



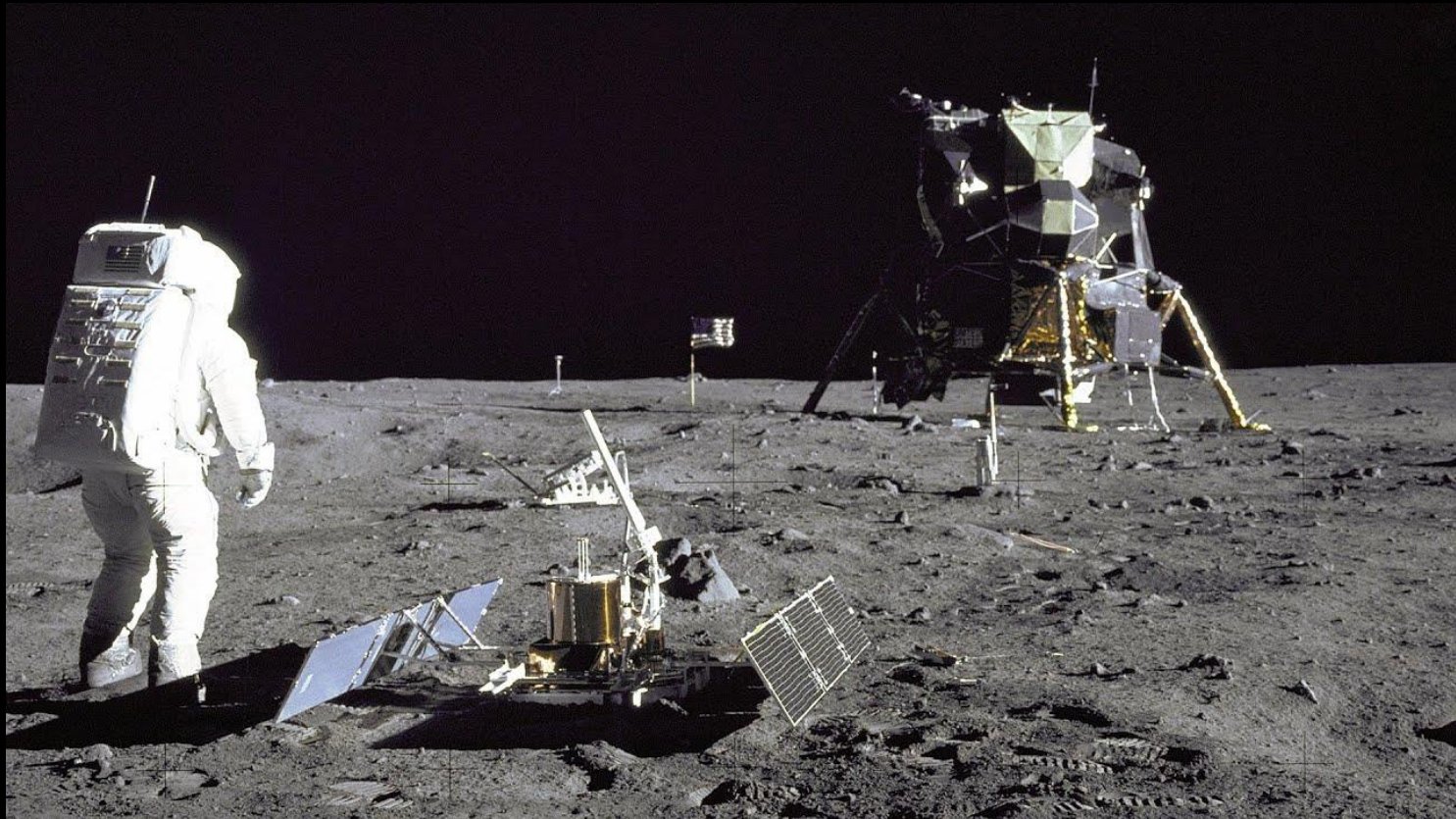
# Computers to the Moon



Mark Schulman

# Agenda

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

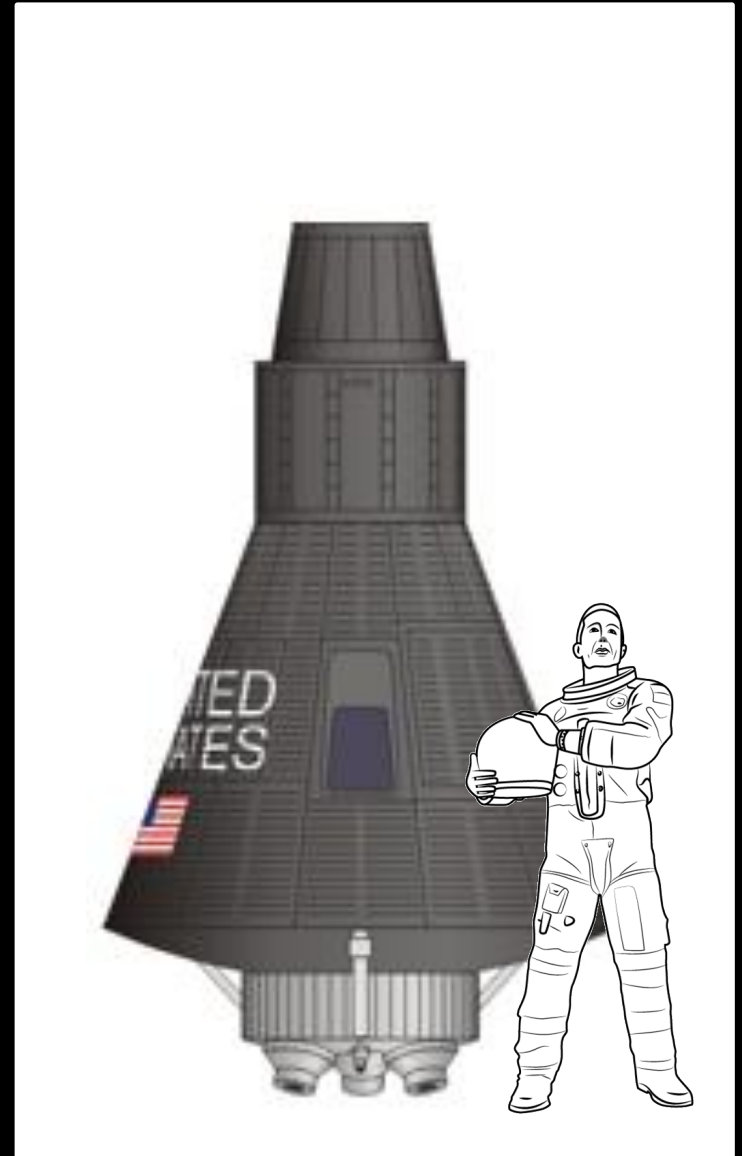


# Dawn of the Space Age

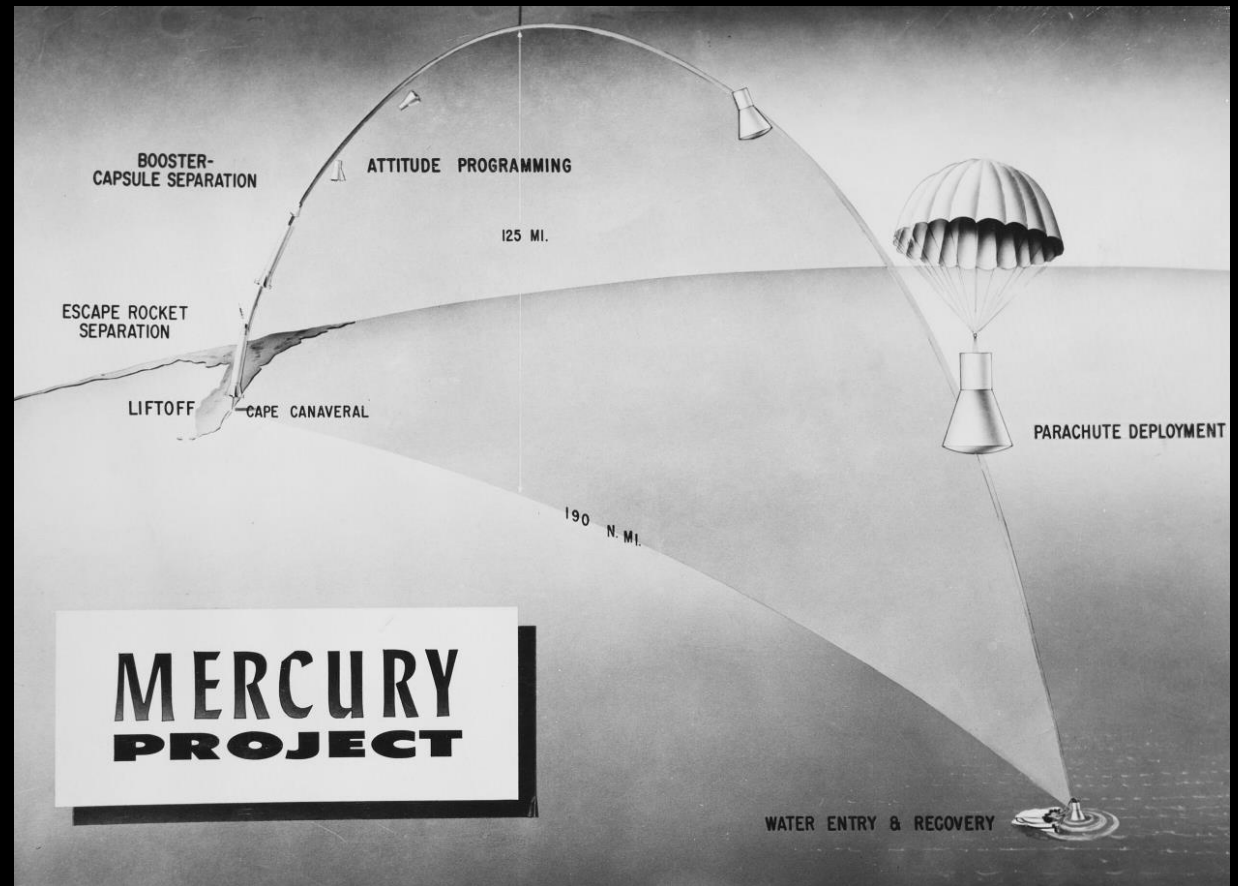


# May 5, 1961 – Freedom 7

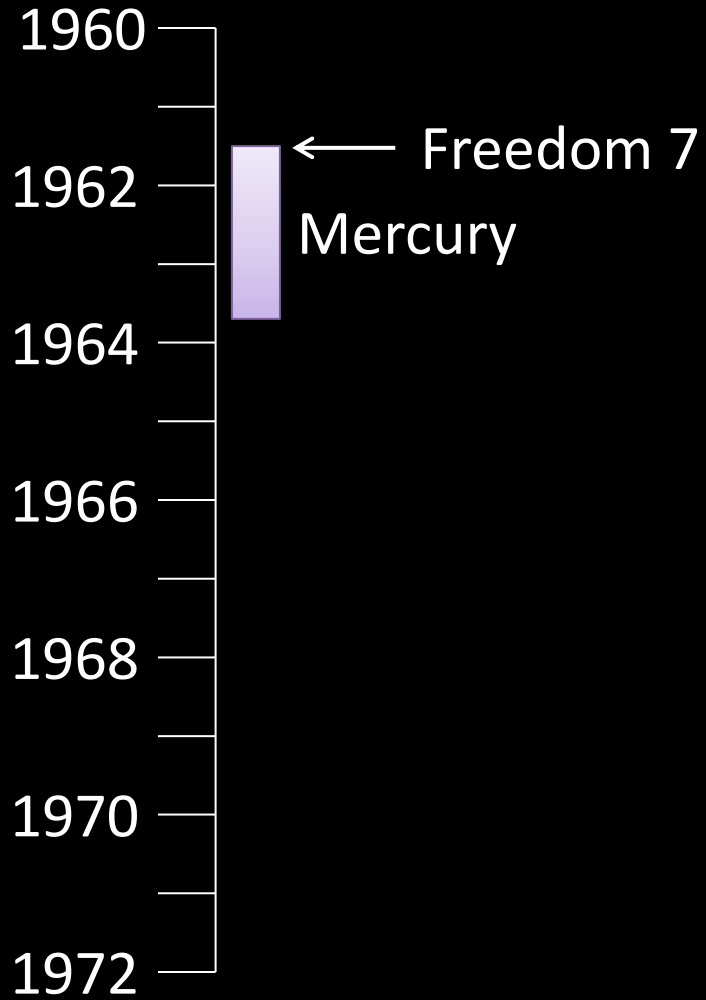
- Mercury capsule launch aboard a Redstone rocket
- Astronaut Alan Shepard
- First American in space



# Freedom 7



# 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



Rice University, September 1962



# Frenzy of Research and Development



# Preparing to Go to the Moon

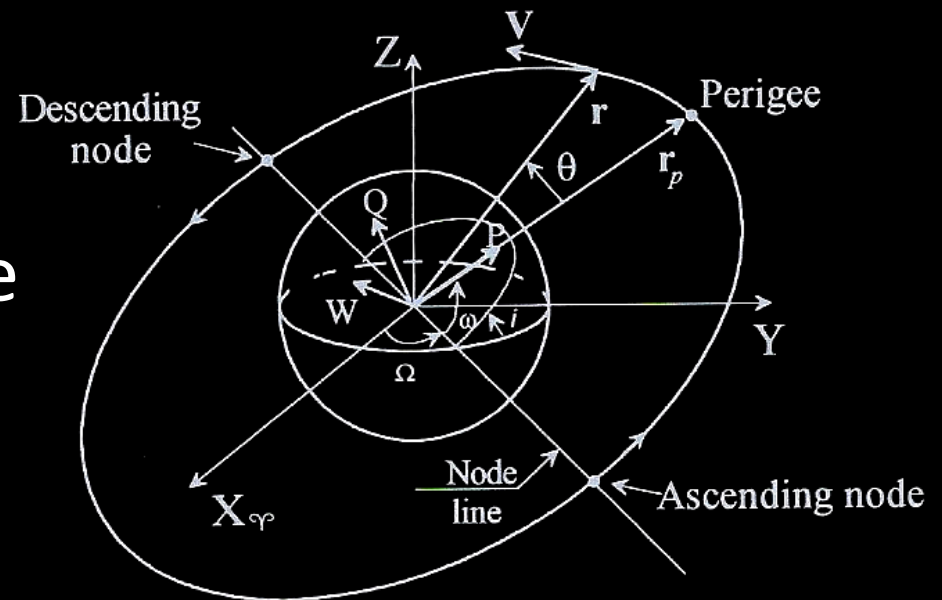
Skills we would need

1. Working outside
2. Rendezvous and docking
3. Maneuvering in space



# Maneuvering in Space

- Highly mathematical
  - Completely non-intuitive
  - There's a reason they call it rocket science
- 
- Just about impossible without a computer



# Example: Translunar Injection (TLI)

On the side of the Earth opposite the Moon ...

... while traveling at 17,500 mph

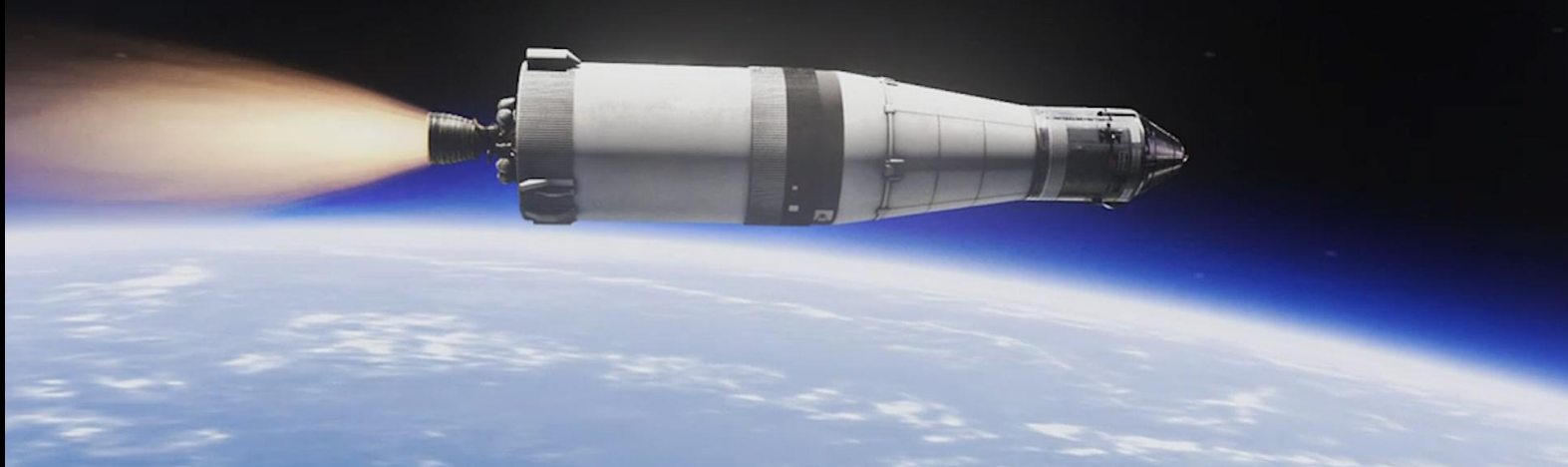
... with no sensation of speed

... add exactly the right amount of speed (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.





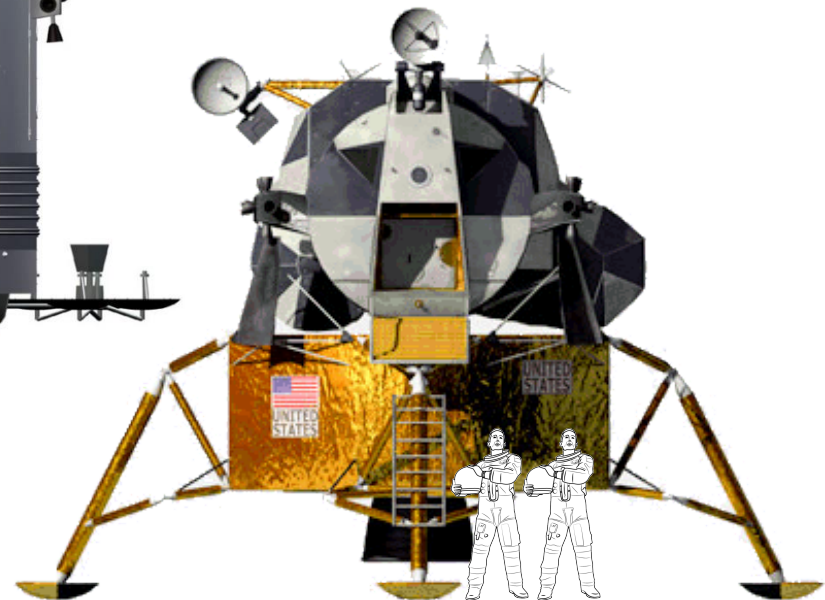
# A Computer for Apollo

# Apollo – Going to the Moon

Command and  
Service Module



Lunar Module



# Computer Requirements

- Execute trajectories to get from the Earth to the Moon
- Continuously update position and attitude
- Control spacecraft's engines and thrusters
- Display flight data
- Receive remote updates from the ground



# 1960s Computing



NASA Real Time Computing Center, 1966



## A yellow Ticker Model M4-25 Vector-Type Log Log slide rule. The device features multiple logarithmic scales for various mathematical functions, including multiplication, division, and vector calculations. The scales are labeled with 'D', 'DI', 'DF', 'CF', 'T', 'ST', 'C', and 'S'. The brand name 'Ticker' is visible on the right side. The slide rule is mounted on a metal frame with adjustment screws. The left end of the frame is labeled 'MODEL M4-25 Vector-Type LOG LOG' and 'DUAL-BASE SPEED BUILD'. The right end of the frame is labeled 'DUAL-BASE SPEED BUILD' and 'DUAL-BASE SPEED BUILD'. The scales are yellow with black markings and numbers. The metal frame is silver-colored. The slide rule is shown against a black background.

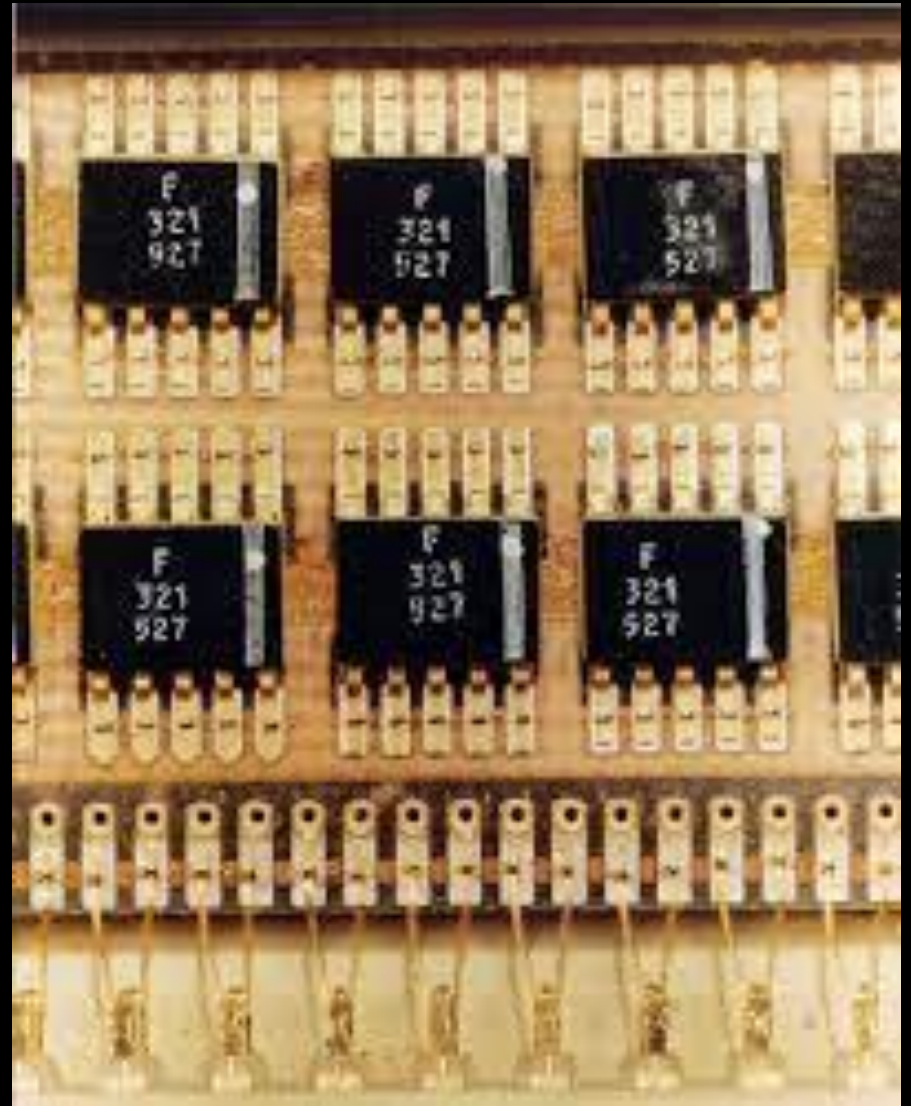
# Charles Stark “Doc” Draper

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

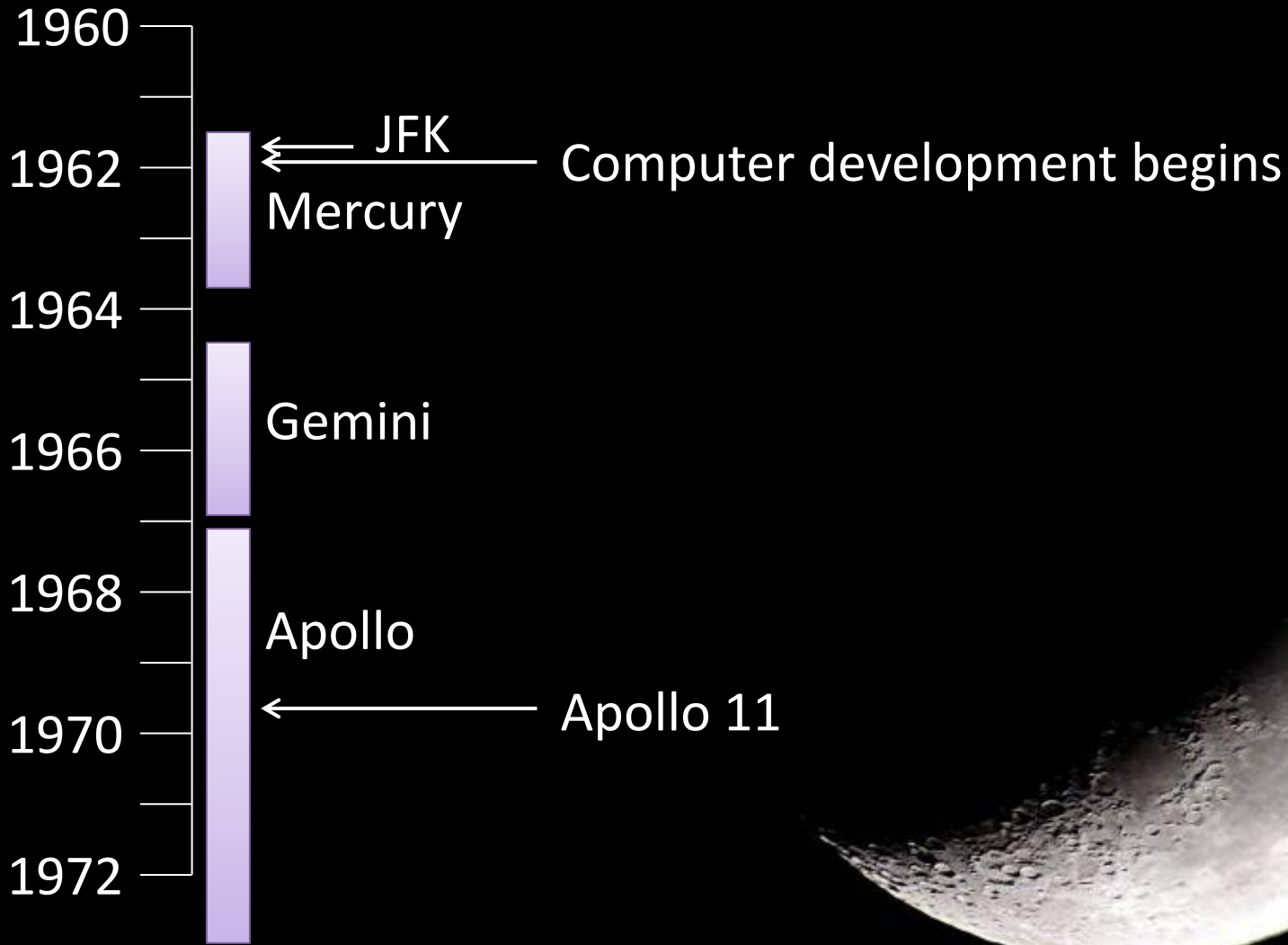


# Crucial Decisions

- Computer would be digital
- Save weight and power by using integrated circuits
- Simplify by using identical integrated circuits
- Work began in 1961



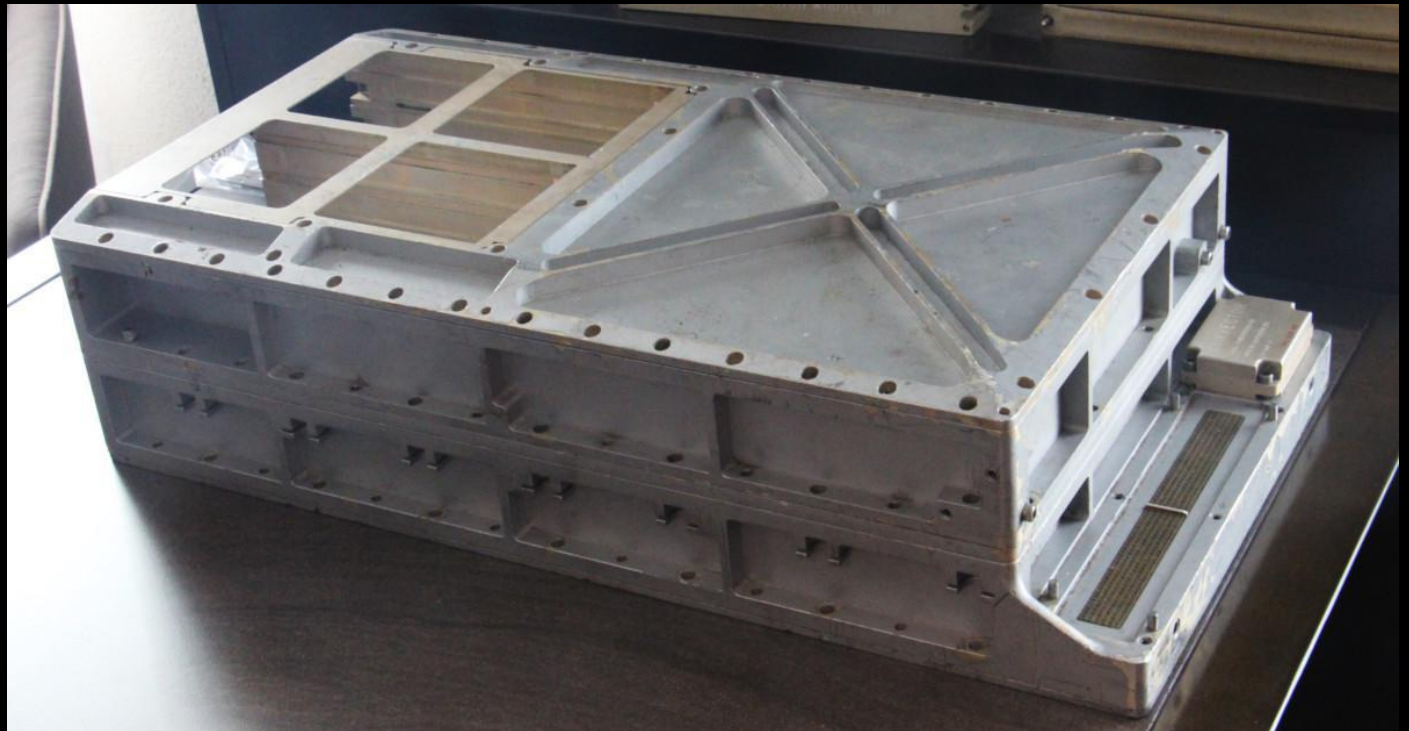
# Apollo – Going to the Moon





# The Apollo Guidance Computer (AGC)

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

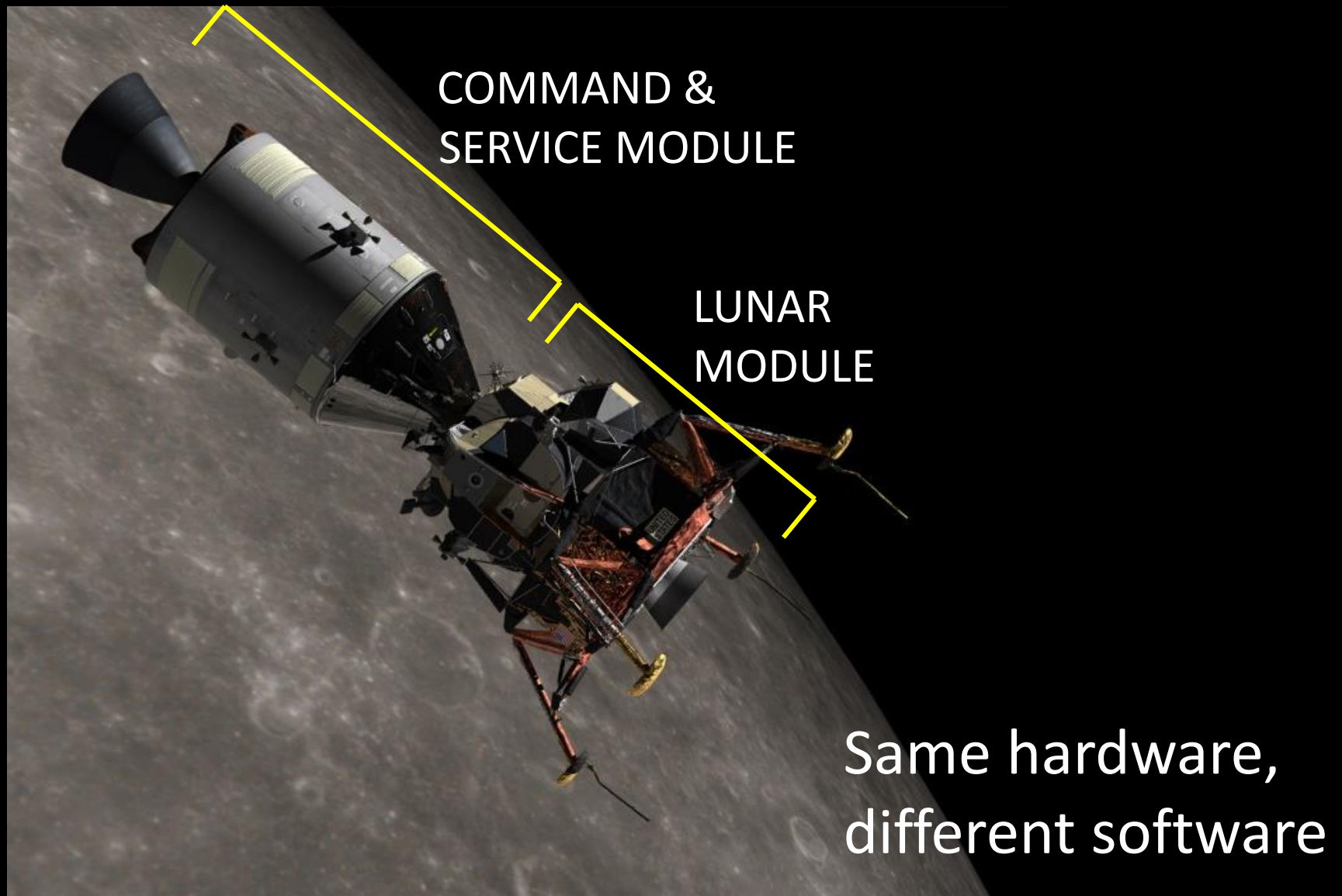


# AGC Hardware

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



# Two Spacecraft, Two Computers





# The Innards





# What Did the AGC Actually Do?



# 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

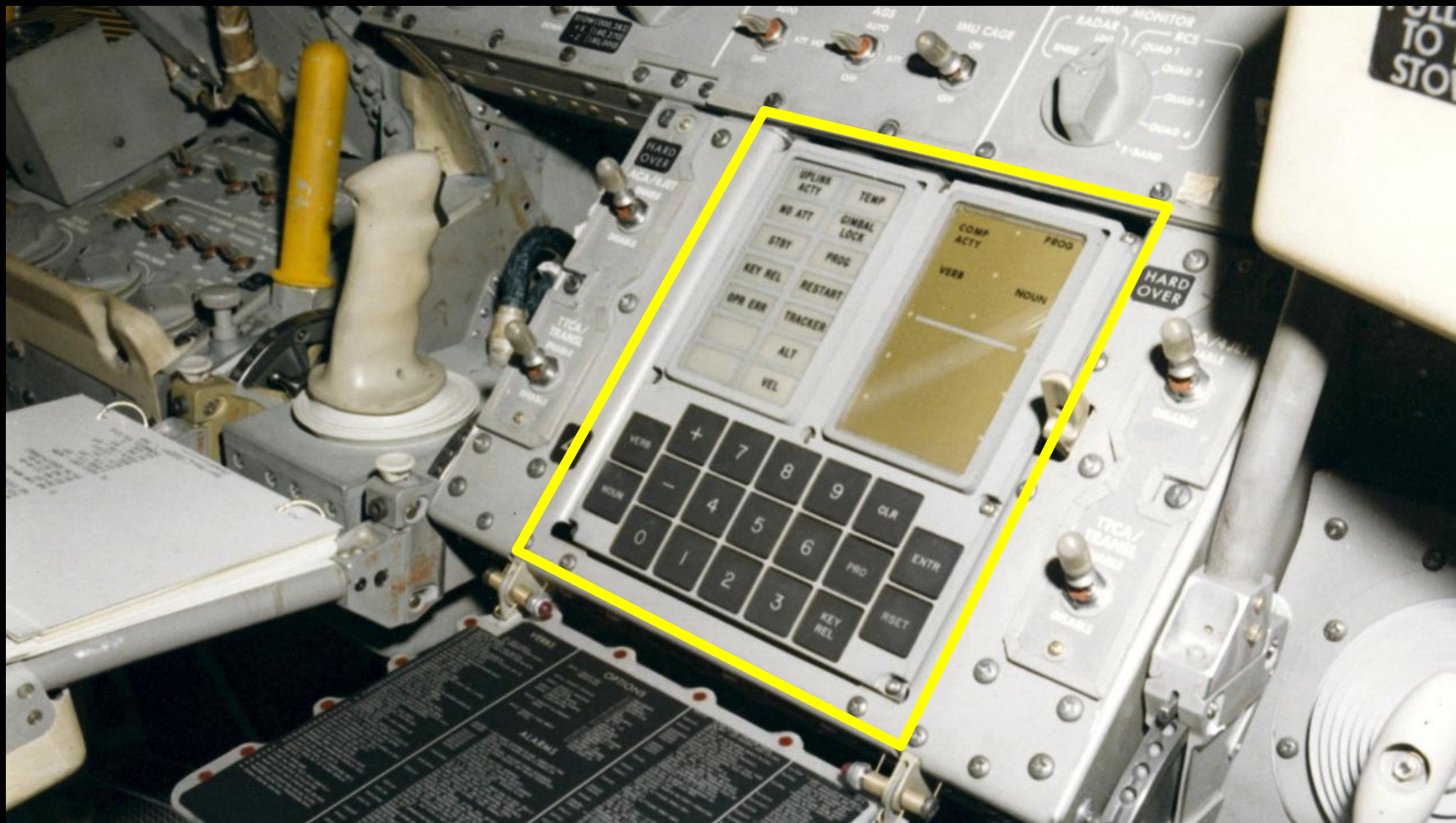


# Where's the Mouse?

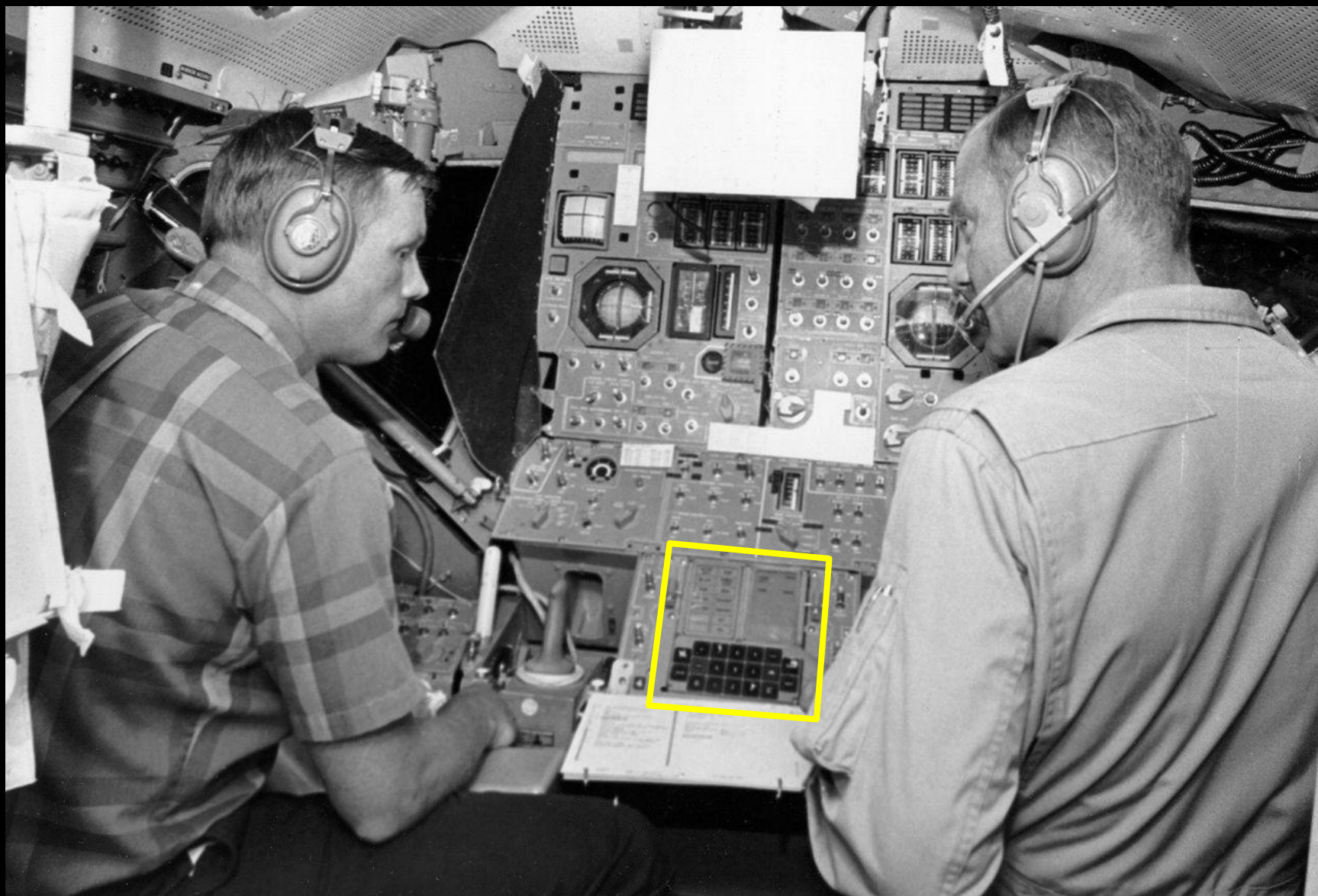
- How do we talk to this thing?



# Display/Keyboard (DSKY)

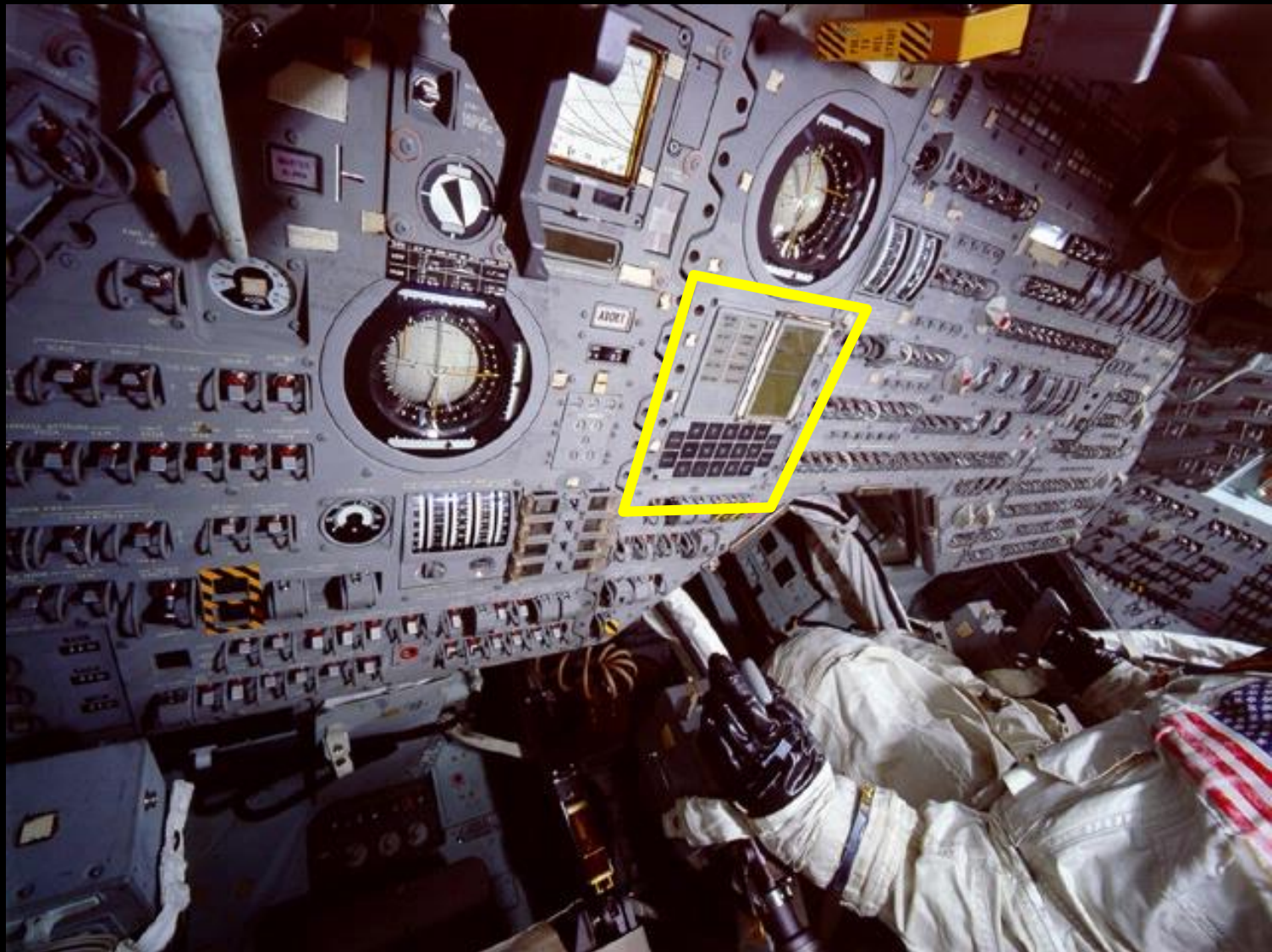


# DSKY in the Lunar Module





# DSKY in the Command Module

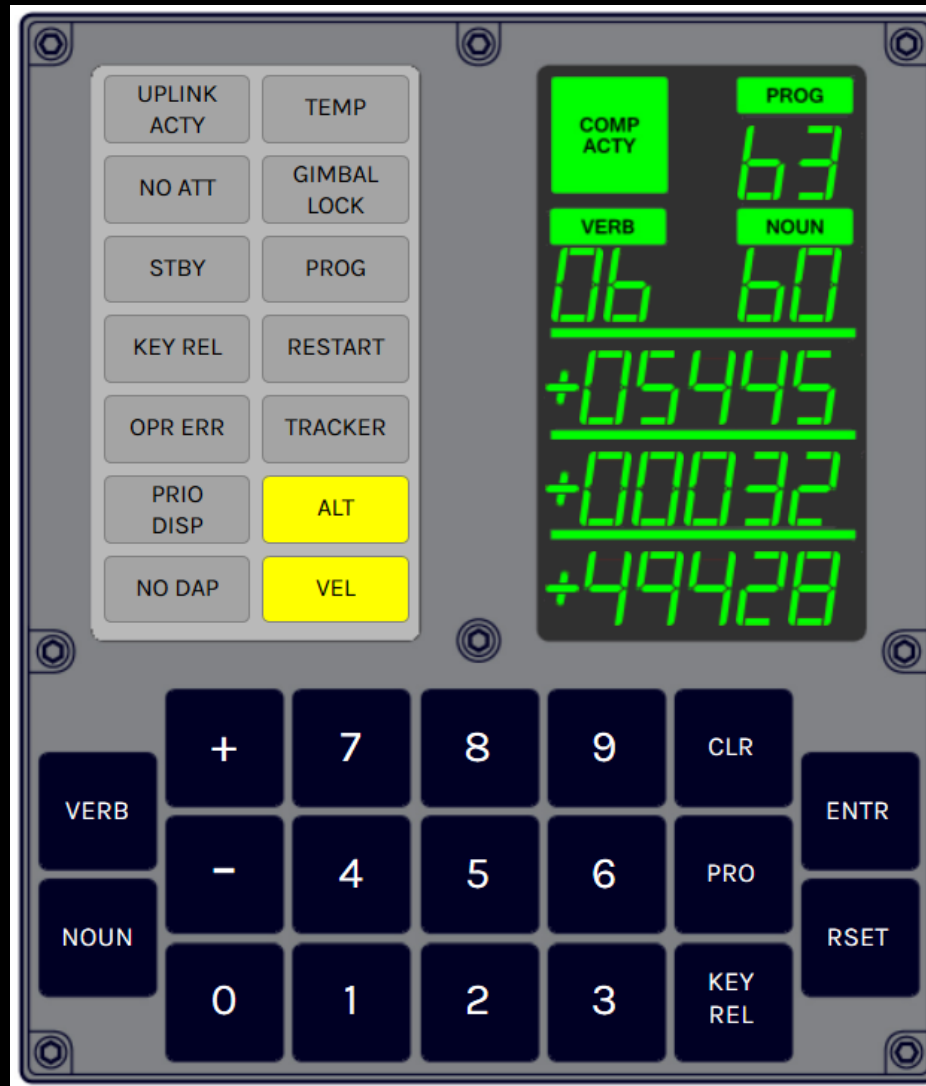




# The DSKY (Display and Keyboard)

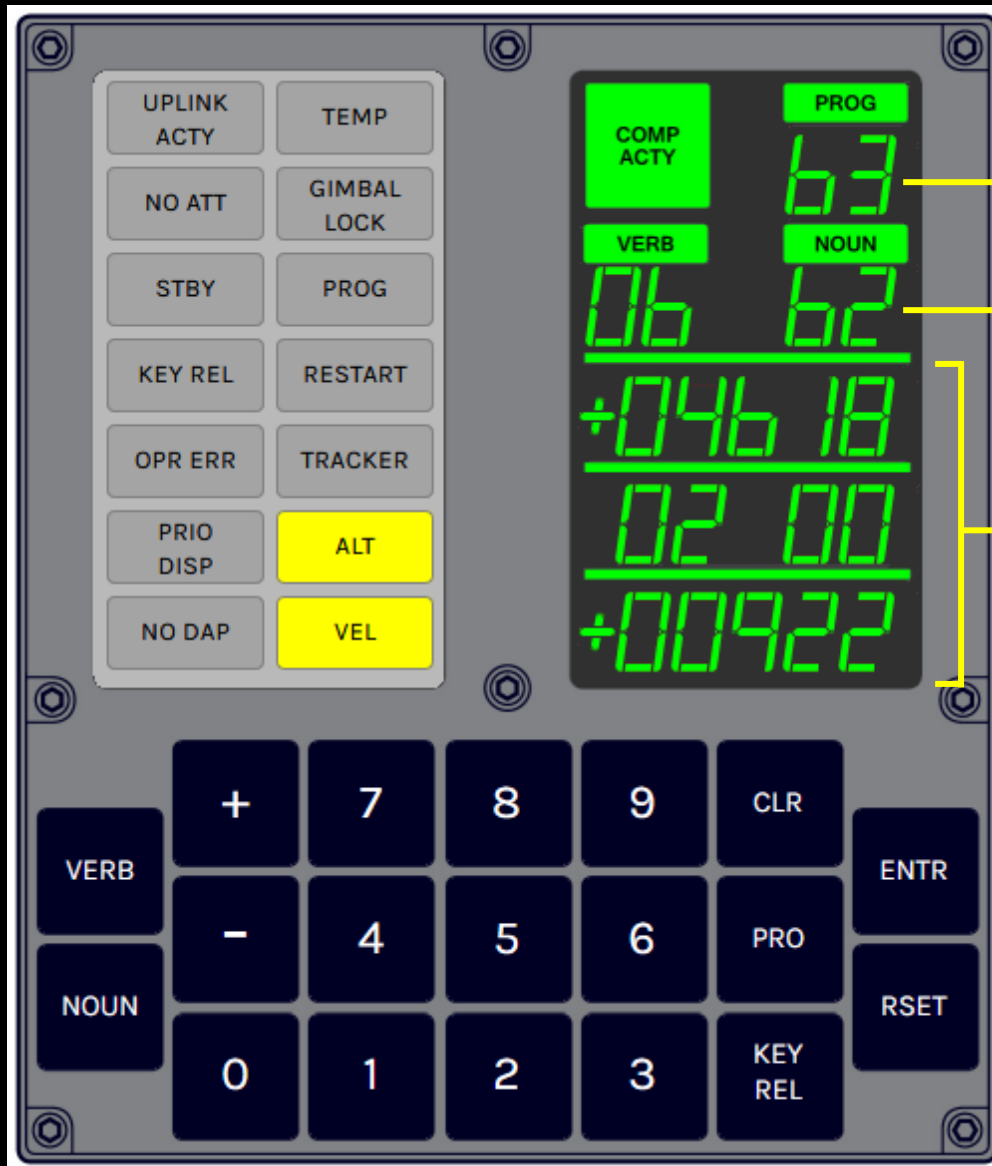
INDICATORS  
LIGHTS

KEYBOARD



DISPLAYS

# Communicating with the AGC



Program

Verb and Noun

Registers

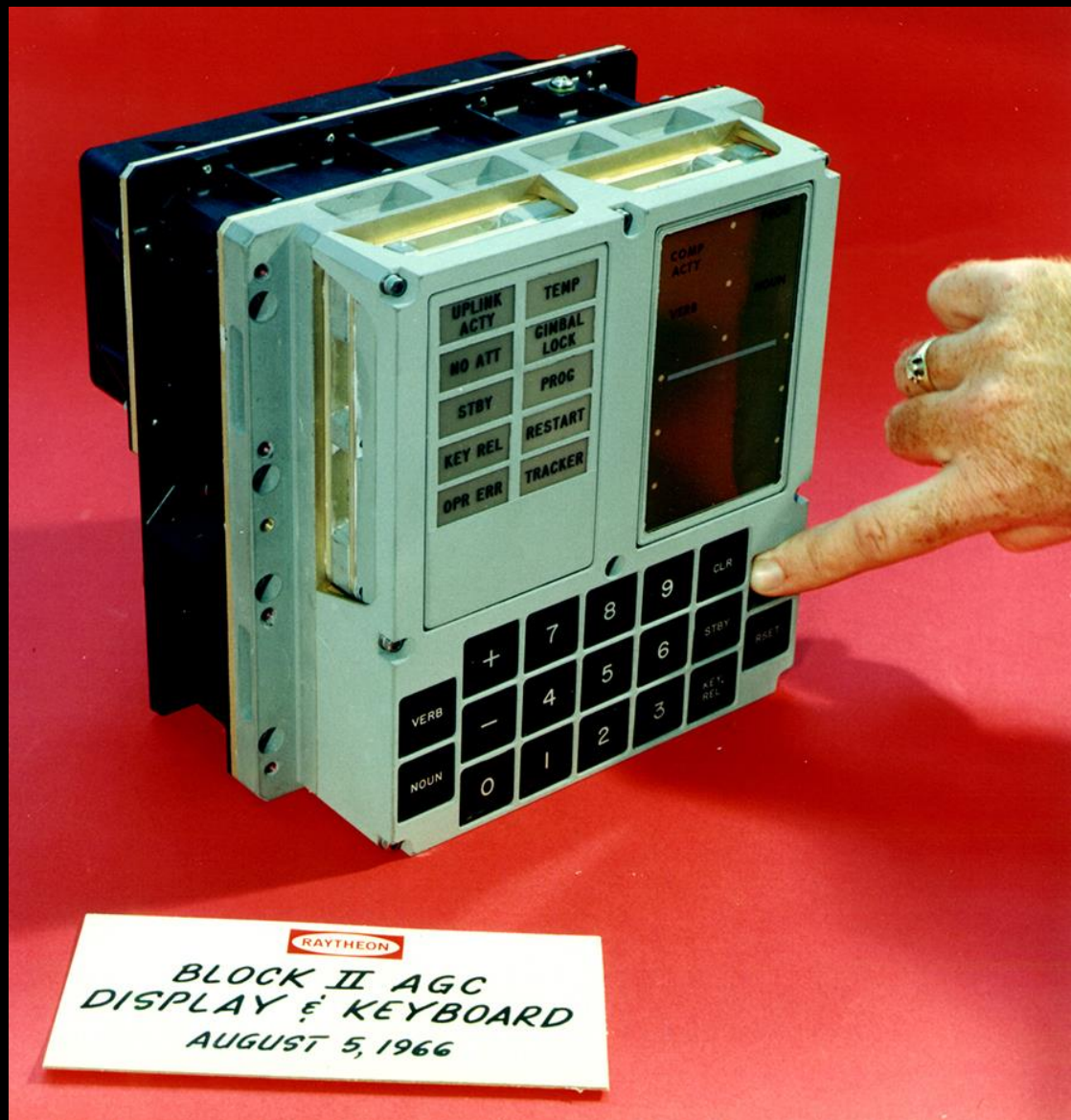
# Verbs and Nouns

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

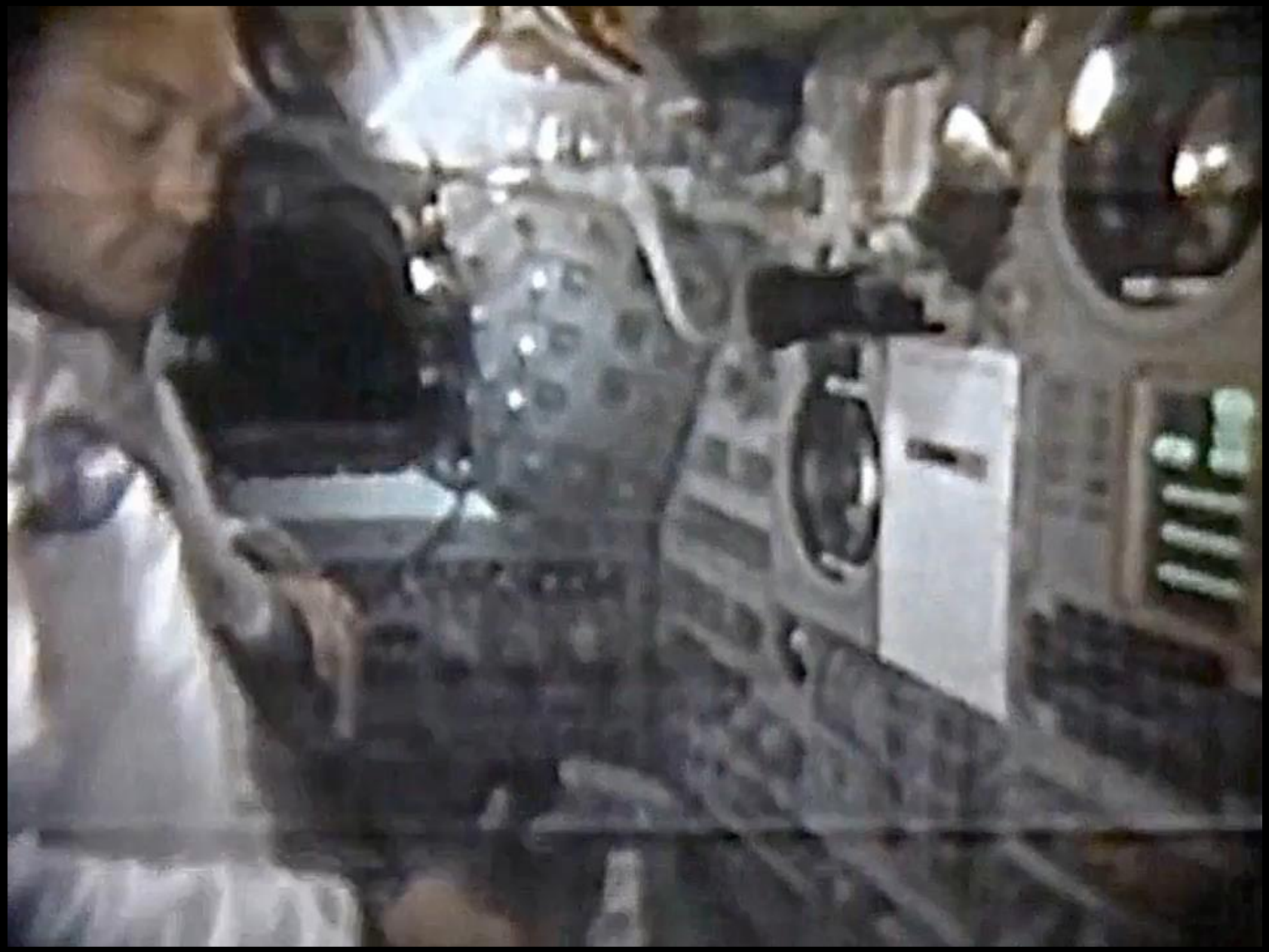


nouns  
verbs

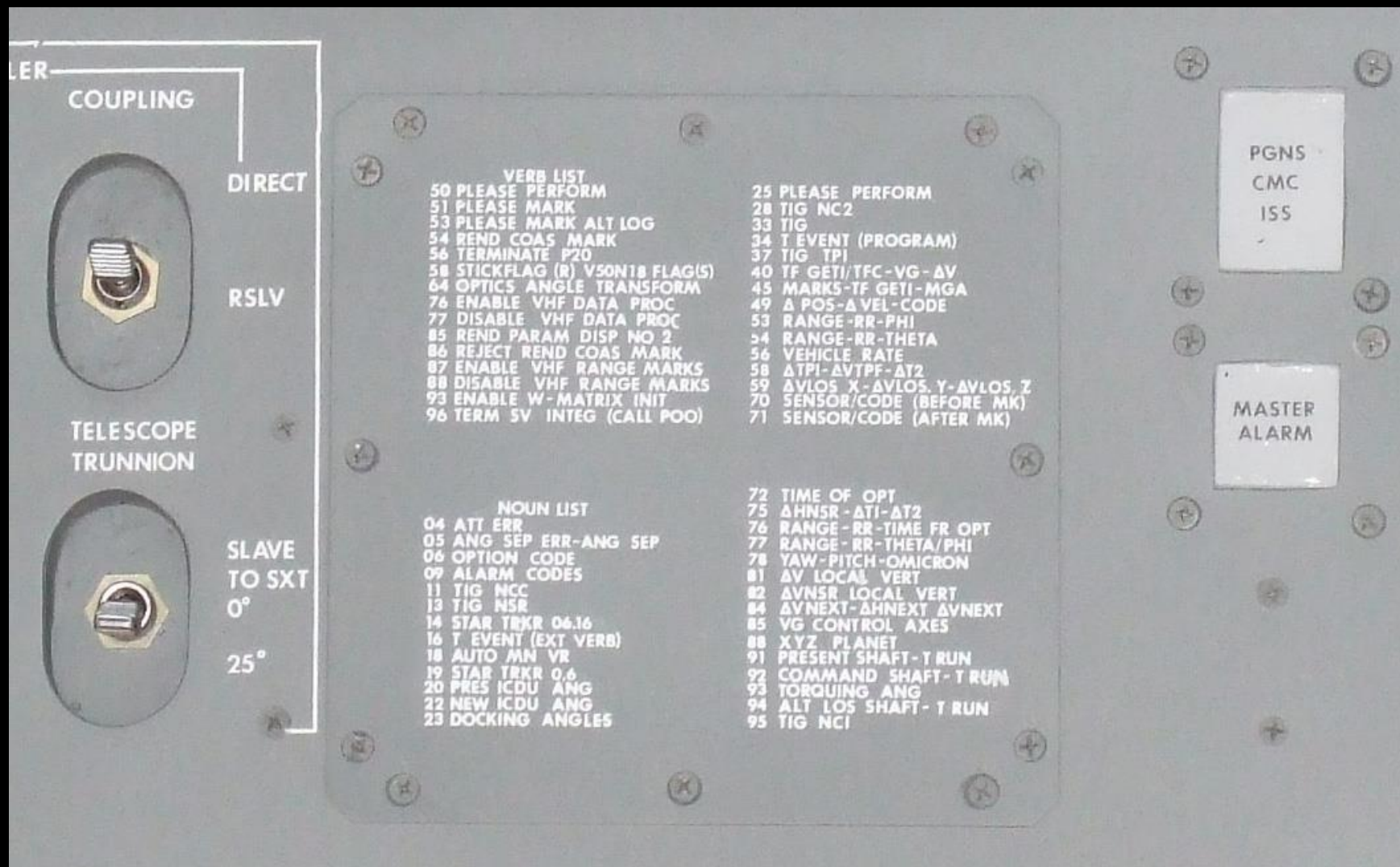
# Sample DSKY Operations





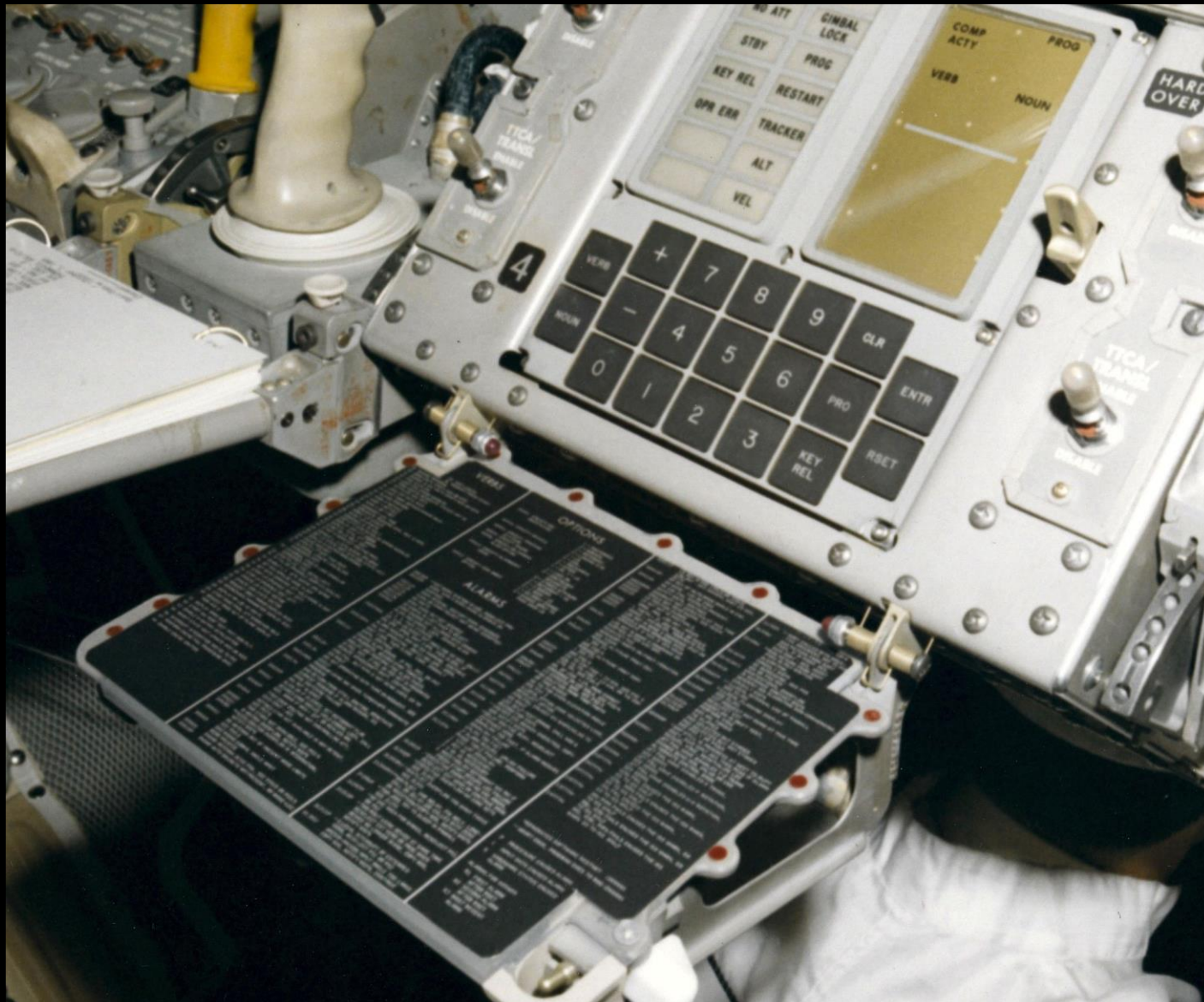


# DSKY Cheat Sheets (Command Module)





# DSKY Cheat Sheets (Lunar Module)



# FLIGHT PLAN

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

LM

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

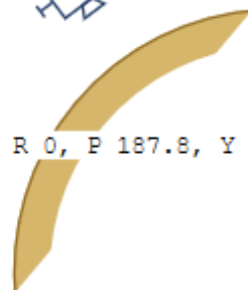
V76, P33 CDH PRETHRUST

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

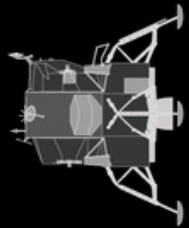
# Landing on the Moon

- One attempt, no second chances!
- Most of the flying is done by the AGC
- Three phases, each handled by a separate computer program: 63, 64, 66

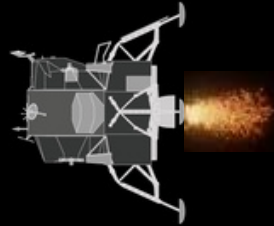


P63

## 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

RESET WATCH  
 -1:00 MASTER ARM-ON  
 - :30 ENG ARM-DES  
 - :07.5 ULLAGE  
 - :05 PRO  
 + :00 **POI**  
 + :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

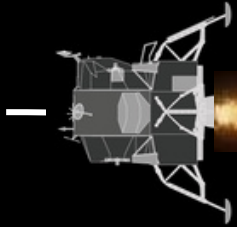
223E @ 12K

POI THRU TD+3 MIN

TFI	Q	VI	(-HMAX) -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

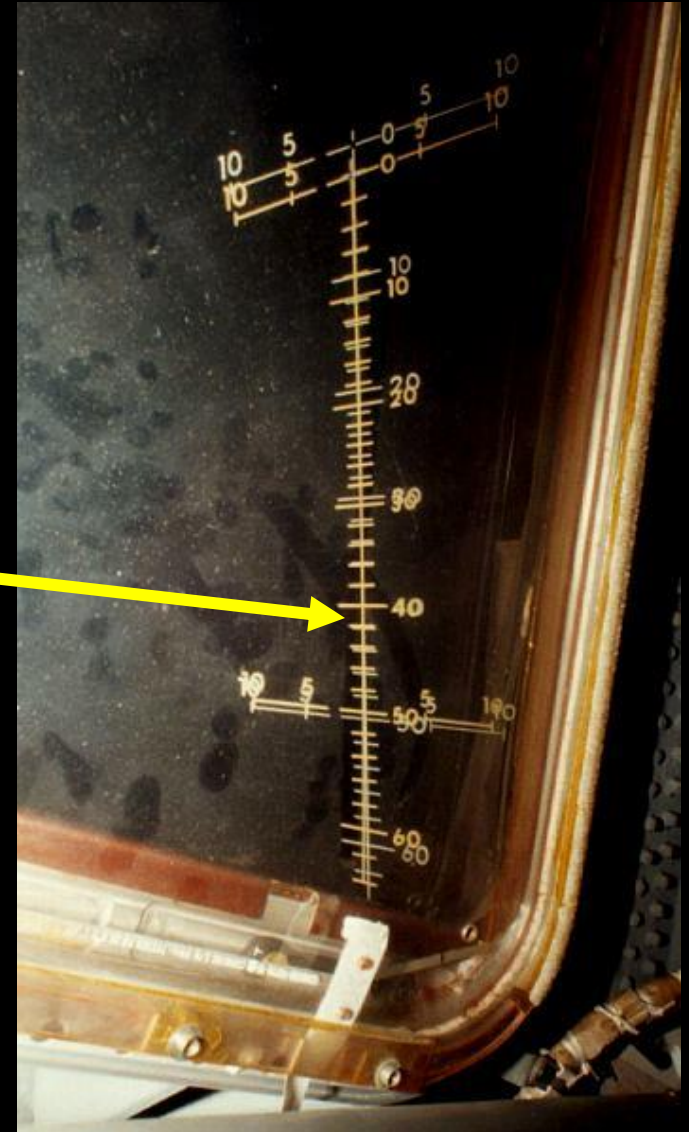
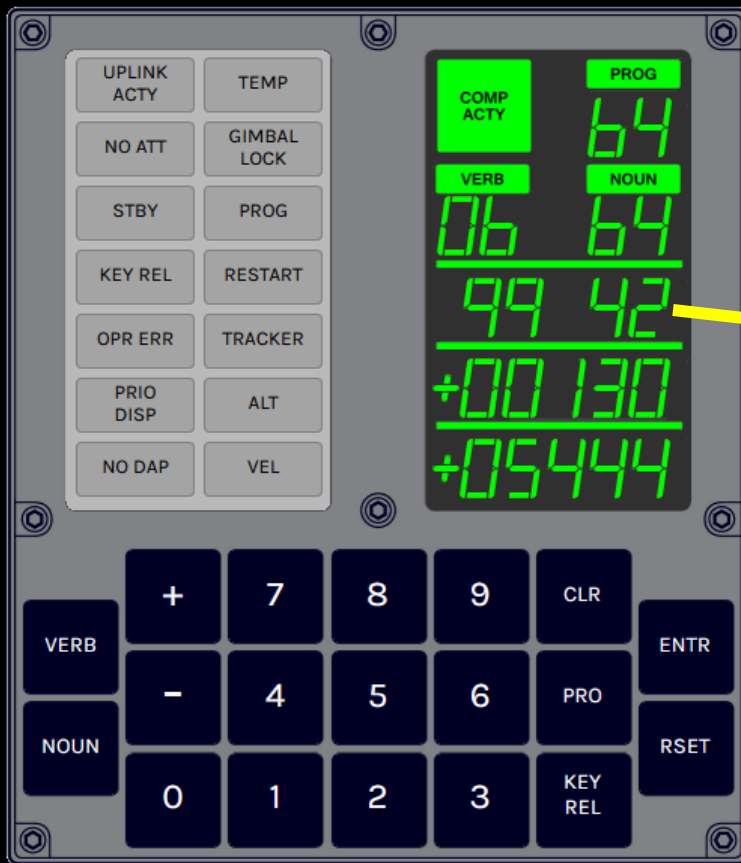
7,000 feet altitude  
477 mph  
2 miles to go





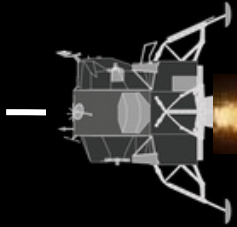
# P64 - Approach Phase

- Landing Point Designator (LPD)



## **BRAKING PHASE**

**P63**



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

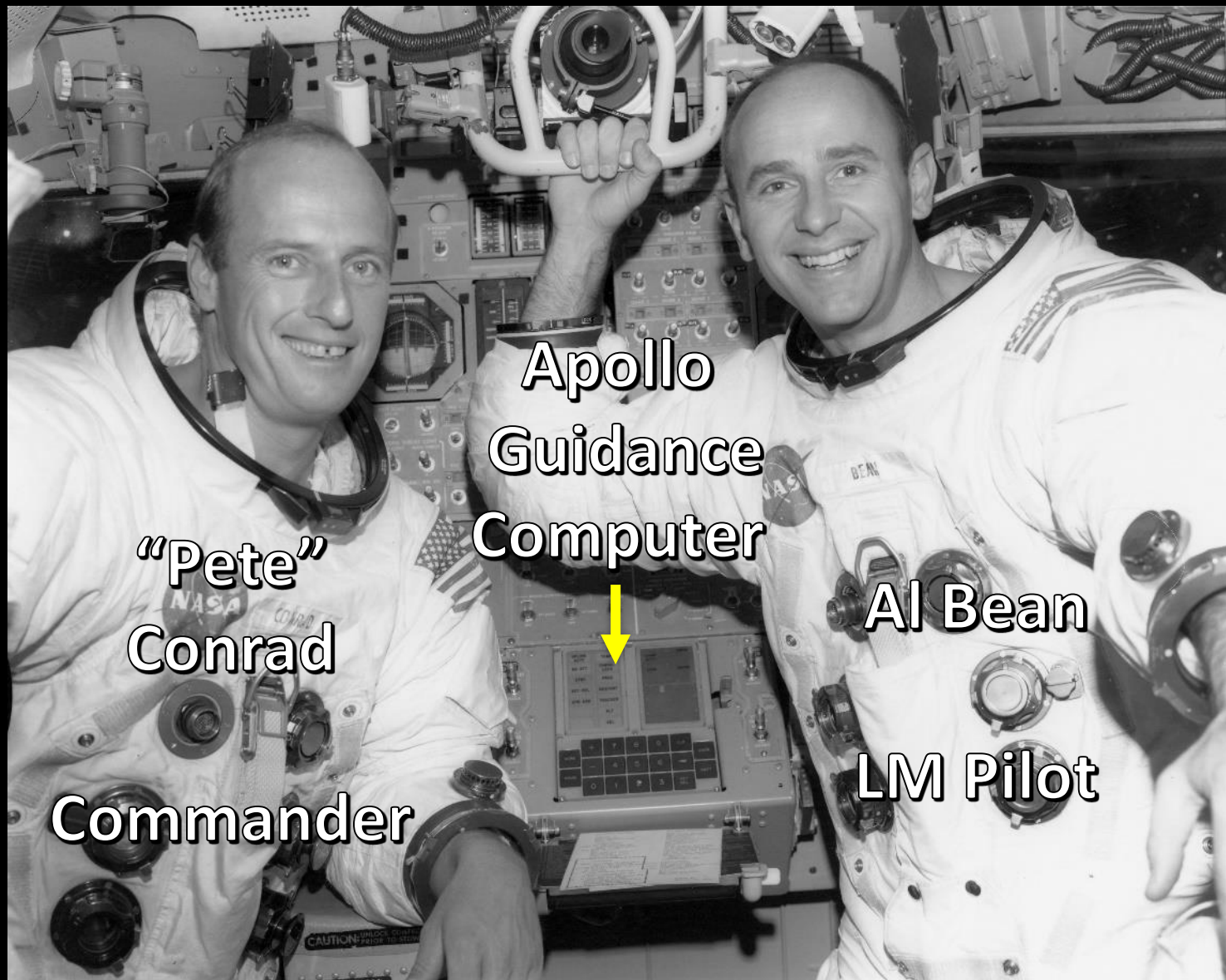
# Apollo 12 Landing

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





# Apollo 12 Dramatis Personae



**"Pete"**  
**Conrad**  
**Commander**

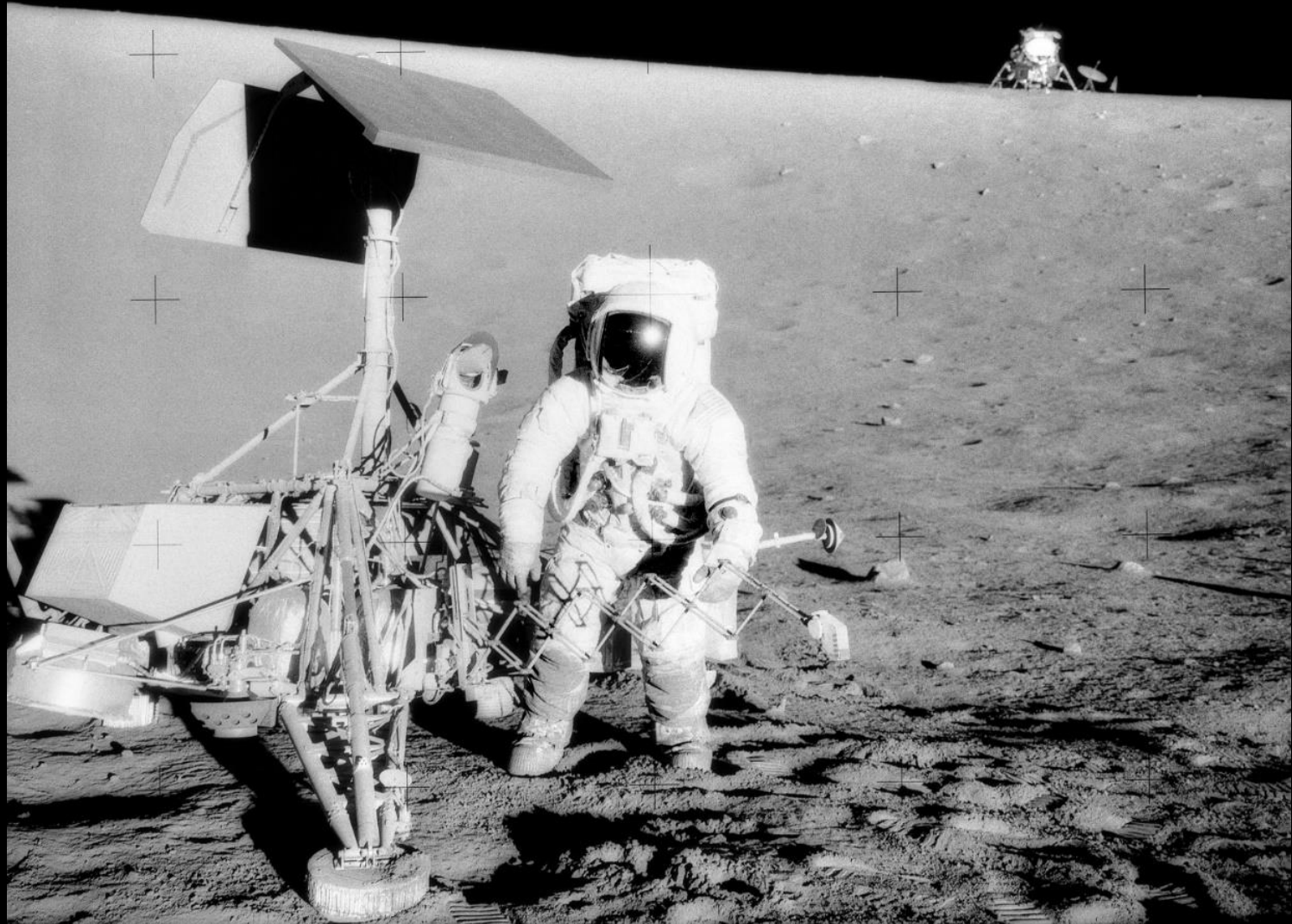
**Apollo**  
**Guidance**  
**Computer**

**Al Bean**  
**LM Pilot**

# 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 Software Engineering Division of MIT's Instrumentation Lab



# Margaret Hamilton





# Presidential Medal of Freedom, 2016





# 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%**

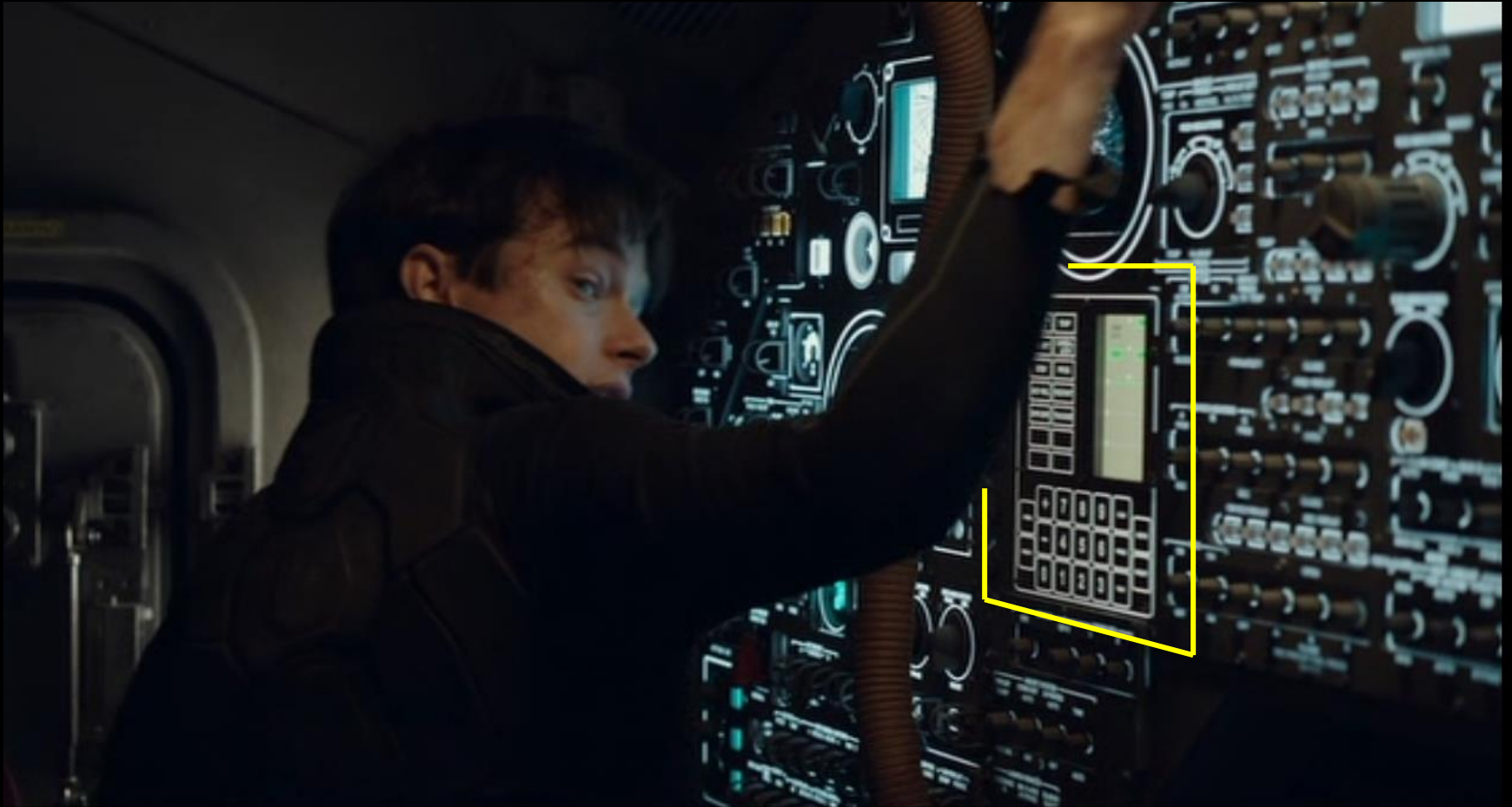
TOMATOMETER  
301 Reviews

 **53%**

AUDIENCE SCORE  
25,000+ Ratings

2017

# Valerian and the City of a Thousand Planets



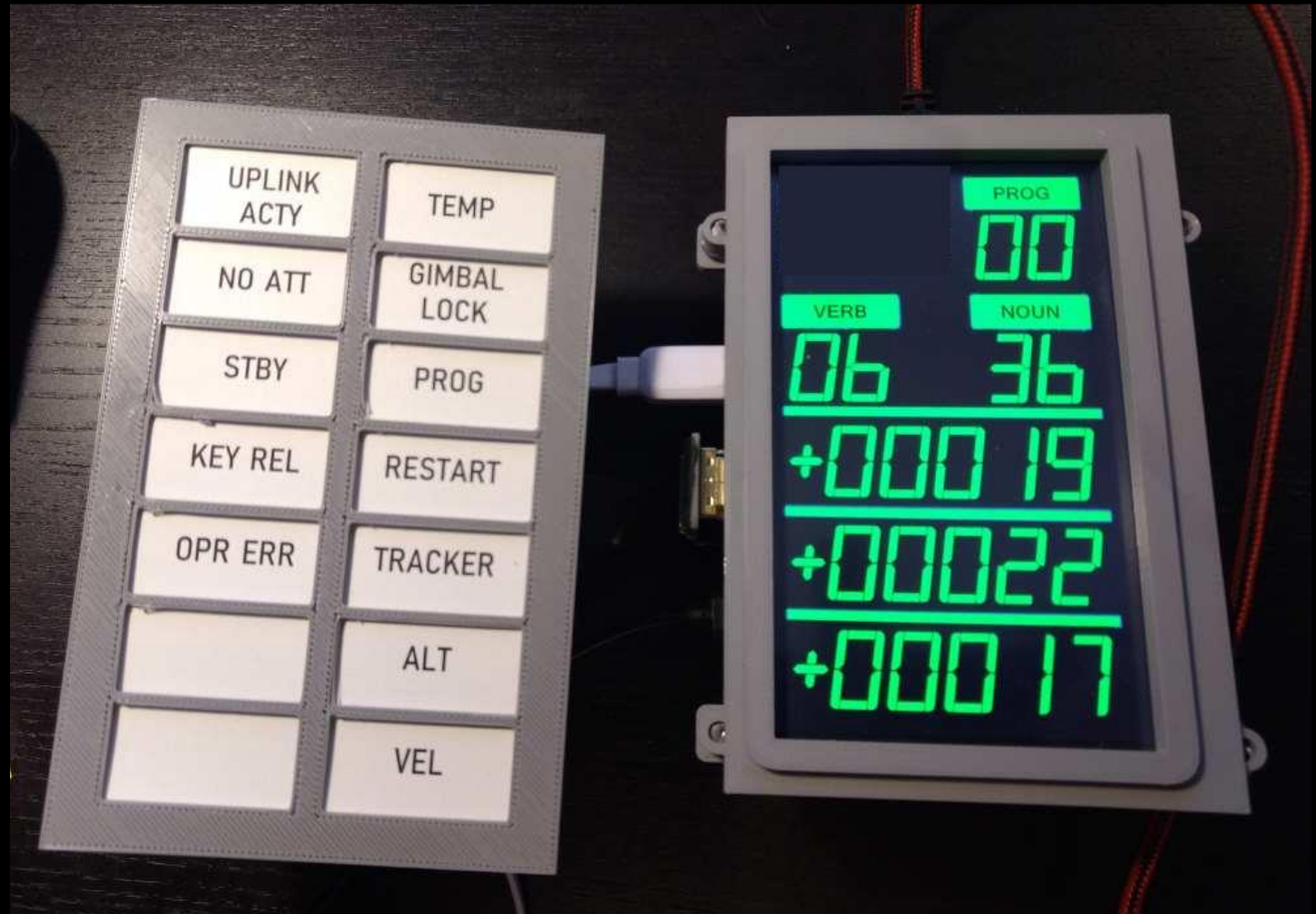


# Reproductions



# Reproductions

- Still a ways to go ...



# Working AGC

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

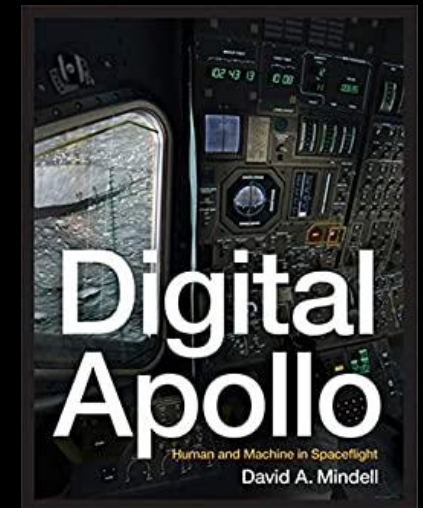
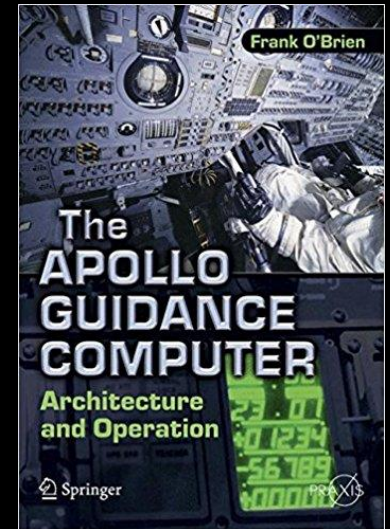


<https://www.curiousmarc.com/space/apollo-guidance-computer>



# 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>



# Questions?

## **Computers to the Moon**

Mark Schulman

Central Florida Computer Society

[marks@schulmans.com](mailto:marks@schulmans.com)