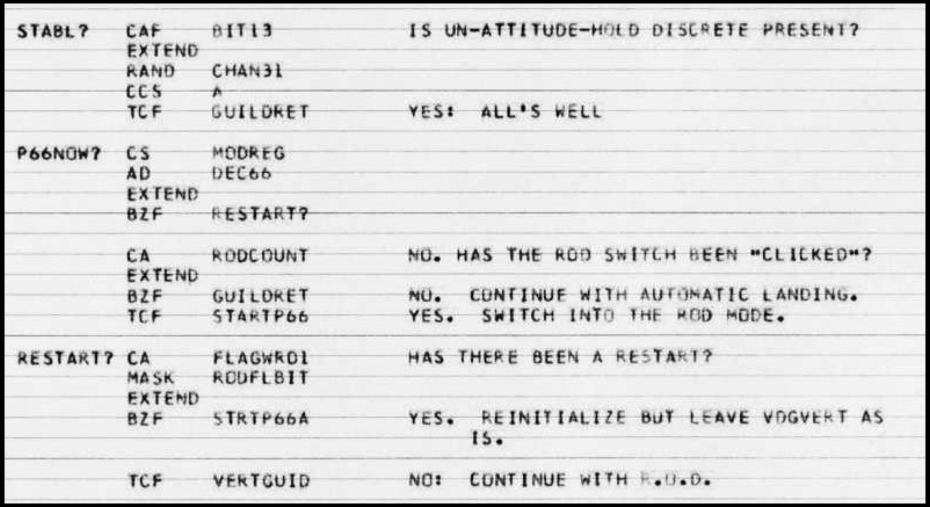


Weaving the AGC Memory



Software

- Hardware the same in both spacecraft
- Different software:
  - Command Module: Colossus
  - Lunar Module: Luminary
- 1400 person-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.
```

A Little Bit of Code

```
#    ********************************
#    GENERAL PURPOSE IGNITION ROUTINES
#    ********************************

BURNBABY    TC      PHASCHNG    # GROUP 4 RESTARTS HERE
            OCT     04024

            CAF     ZERO        # EXTIRPATE JUNK LEFT IN DVTOTAL
            TS      DVTOTAL
            TS      DVTOTAL +1

            TC      BANKCALL    # P40AUTO MUST BE BANKCALLED EVEN FROM ITS
            CADR    P40AUTO     # OWN BANK TO SET UP RETURN PROPERLY

B*RNB*B*    EXTEND
            DCA     TIG         # STORE NOMINAL TIG FOR OBLATENESS COMP.
            DXCH    GOBLTIME    # AND FOR P70 OR P71.
```

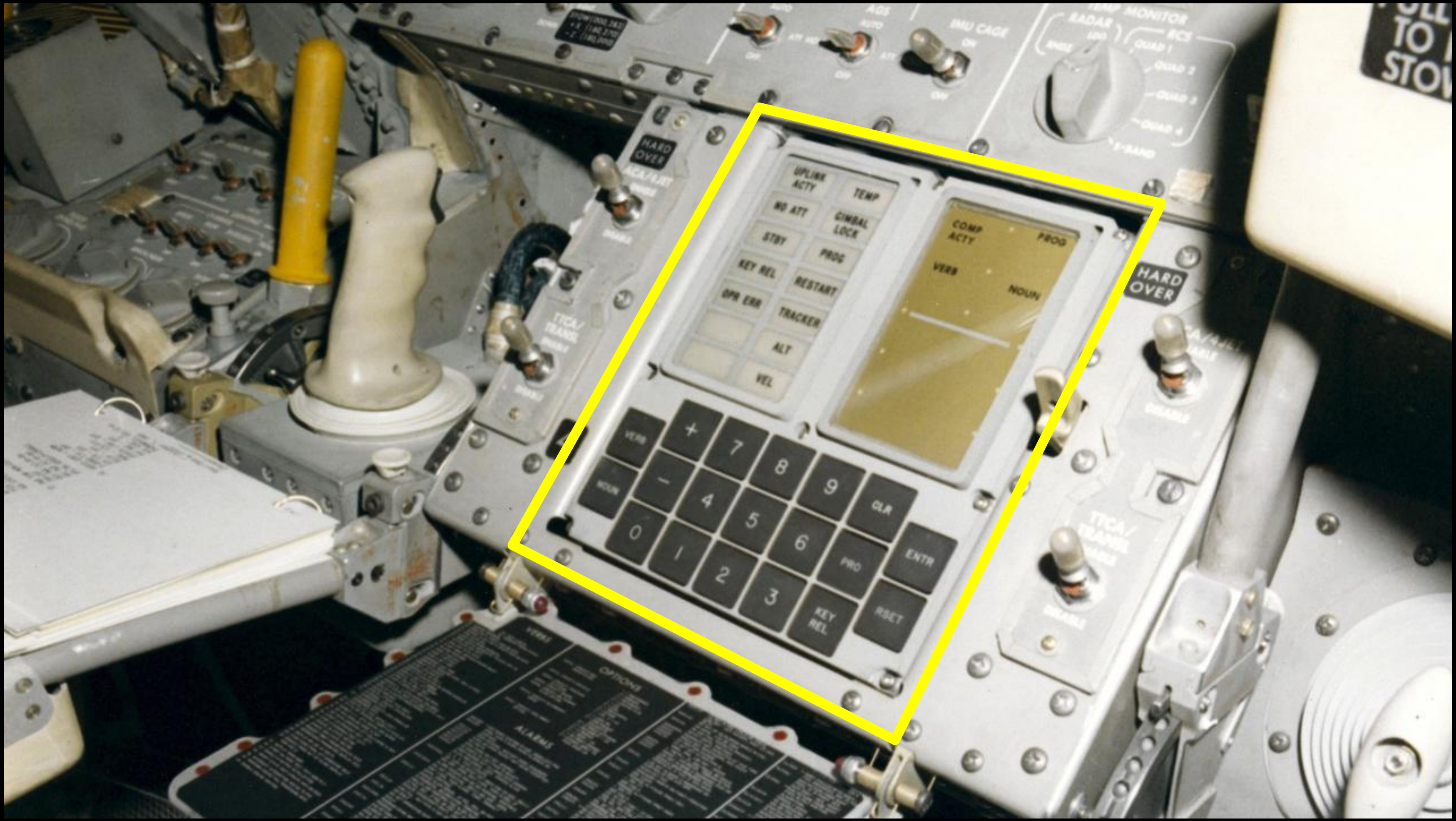
Using the Apollo Guidance Computer

Where's the Mouse?

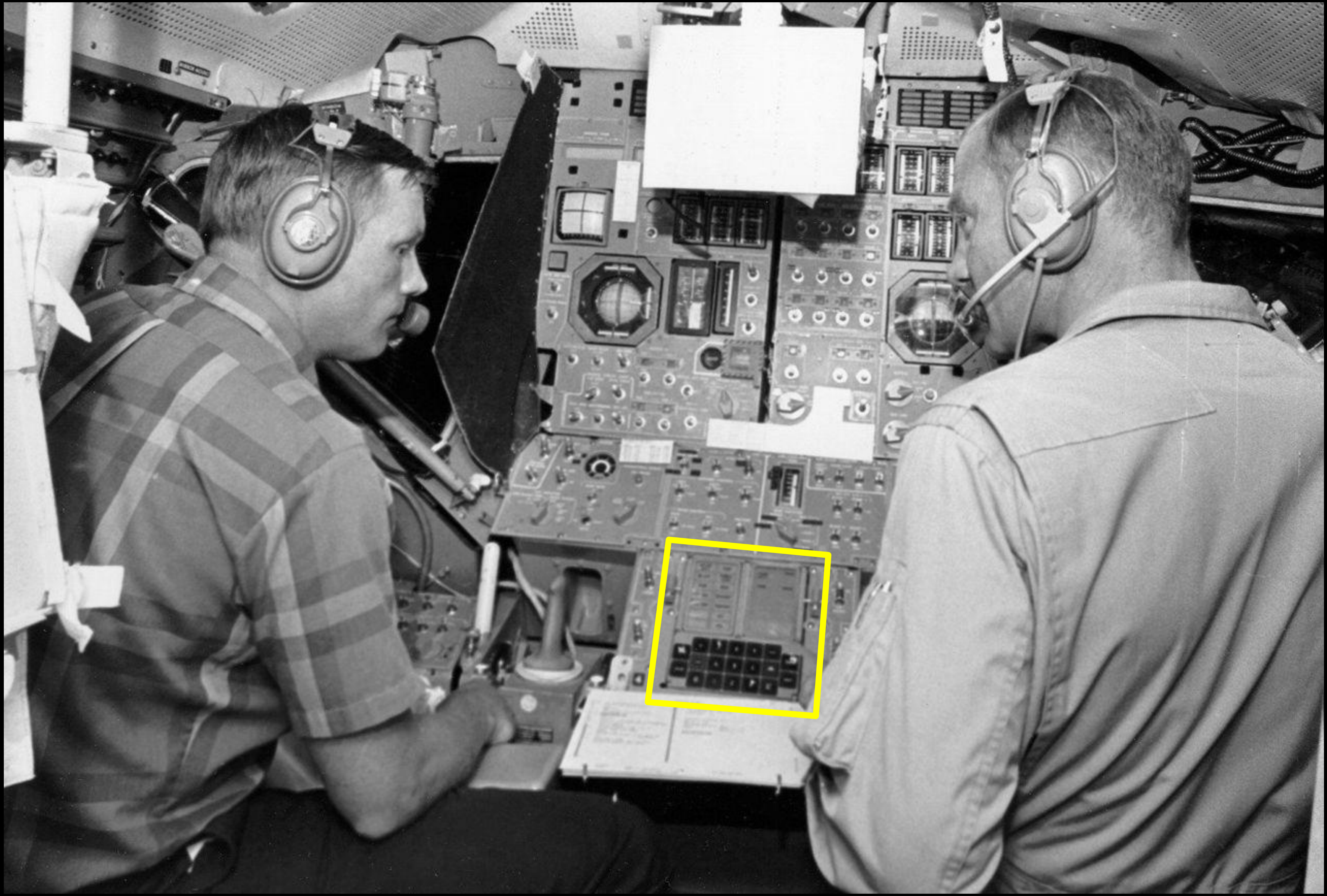
How do we talk to this thing?

- Keyboards were big, bulky, and heavy
- Mice didn't exist
- Flat panel displays didn't exist
- Displays were heavy and power-hungry

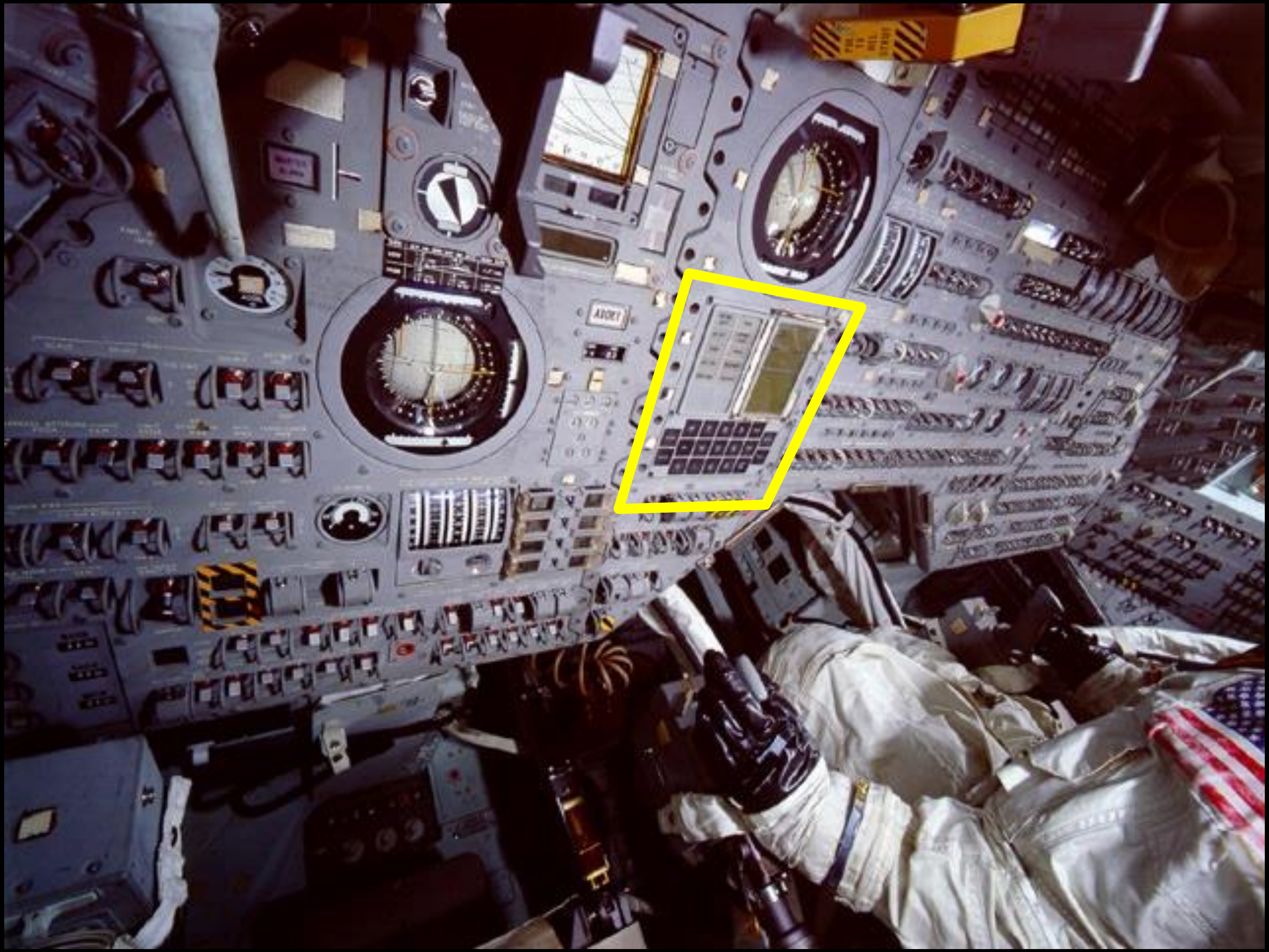
Display/Keyboard (DSKY)



DSKY in the Lunar Module

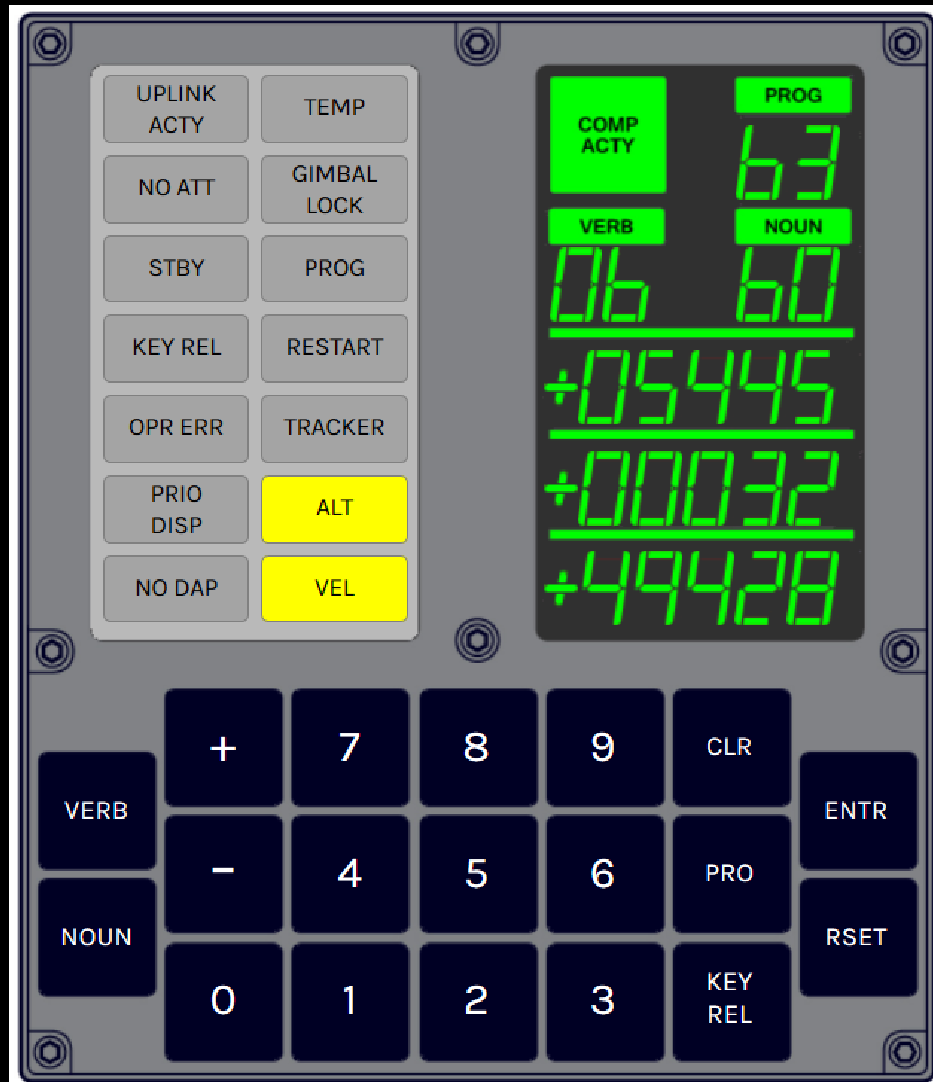


DSKY in the Command Module



The DSKY (Display and Keyboard)

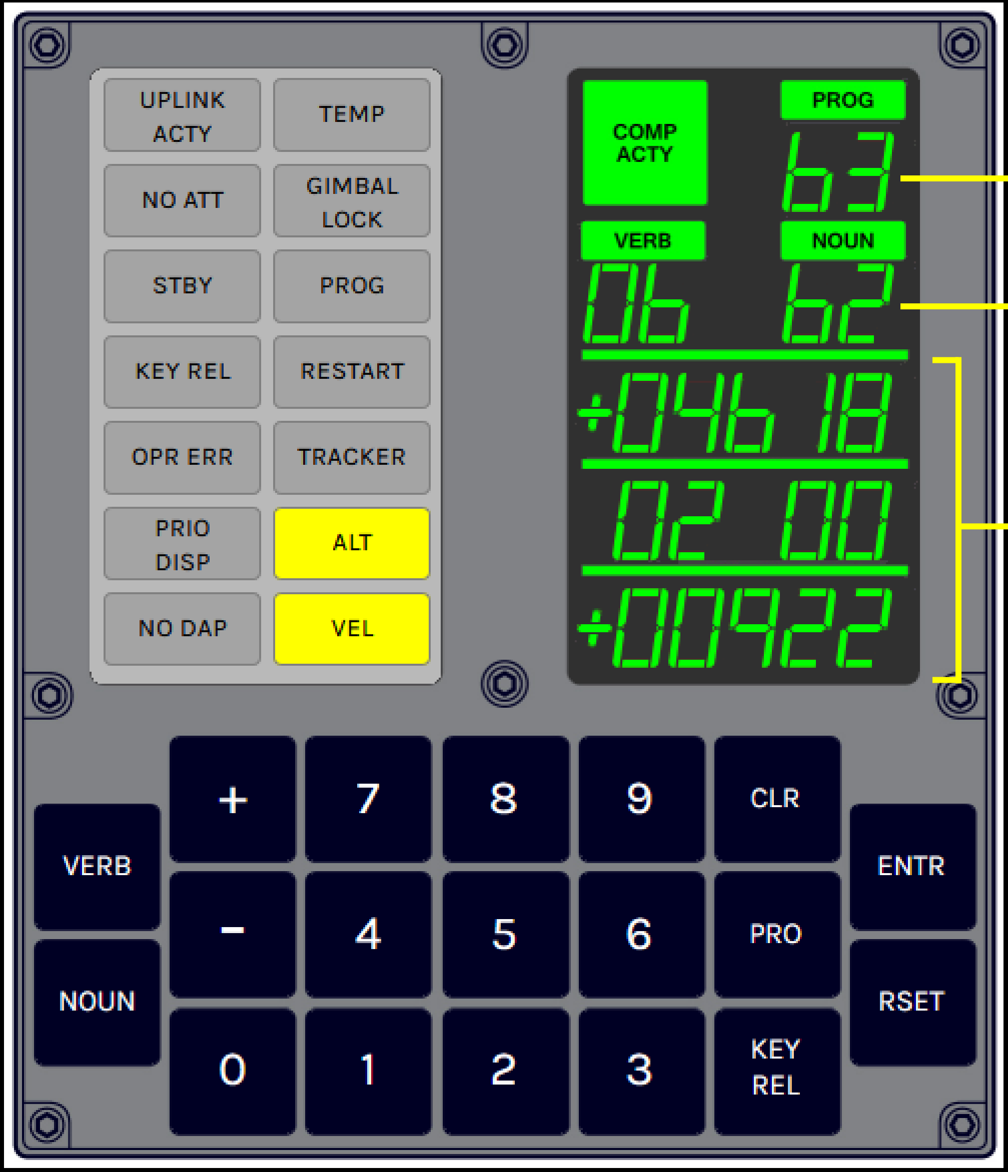
INDICATORS LIGHTS



DISPLAYS

KEYBOARD

Communicating with the AGC



Program

Verb and Noun

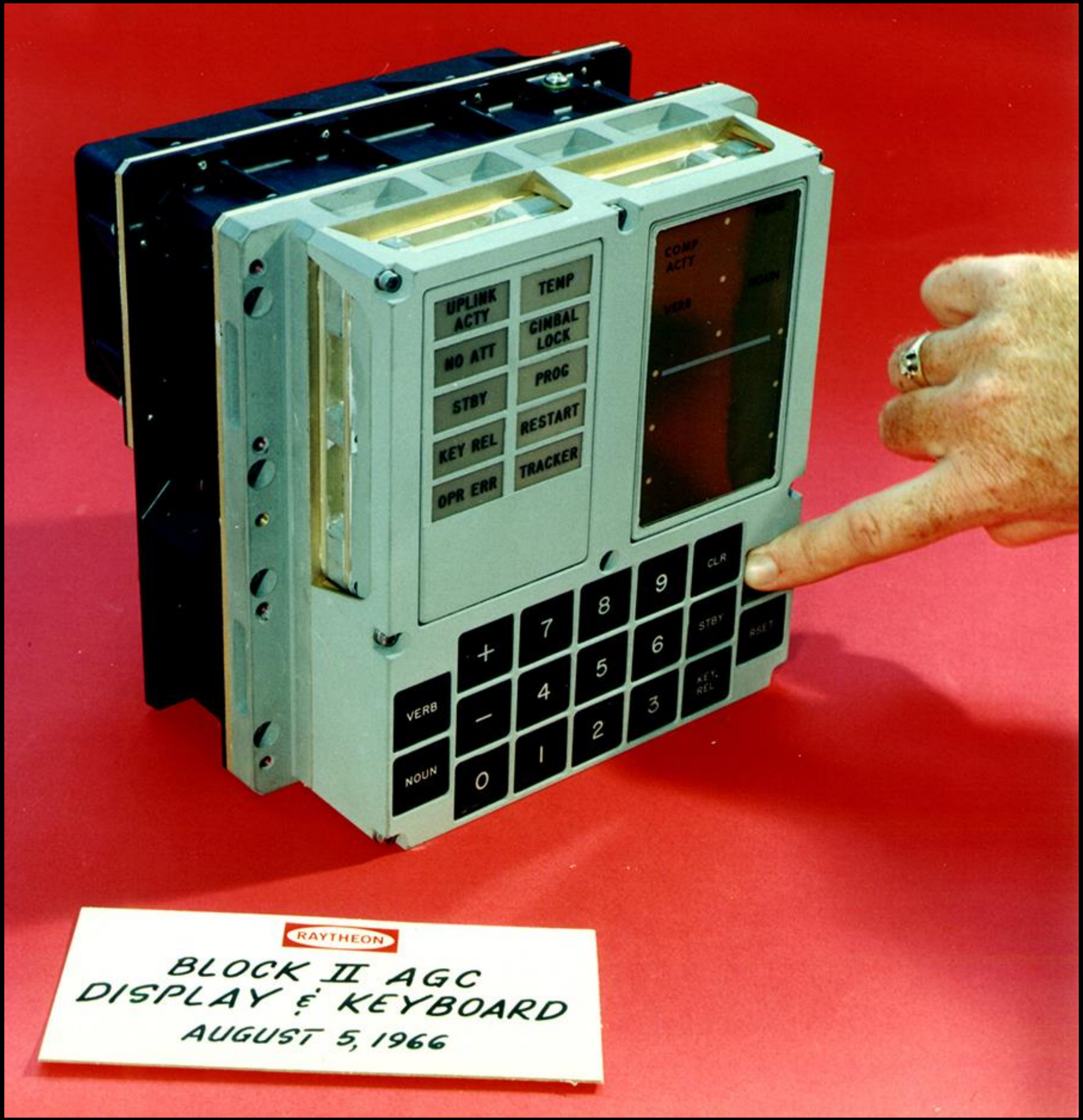
Registers

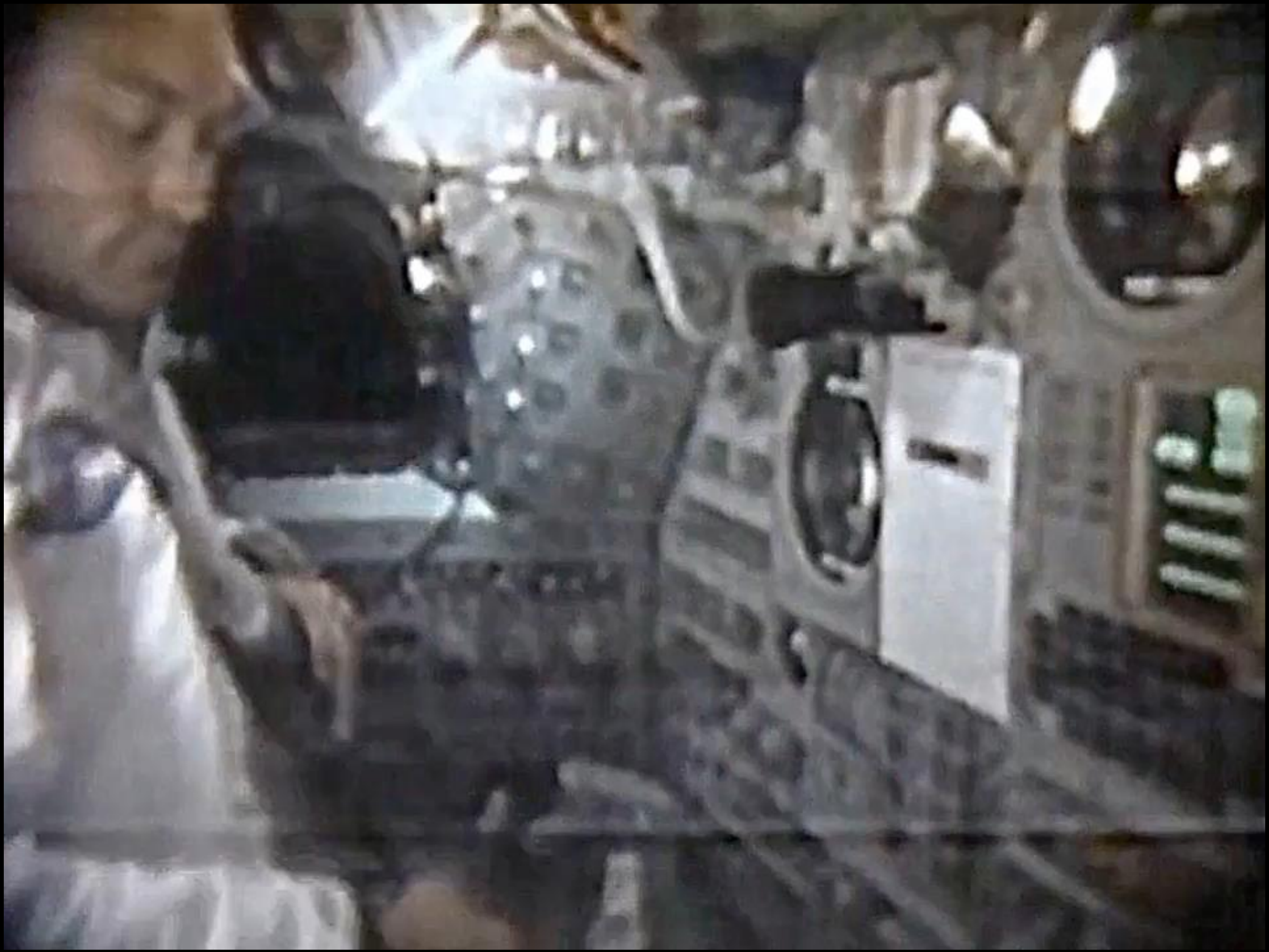
Verbs and Nouns

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

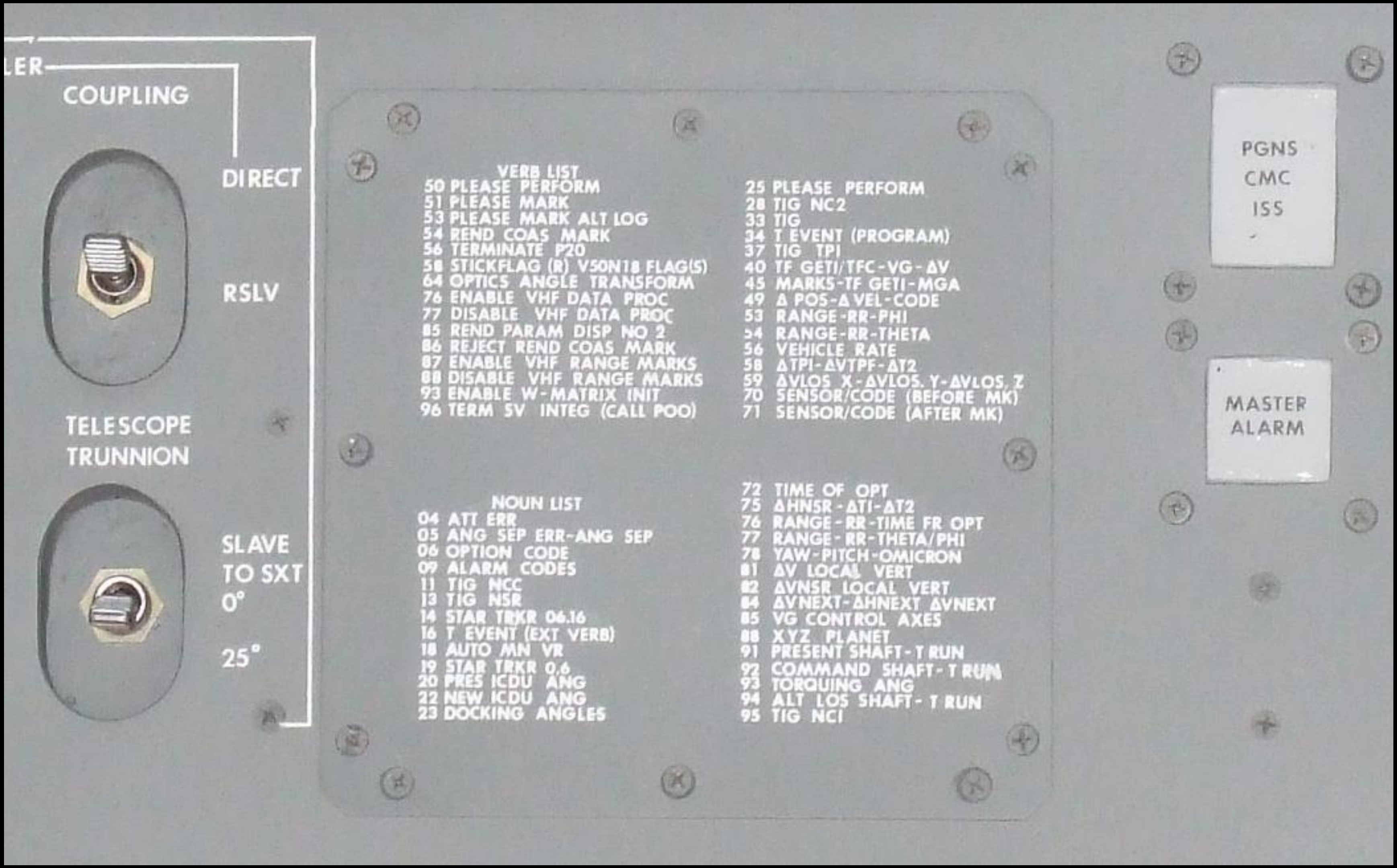
- Works both ways

Sample DSKY Operations

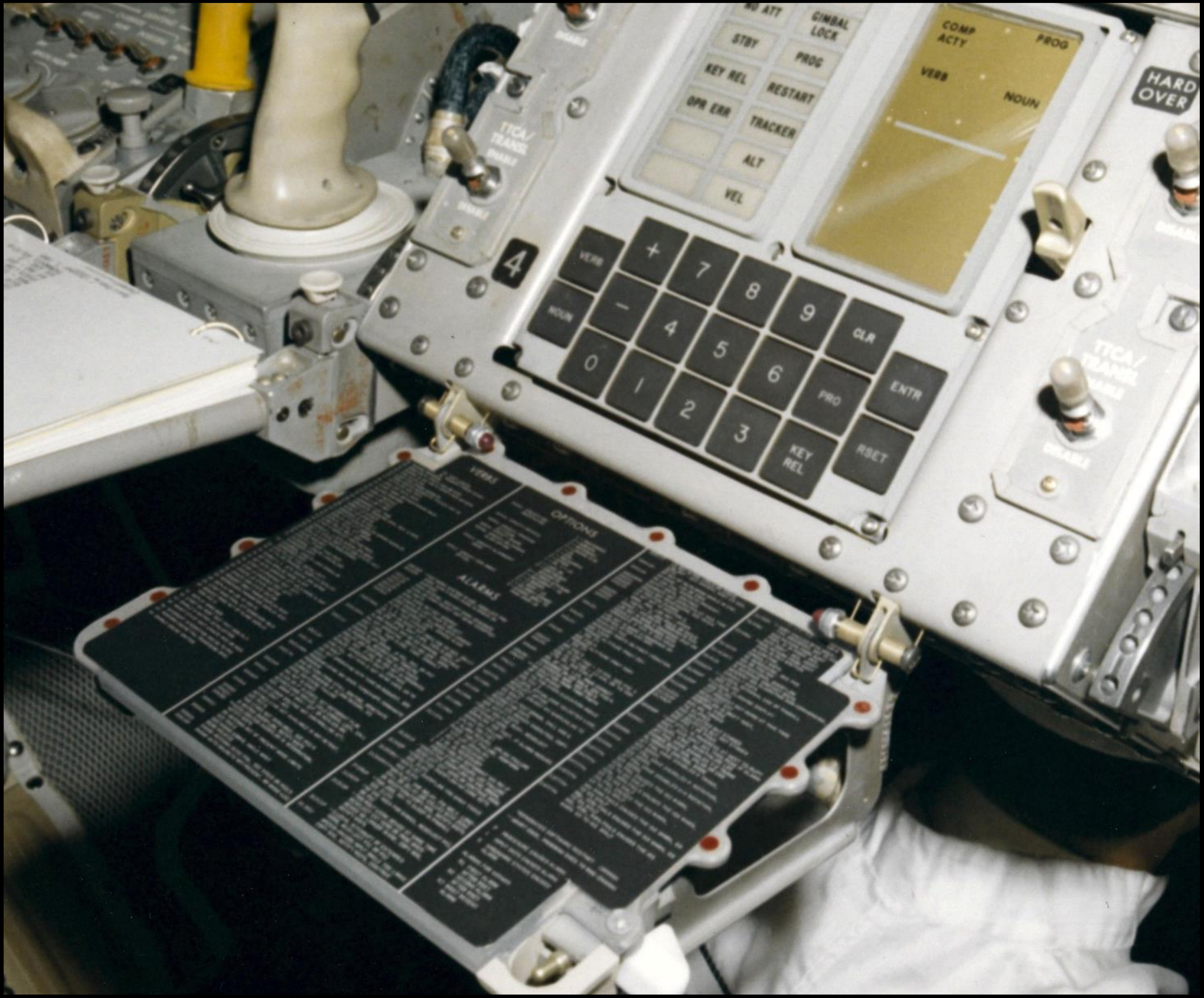




DSKY Cheat Sheets (Command Module)



DSKY Cheat Sheets (Lunar Module)



FLIGHT PLAN

LM

CDR

P20 RENDEZVOUS NAVIGATION
ACQUIRE AND TRACK CSM
MAINTAIN RR
TRACKING ATTITUDE
SLEW STEERABLE ANT
ANT P 58, Y -38

V83 SET ORDEAL

P41 RCS THRUSTING

RCS, CSI

VERIFY RESIDUALS

Z AXIS BORESIGHT

MAINTAIN RR AND
VHF TRACKING ATTITUDE

P41 RCS THRUSTING

RCS, PLANE CHANGE

LMP

V32 - MARKS = 5

V32 - MARKS = 10
RCS TEMP/PRESS/QTY CK

AFT OMNI, PCM LBR

FINAL CSI COMPUTATION
V90 OUT OF PLANE
V47 INITIALIZE AGS (PCM-HI)

CSI DATA TO CSM (PCM-LO)
LOAD AGS ΔV

TIG: 125:21:19
BT: 45 SEC
ΔV: 49.5 FPS

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

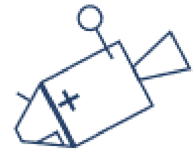
LOAD AGS ΔV

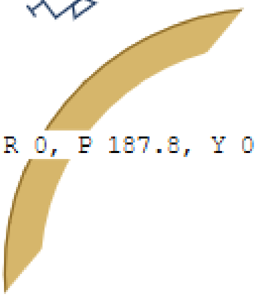
TIG: 125:50:28
ΔV=NOMINALLY ZERO

V76, P33 CDH PRETHRUST

MCC-H

CSM: R 0, P 180/271, Y 0





LM FDAI: R 0, P 187.8, Y 0

Verbs and Nouns

"But how do you take a pilot, and put him in a space ship, and have him talk to a computer? ... Somebody came up with the verb-noun concept ... It was very simple for us to operate with a series of two-digit numbers representing verbs and another series of two-digit numbers representing nouns. And it's so straightforward and simple that even pilots could learn how to use it."

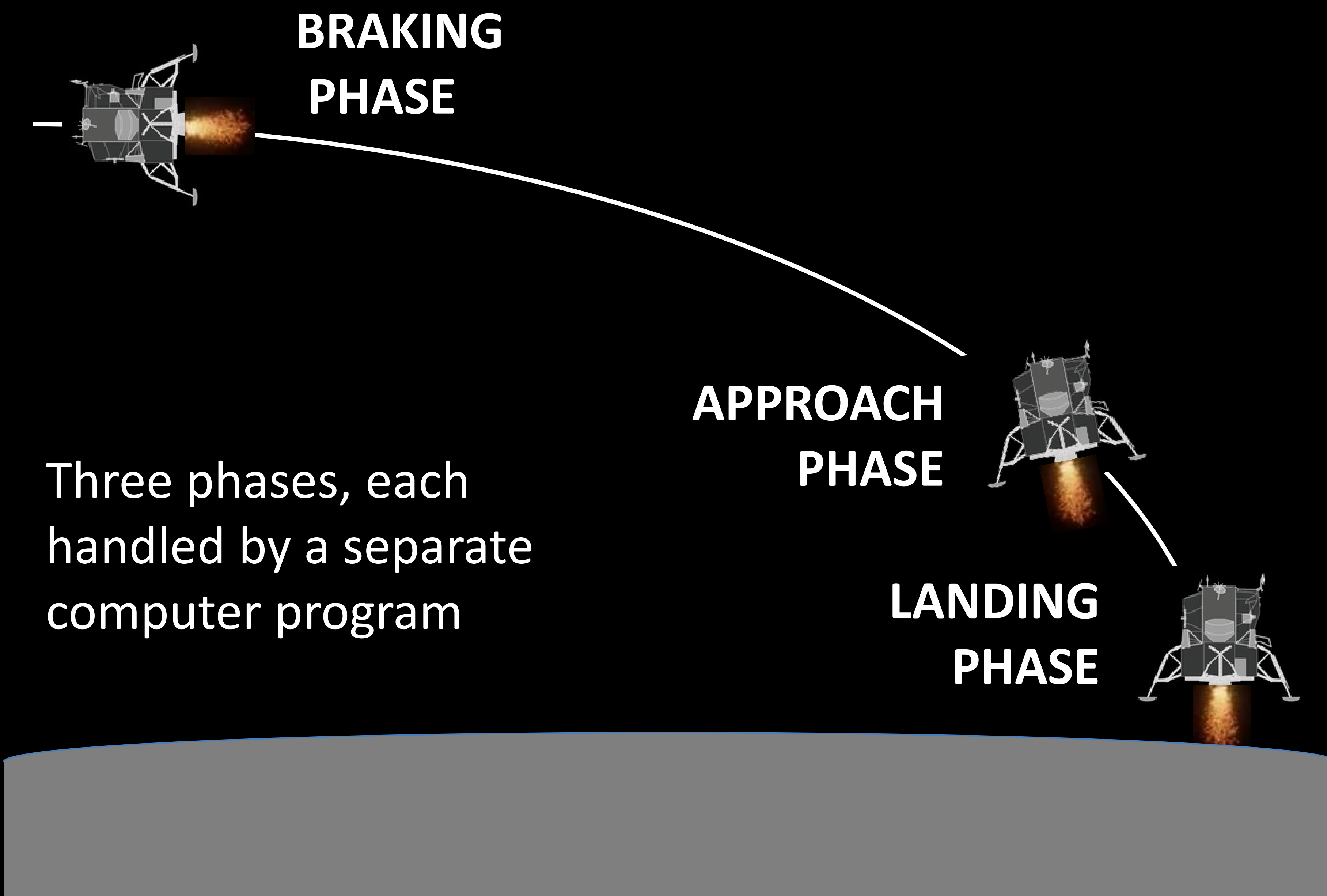
-- Astronaut David Scott
Gemini 8, Apollo 9, Apollo 15

Landing on the Moon

Landing on the Moon

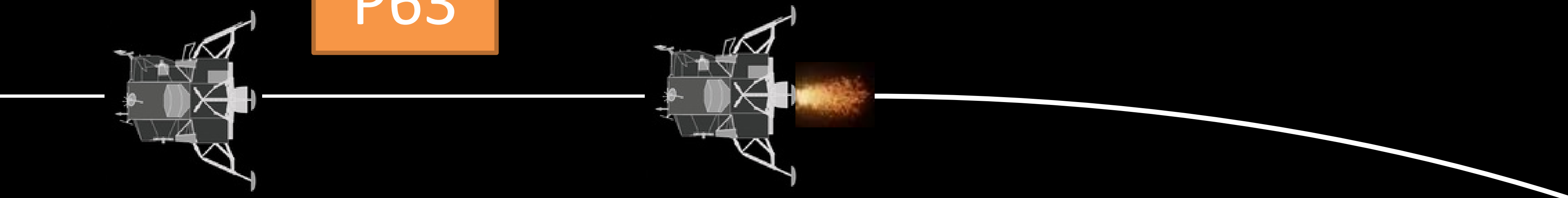
- One attempt, no second chances!
- Most of the flying is done by the AGC

Photo: HBO series “From the Earth to the Moon”


BRAKING
PHASE
APPROACH
PHASE
LANDING
PHASE
Three phases, each handled by a separate computer program

P63

BRAKING PHASE



P63 PROGRAM STARTED
Orbit 50,000 feet altitude

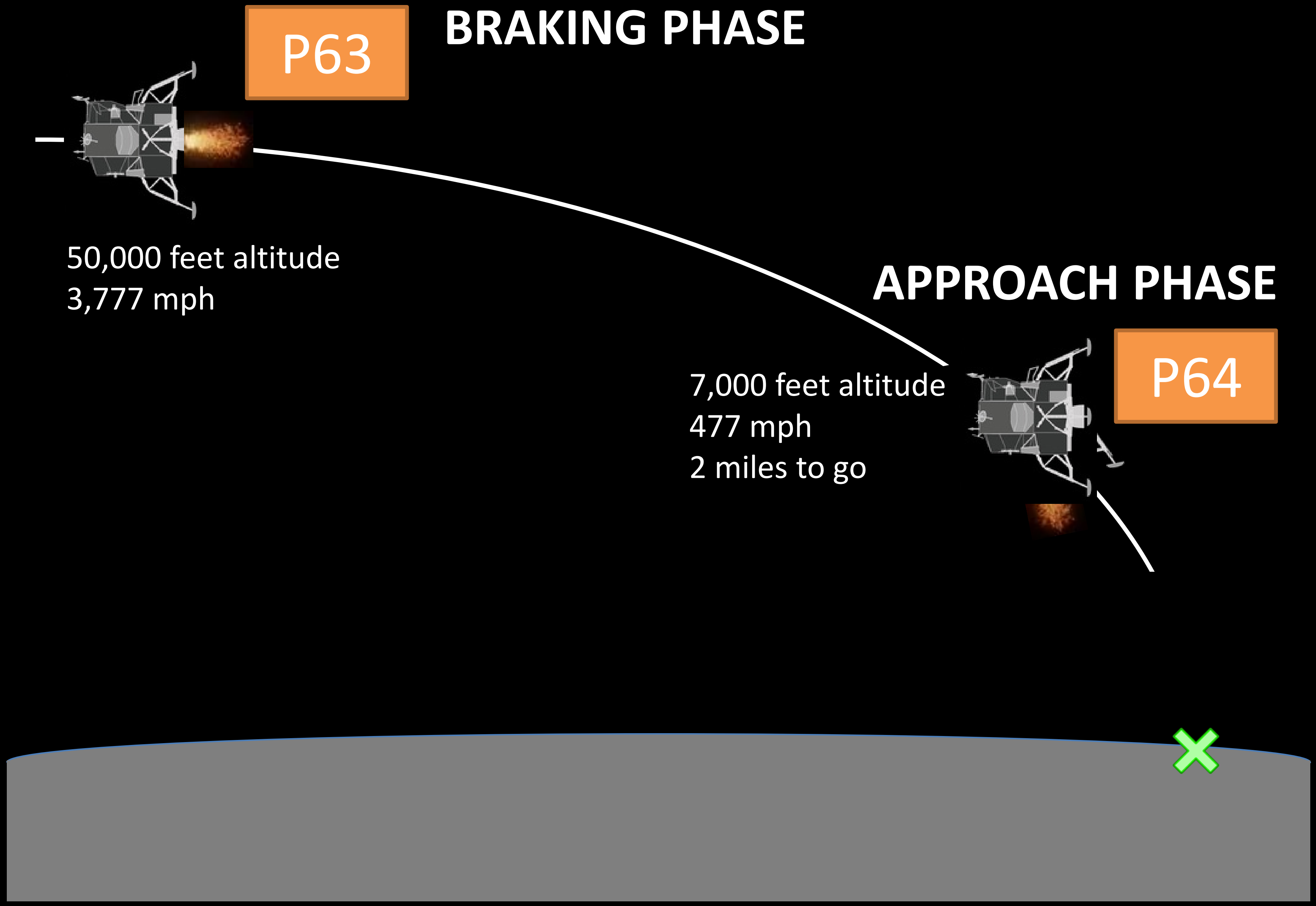
ENGINE IGNITION
PDI: POWERED DESCENT INITIATION
50,000 feet altitude
240 miles from landing site
3,777 mph
12 minutes from landing

Landing Cue Cards

PDI THRU TD+3 MIN

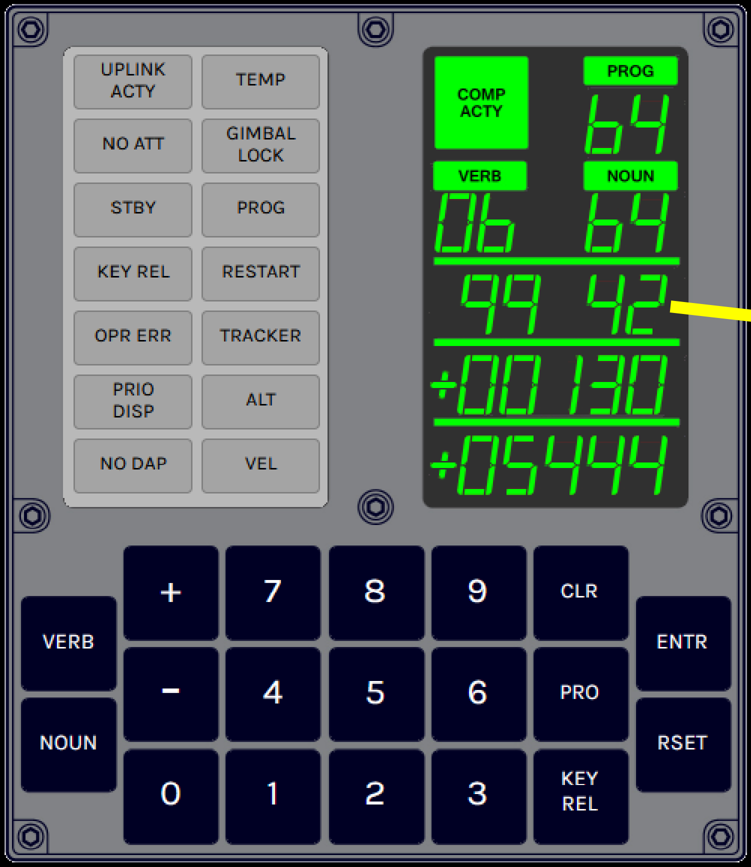
RESET WATCH
-1:00 MASTER ARM-ON
- :30 ENG ARM-DES
- :07.5 ULLAGE
- :05 PRO
+ :00 PDI
+ :02 (NO IGN) - START PB - PUSH
+ :05 DES ENG OVRD -ON
MASTER ARM-OFF
+0:26 THROTTLE UP
√T/W > 1.6
V21N69
V57E - (+) LR HIGHER THAN LGC PRO TO PERMIT LR DATA
√ED BATTS
N68
223+00120 (DO NOT ENTR)
SEQ CAMR - ON
EVAL MAN CONT
223E @ 12K

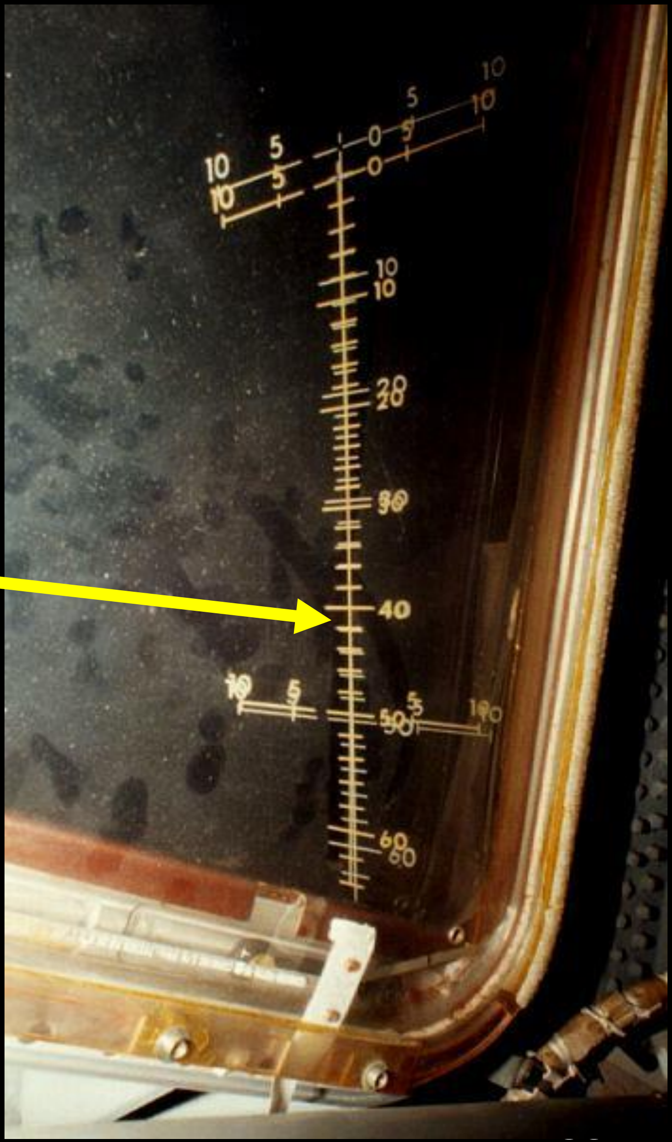
TFI	θ	VI	(-ḢMAX) -HDOT	(ΔHMAX) H	DPS	SBD
0:00	113	5560.0	2.0	50000	95	2/1
0:30	112	5490.0	7.0	49900	95	
1:00	106	5210.0	37.0	49300	91	7/-3
1:30	100	4910.0	59.0	47800	86	
2:00	95	4610.0	73.0	45800	80	15/-11
2:30	90	4310.0	82.0	43500	75	
3:00	86	3990.0	87.0	40900	70	22/-16
3:30	83	3670.0	89.0	38300	65	
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	73	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
8:30	59	480.0	(252.0) 154.0	(+2400) 8300	20	

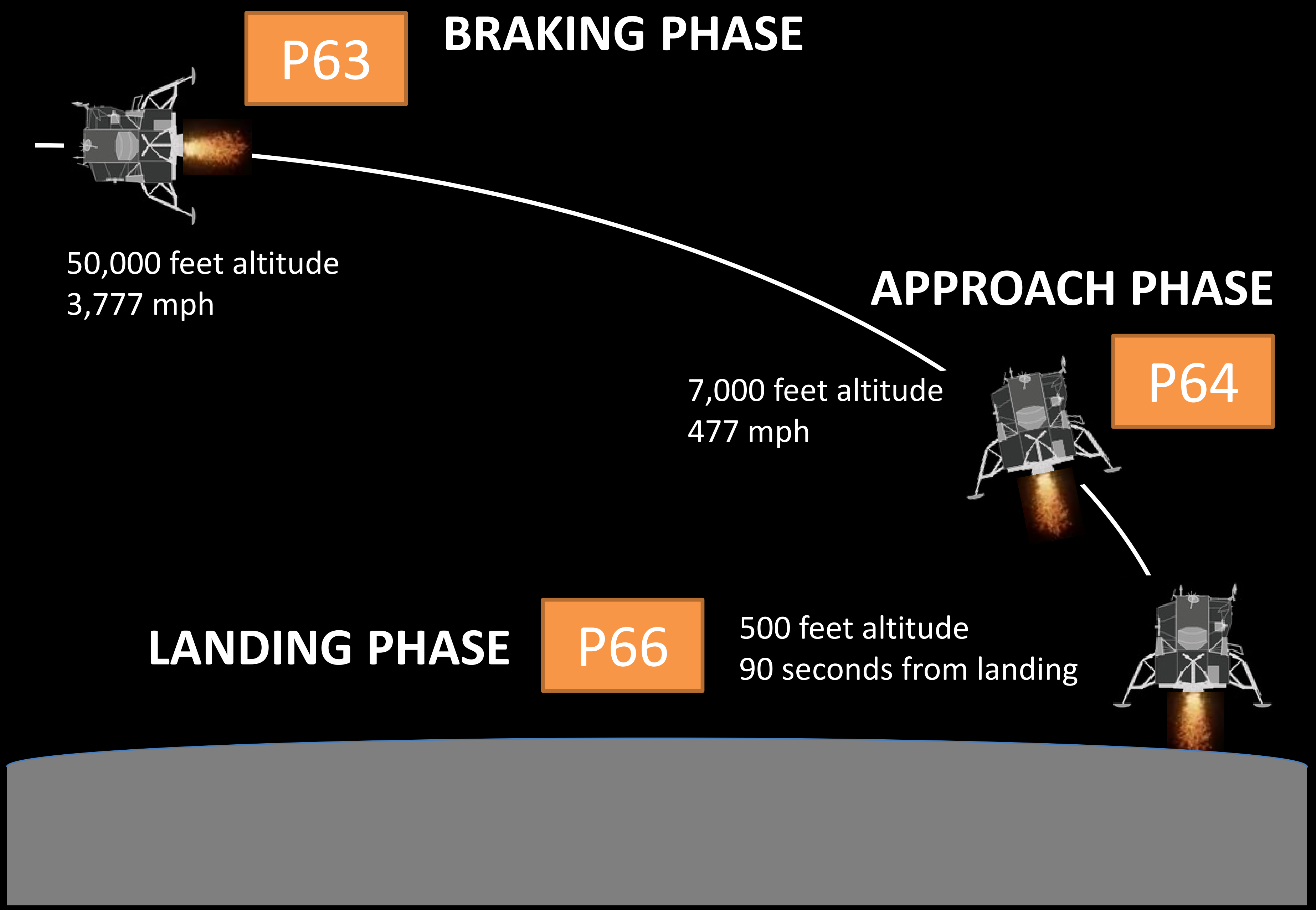

P63
BRAKING PHASE
50,000 feet altitude
3,777 mph
APPROACH PHASE
P64
7,000 feet altitude
477 mph
2 miles to go

P64 - Approach Phase

- Landing Point Designator (LPD)





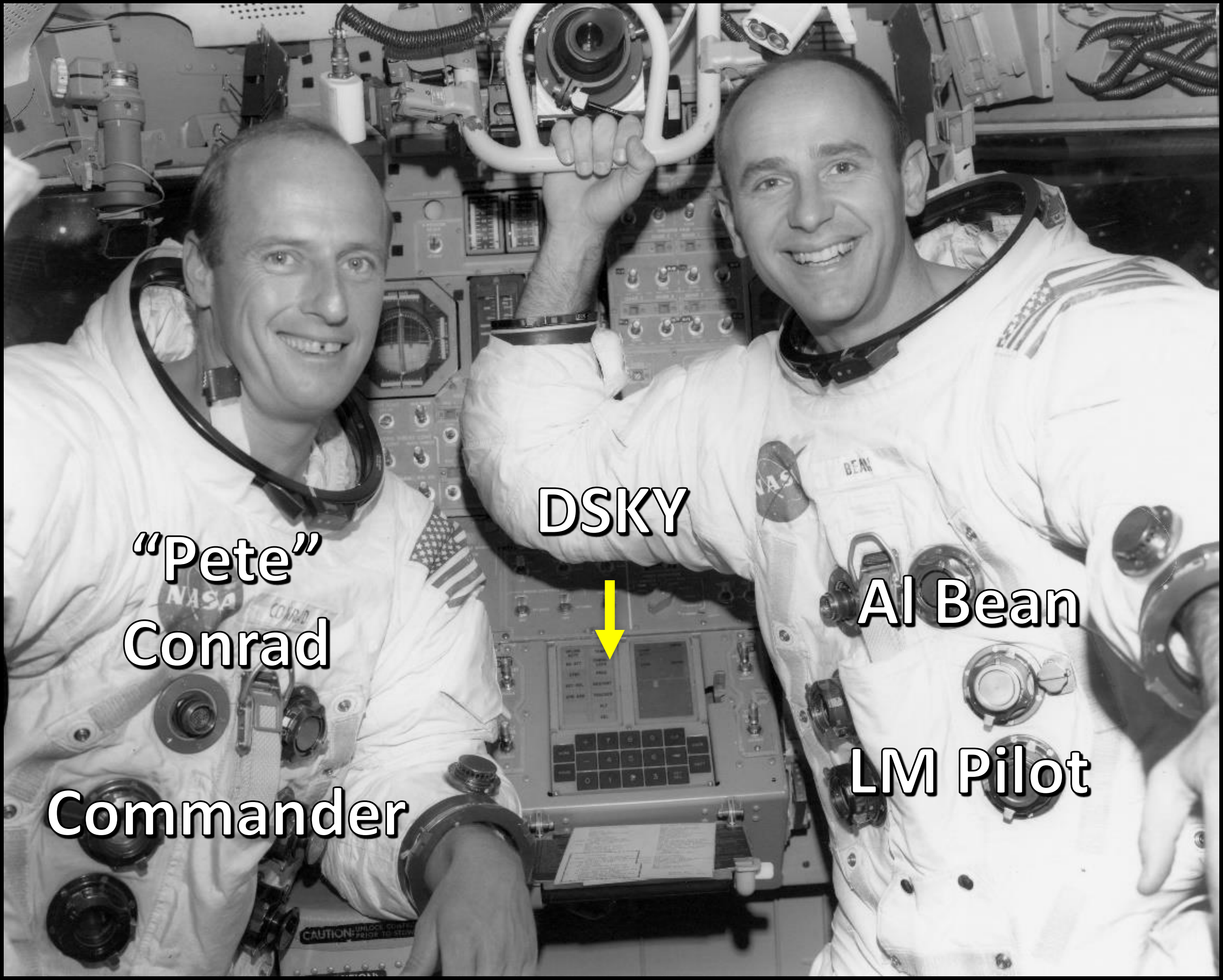

P63
BRAKING PHASE
50,000 feet altitude
3,777 mph
APPROACH PHASE
P64
7,000 feet altitude
477 mph
LANDING PHASE
P66
500 feet altitude
90 seconds from landing

Ride Along with Apollo 12

Apollo 12 Landing

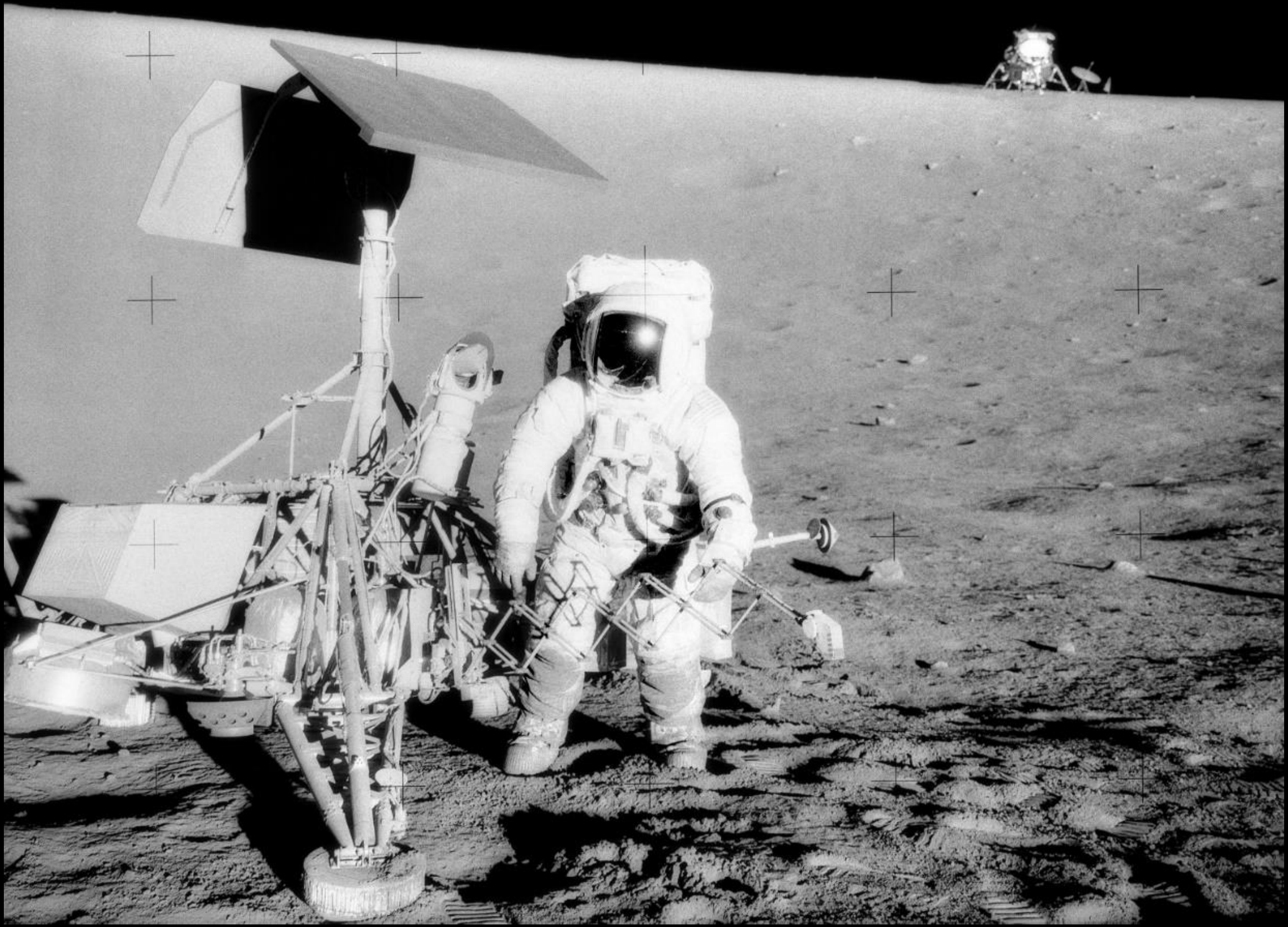
- Second lunar landing mission
- November 19, 1969 - Ocean of Storms
- Pete Conrad, Dick Gordon, Al Bean
- First precision landing

Apollo 12 Dramatis Personae



Demo

Apollo 12 and Surveyor 3



Legacy

A Few Pioneering Things

- Logic built entirely with integrated circuits
- Real-time processing
- Priority multitasking
- Digital fly-by-wire
- Discipline of software engineering
- Crash and restart

Margaret Hamilton

Margaret Hamilton

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

Presidential Medal of Freedom, 2016

LEGO Margaret Hamilton

Dr Charles Draper

Charles Stark Draper Laboratory

The AGC in Popular Culture

Apollo 13

1995

Apollo 13

Valerian and the City of a Thousand Planets

VALERIAN AND THE CITY OF A THOUSAND PLANETS

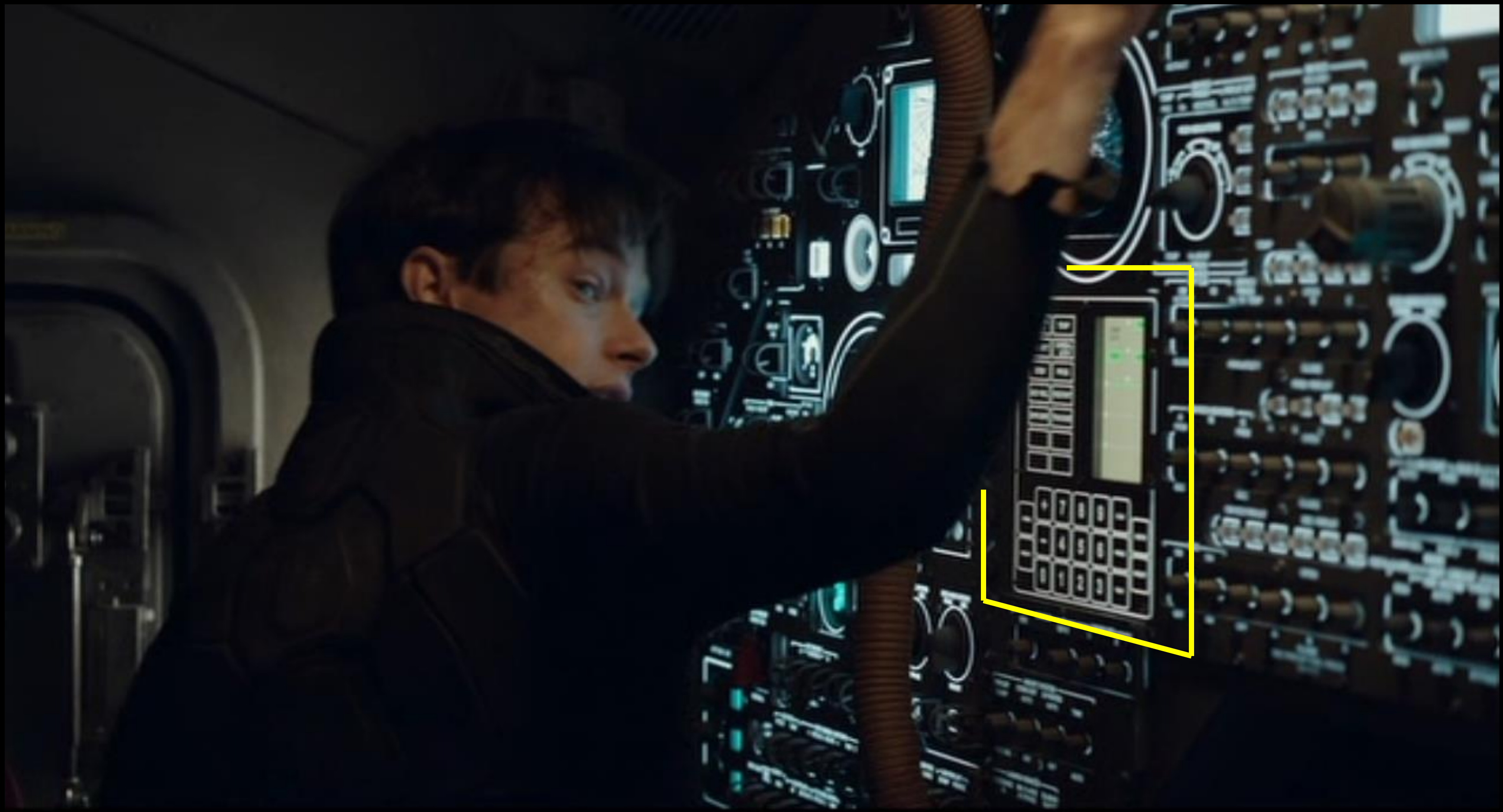
PG-13 2017, Sci-fi/Adventure, 2h 17m

48% TOMATOMETER 301 Reviews

53% AUDIENCE SCORE 25,000+ Ratings

2017

Valerian and the City of a Thousand Planets



Reproductions

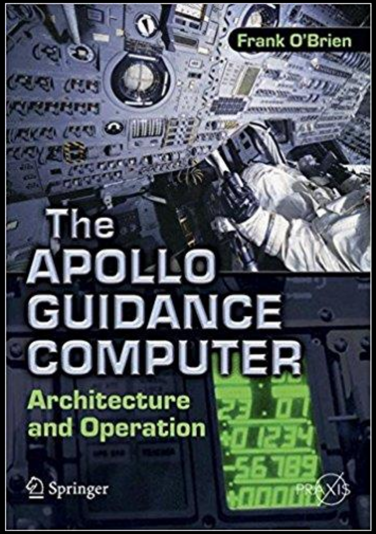
Working AGC

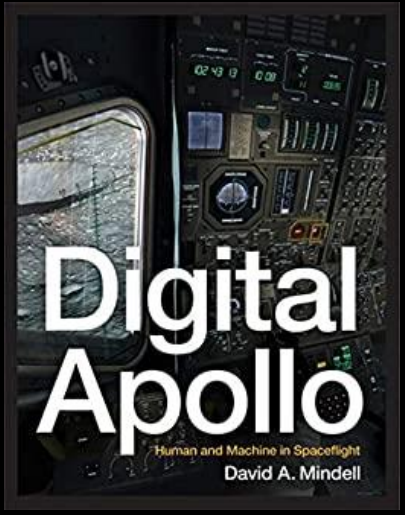
- Only a single working AGC exists
- Restored by YouTuber CuriousMarc

https://www.curiousmarc.com/space/apollo-guidance-computer

Explore More

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





Saturn V Step-by-Step

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Questions?

Computers to the Moon

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