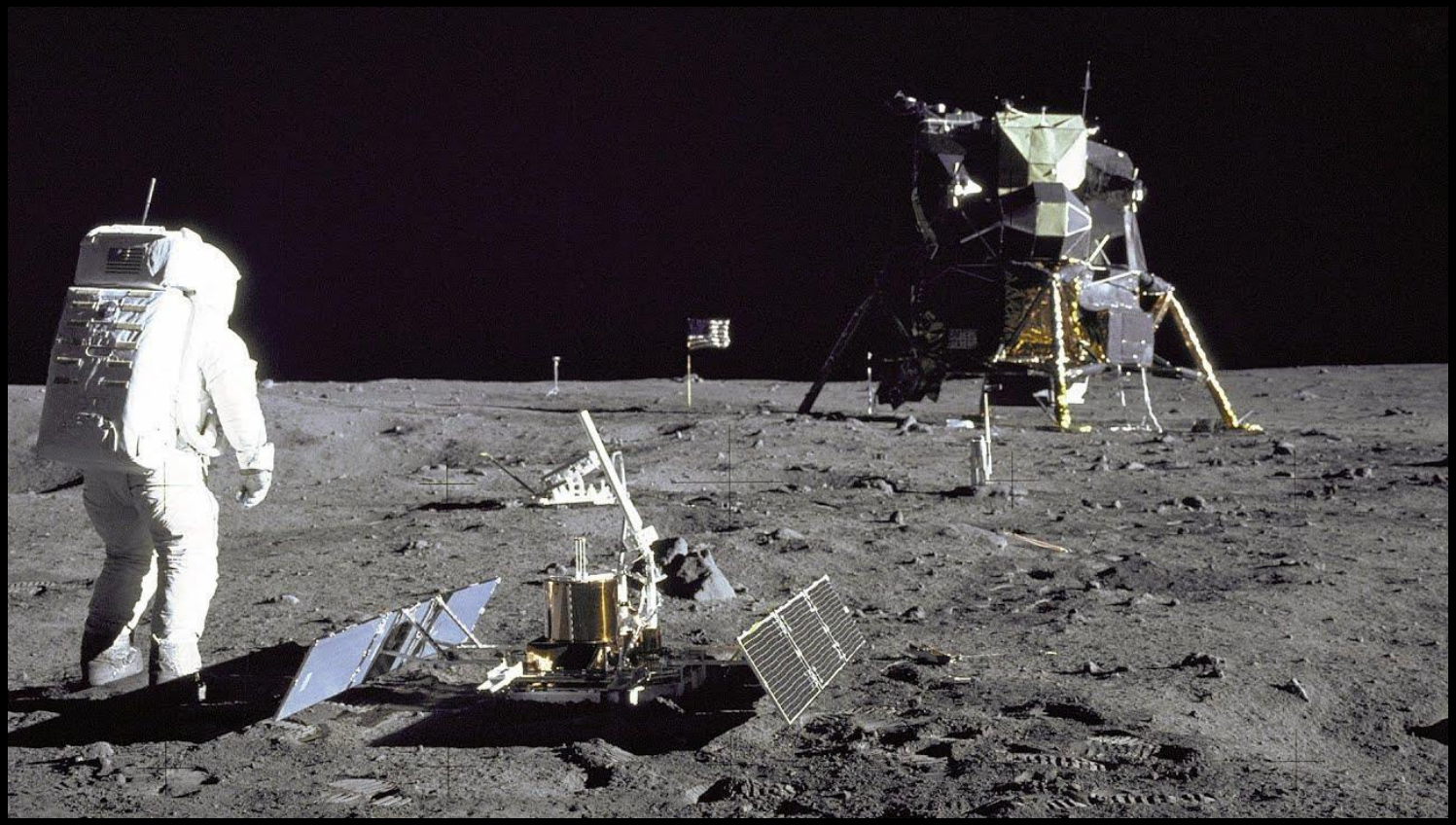
Computers to the Moon

Mark Schulman

Agenda

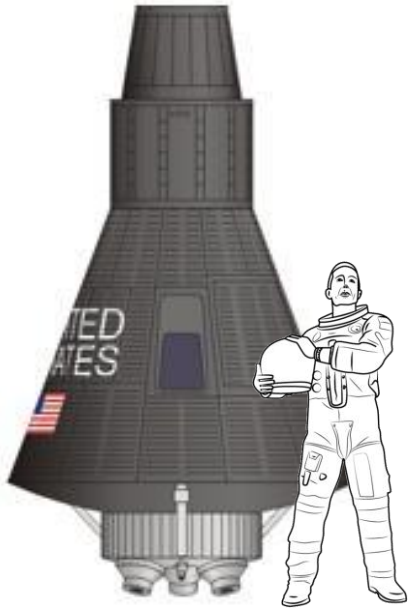
Talk about the development of computers in the early U.S. space program, and the little-known role of how they got us to the Moon.



History

Mercury - First Steps Into Space

Mercury



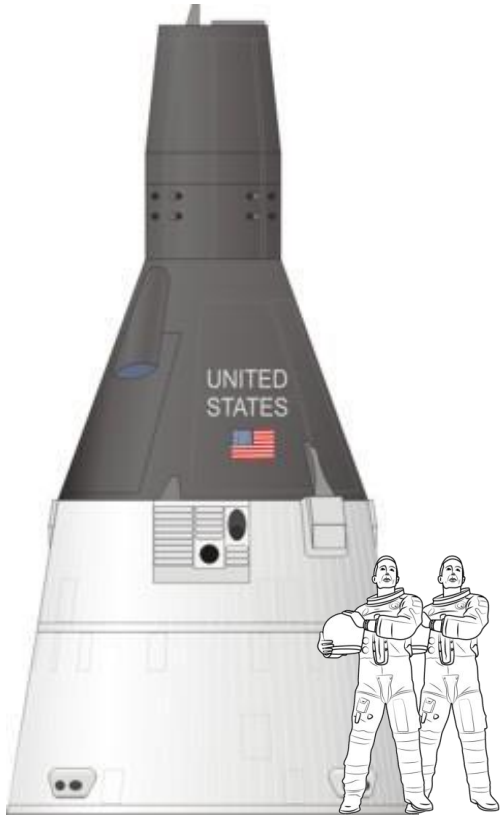
Game Changer

"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."

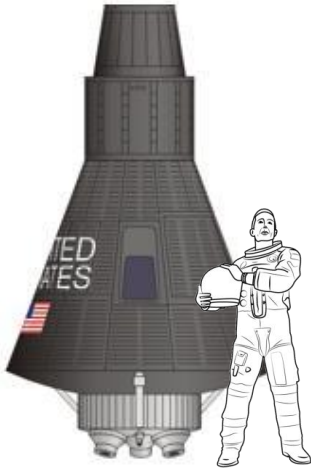
-- JFK, May 25, 1961

Gemini - Preparing to Go to the Moon

Gemini



Mercury



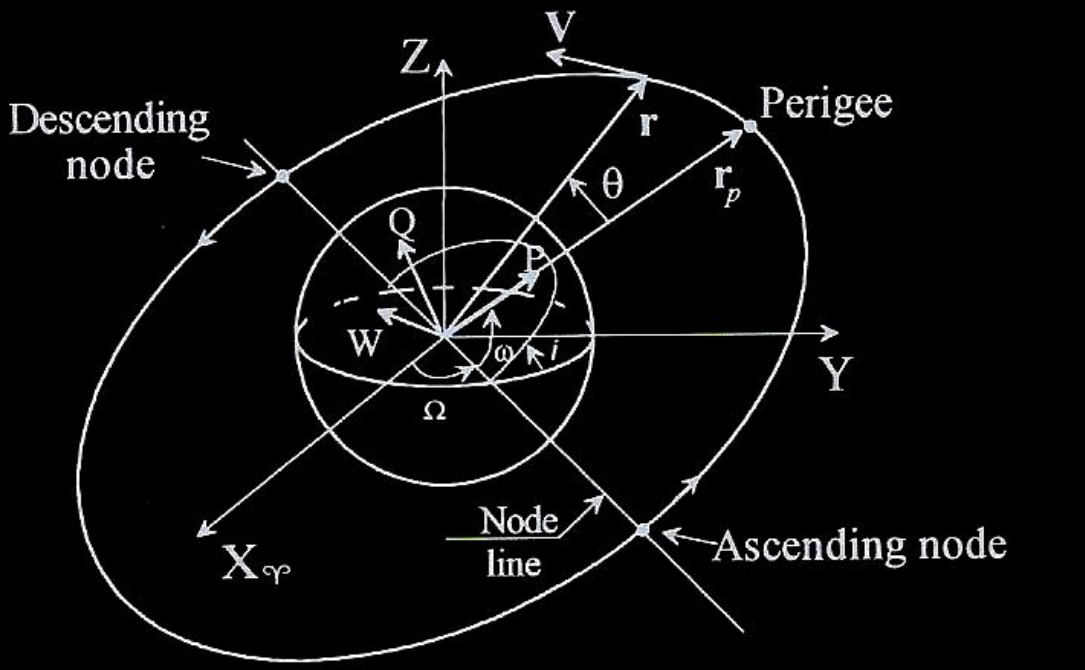
Gemini - Preparing to Go to the Moon

Project goals

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



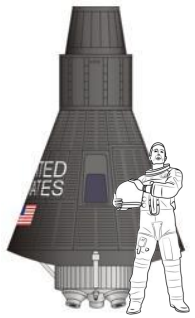
Apollo –Going to the Moon

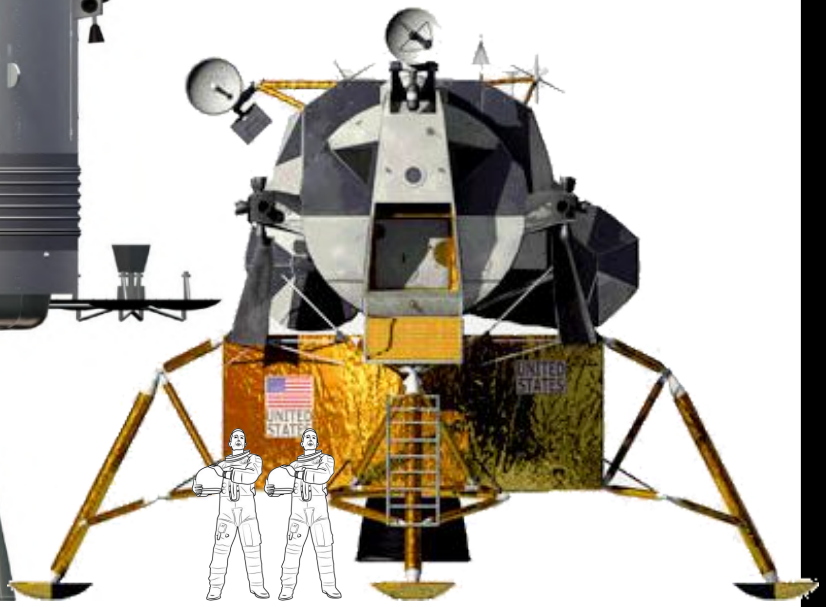
Apollo

Gemini

Lunar Module

Mercury

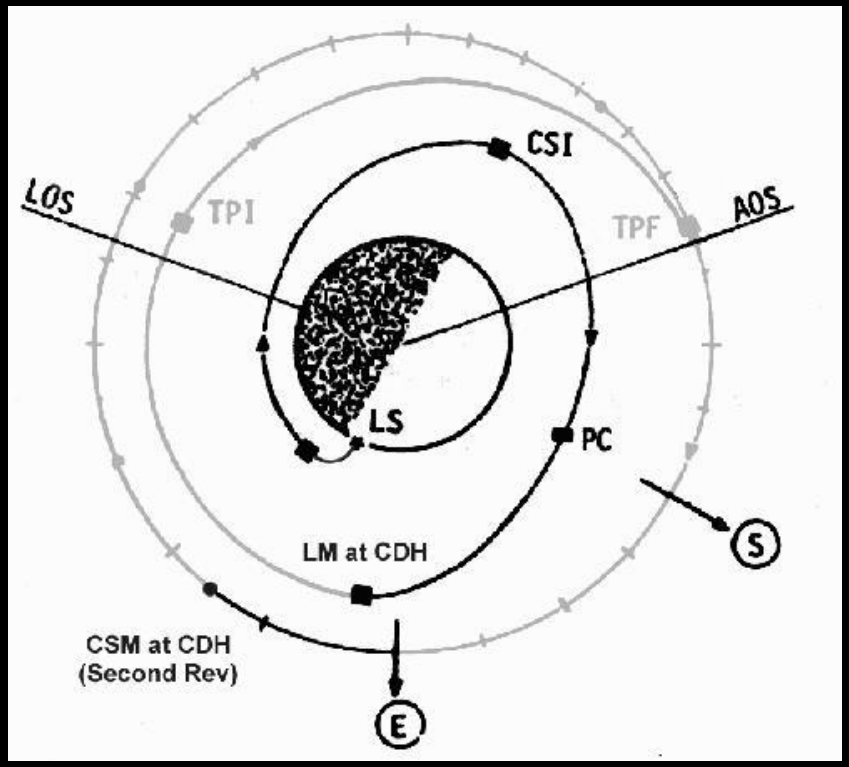




Navigating in Space is Really Hard

- Highly mathematical
- Completely non-intuitive

- Just about impossible without a computer



A Computer for Apollo

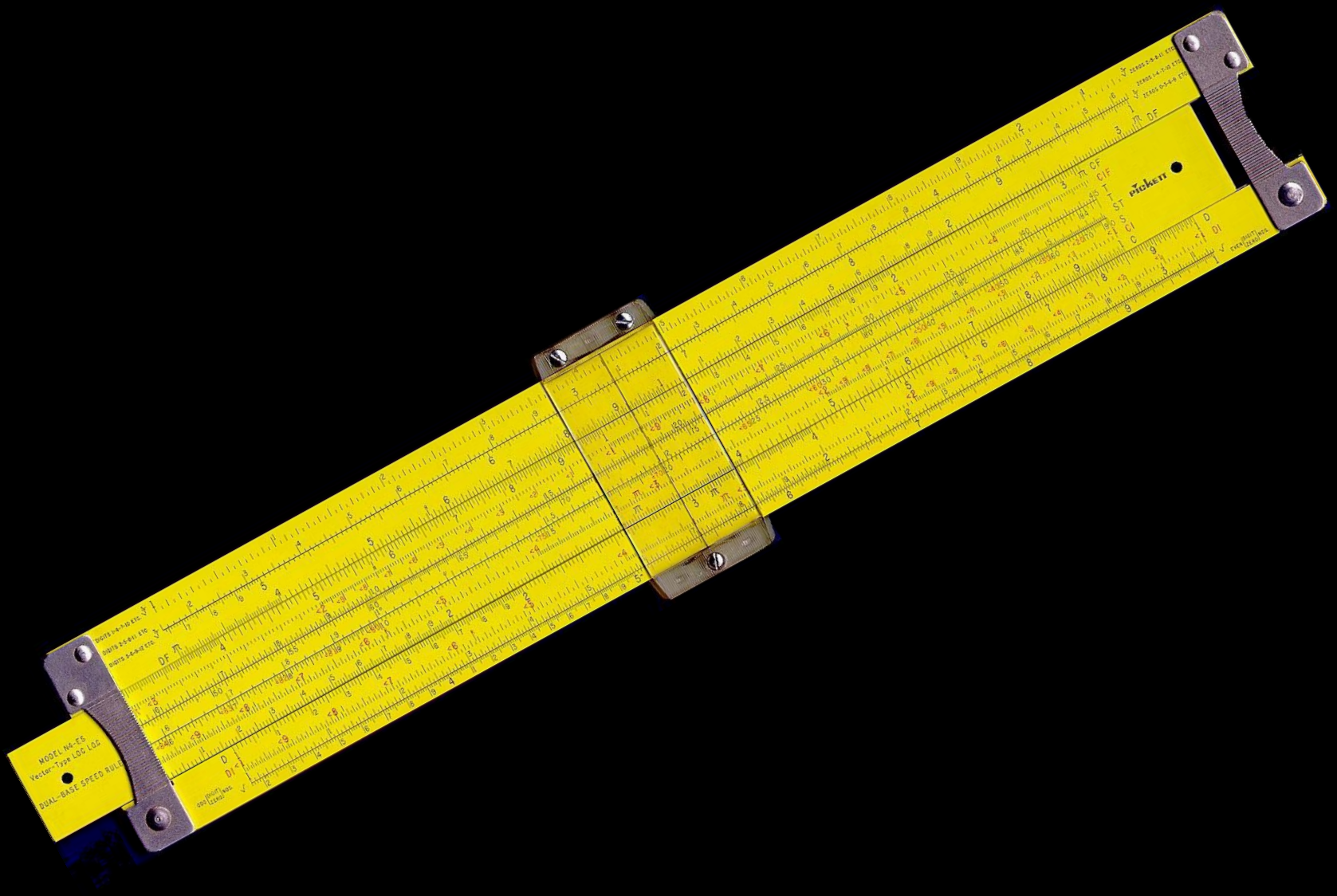
Computer Requirements

- Execute trajectories to get from the Earth to the Moon
- Continuously update position and attitude
- Perform calculations and display data in real time
- Control spacecraft's engines and thrusters
- Receive remote updates from the ground

1960s Computing

NASA Real Time Computing Center, 1966

Personal Computers in 1960

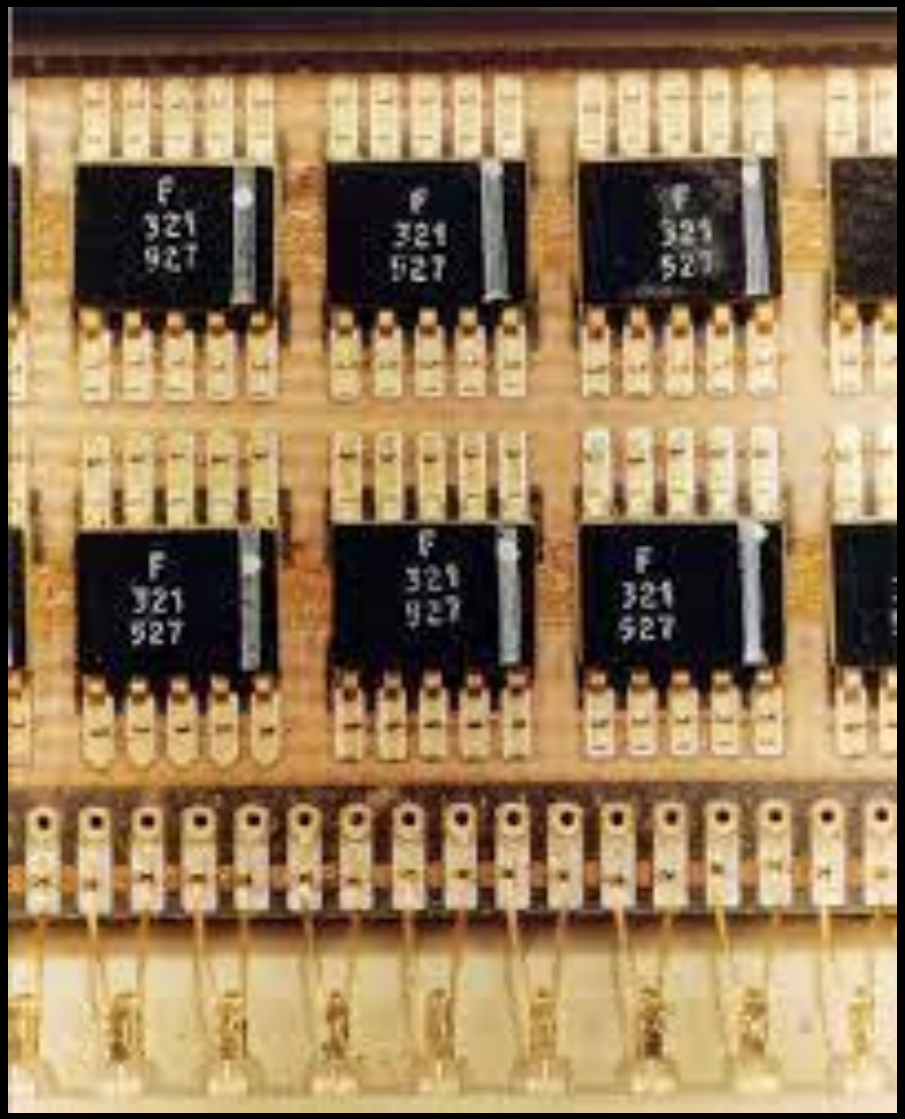


Development of an Apollo Computer

- Head of the MIT Instru-mentation Lab was Charles Stark “Doc” Draper
- Believed his team could build a digital computer for a moon mission

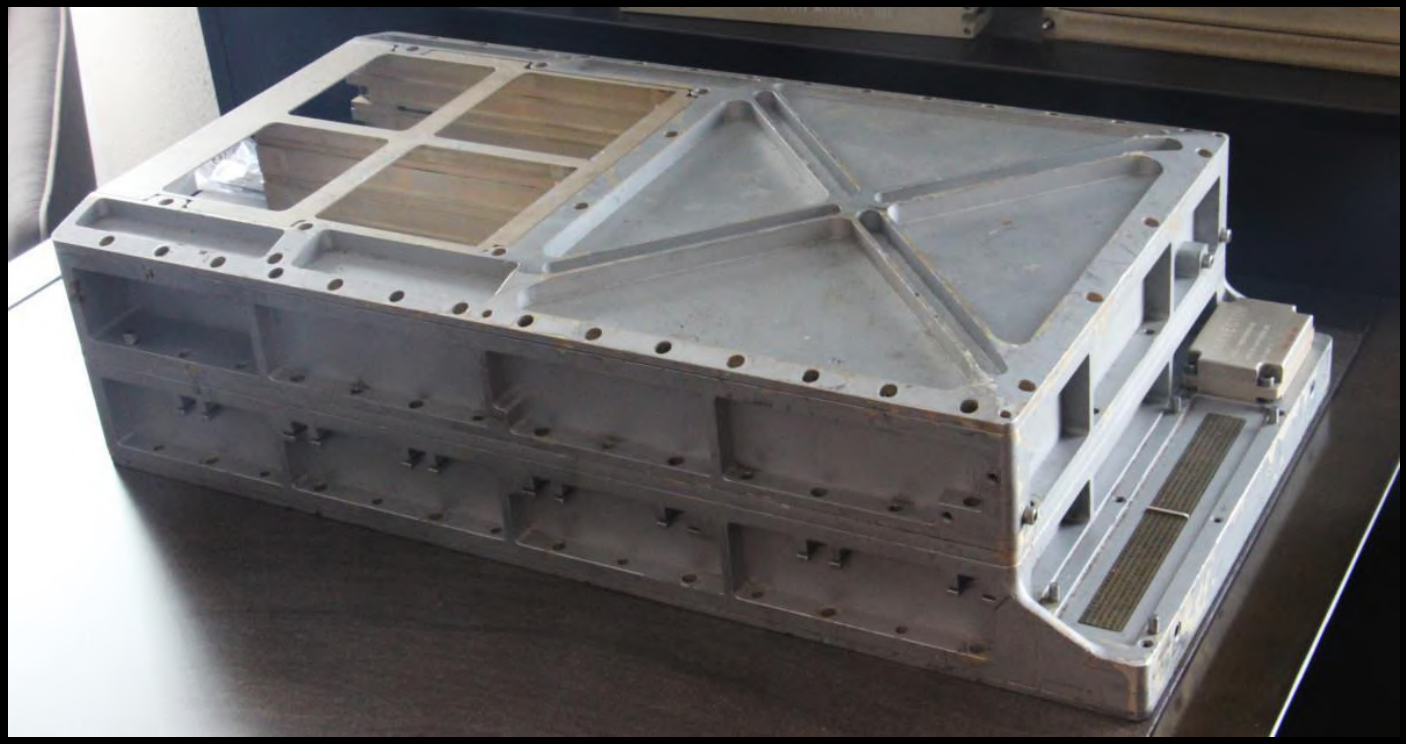
Crucial Decisions

- Computer would be digital
- Save weight and power by using integrated circuits



The Apollo Guidance Computer (AGC)

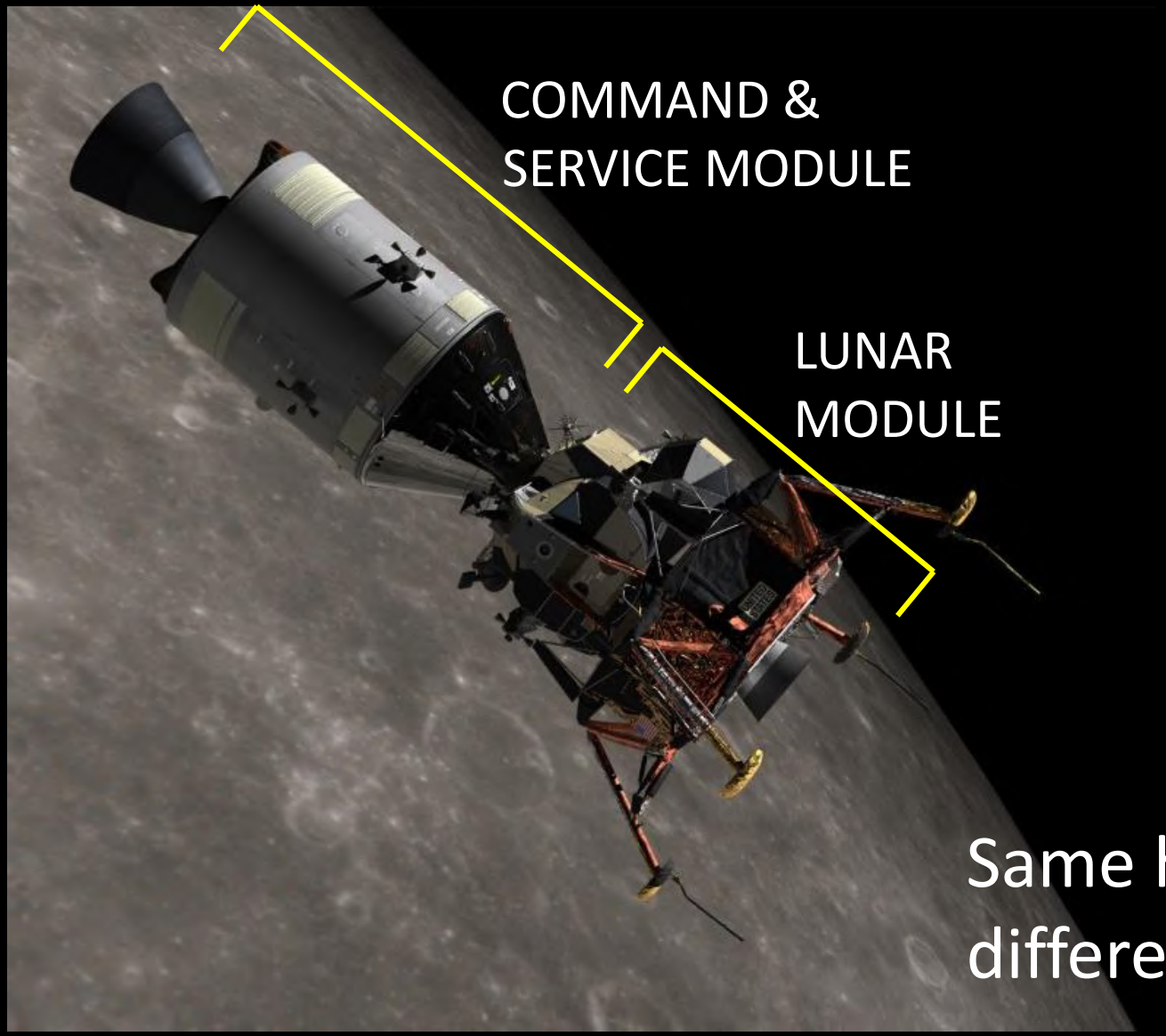
- Developed by MIT Instrumentation Lab
- Manufactured by Raytheon
- Development cost: $26.6 million



AGC Hardware

- 15-bit word (plus a parity bit)
- 36k words of ROM (core rope)
- 2k words of RAM
- Weight: 70 pounds

Two Spacecraft, Two Computers



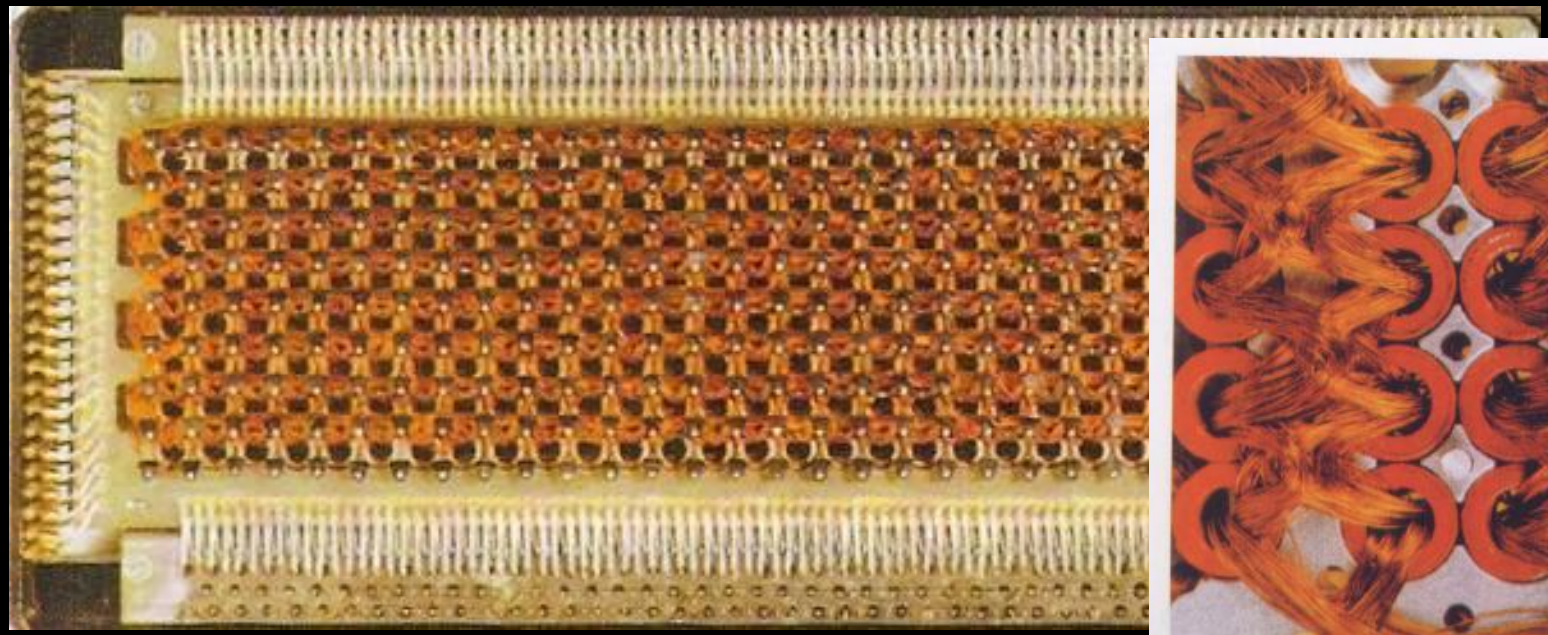
Same hardware,
different software

The Innards


INTERFACE MODULE A21-23
INTERFACE MODULE A21-23
INTERFACE MODULE A21-23
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
OSCILLATOR MODULE B7
ALARM MODULE B8
NON-FLYABLE
ERASABLE DRIVER MODULE B9-10
CURRENT SWITCH MODULE B11
SENSE AMPLIFIER MODULE B13-14
SENSE AMPLIFIER MODULE B15
STRAND SELECT MODULE B16-17
ROPE DRIVER MODULE B16-17
ROPE DRIVER MODULE B16-17

Core Rope Memory

- Wires woven through iron cores

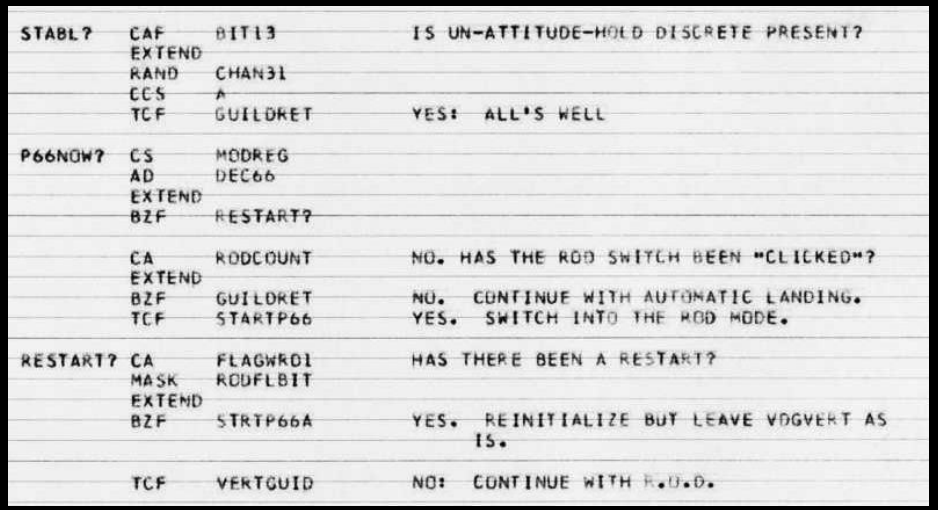


A Few Pioneering Things

- Logic built entirely with integrated circuits
- Real-time processing
- Priority multitasking
- Digital autopilot (vs analog)
- Discipline of software engineering
- Crash and restart

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

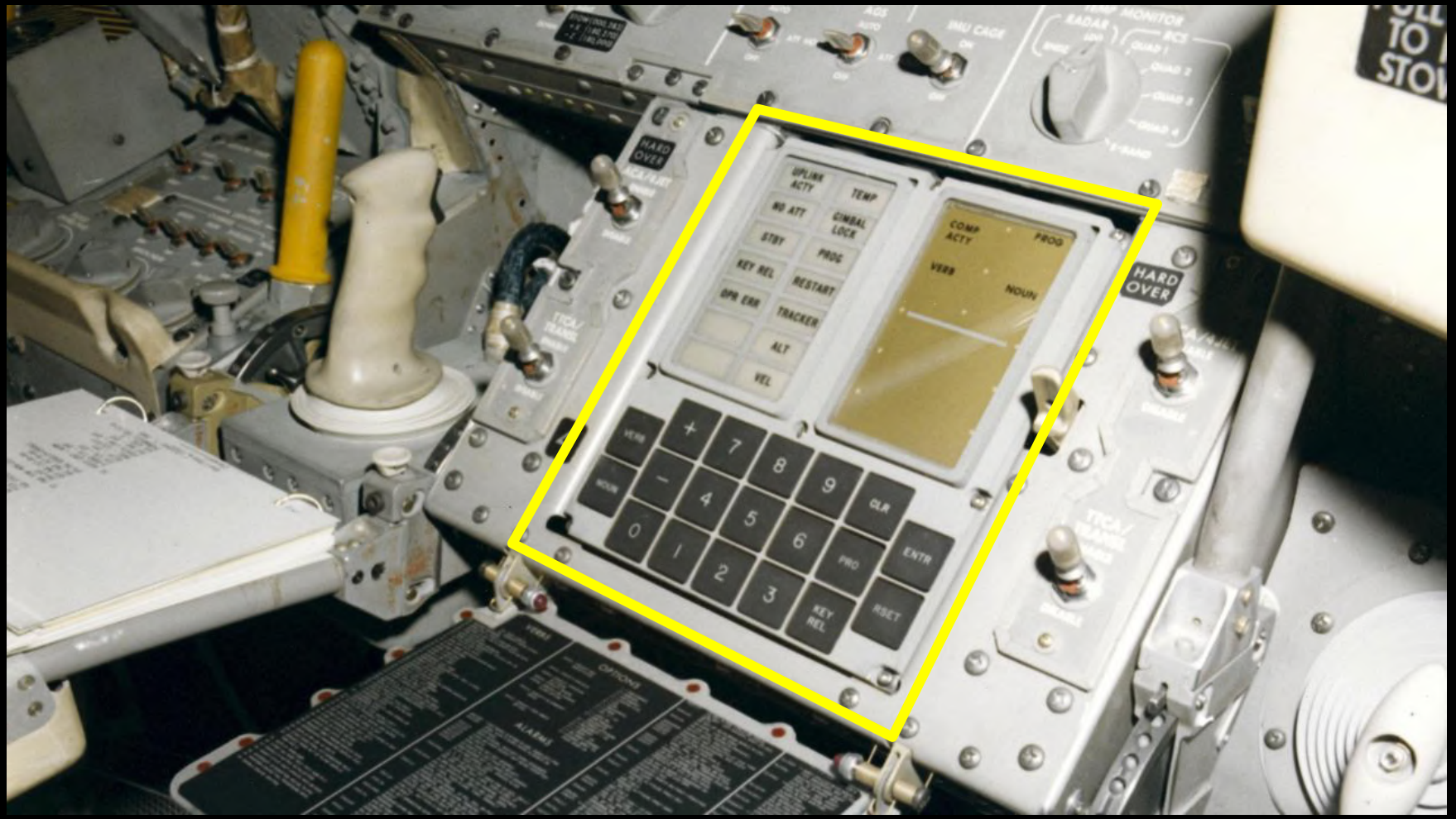
```
#     ********************************
#     GENERAL PURPOSE IGNITION ROUTINES
#     ********************************

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

Interface

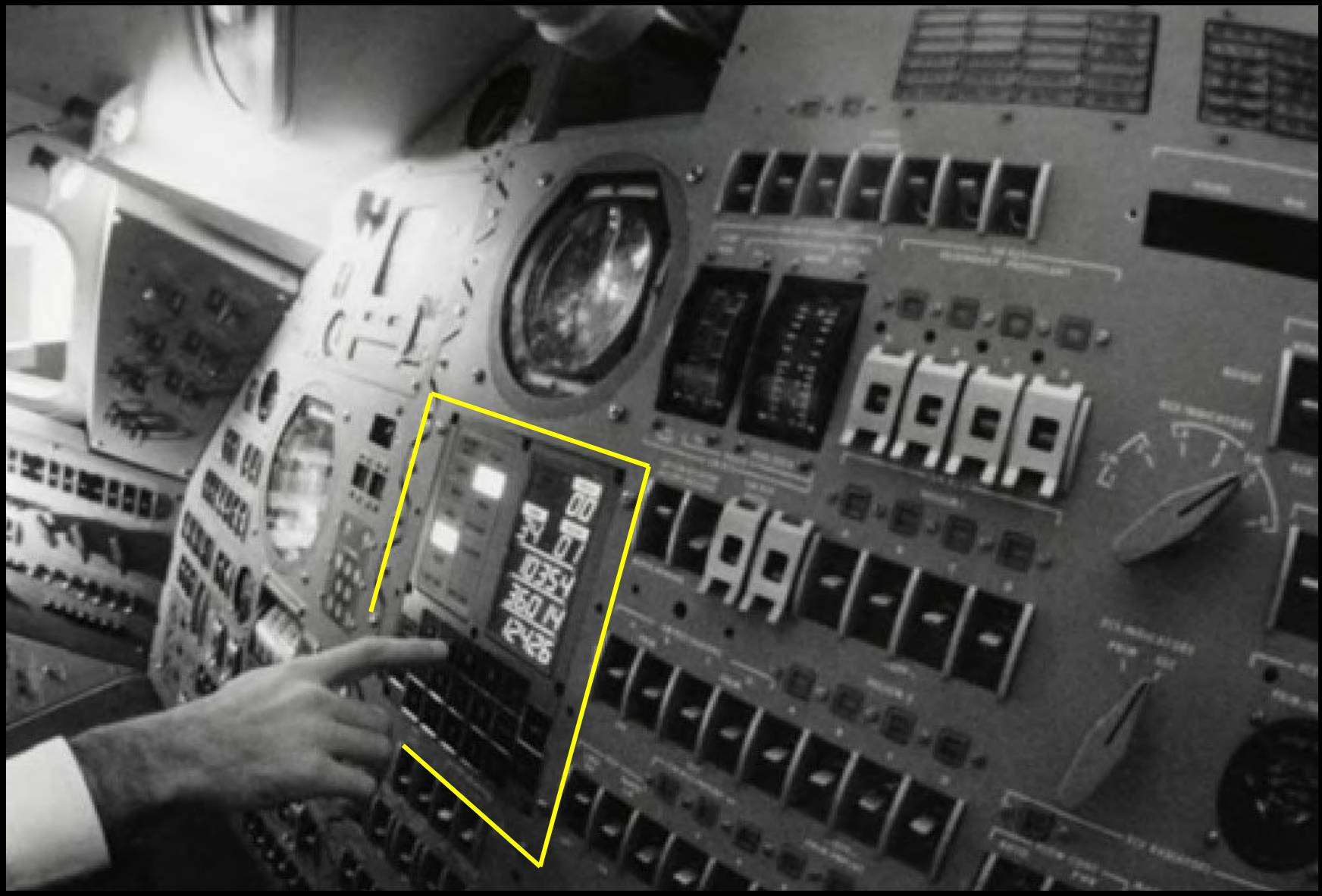
- So how did the crew interact with the computer?
- Mouse/keyboard/widescreen display?

Display/Keyboard (DSKY)



DSKY in the Lunar Module

DSKY in the Command Module



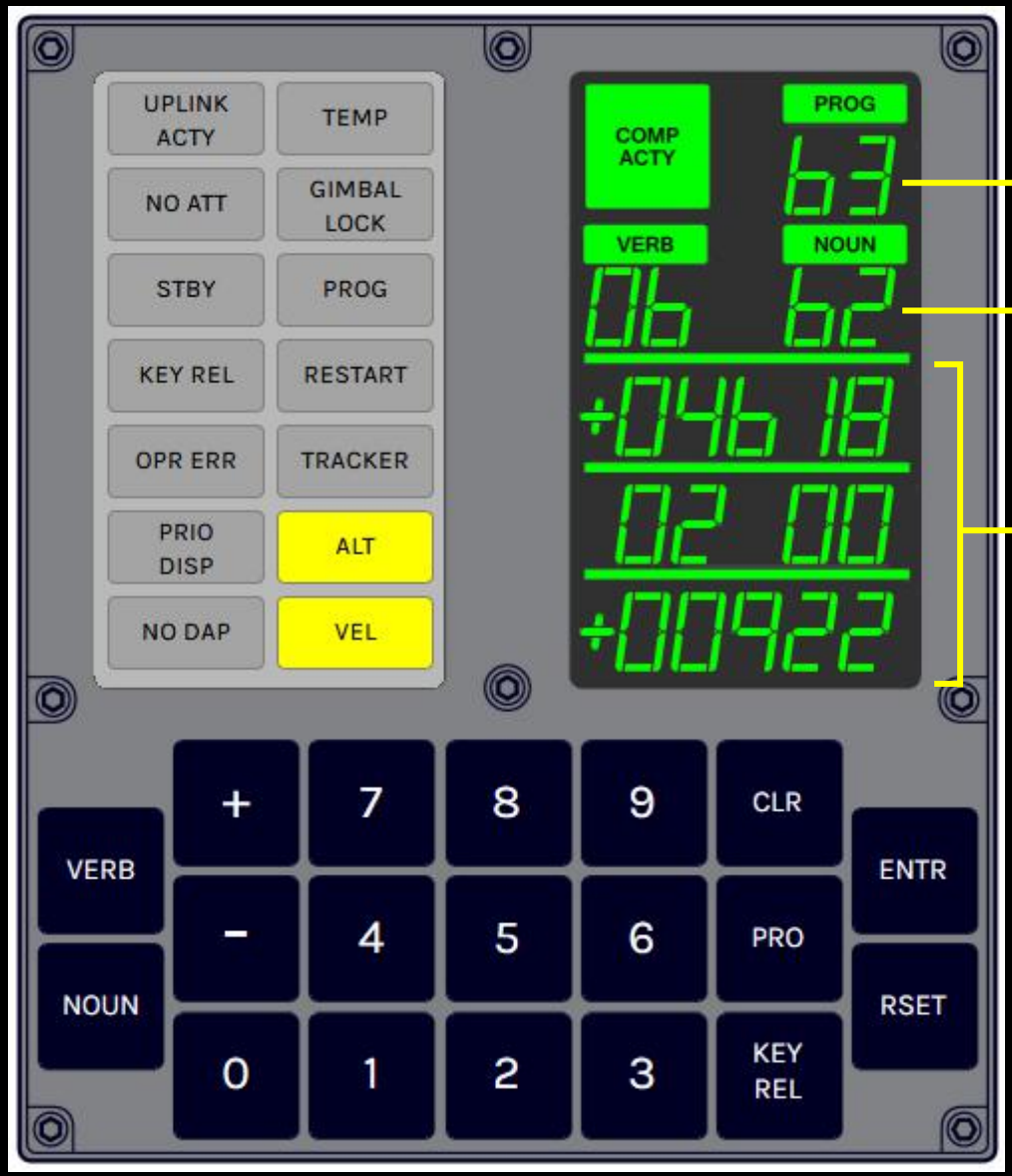
The DSKY (Display and Keyboard)

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

Verbs

Examples:

- 34 - Cancel program
- 06 - Display data
- 37 - Run a program

Nouns

- Data or value
- Up to three numbers
- Related in some way

- A few examples:

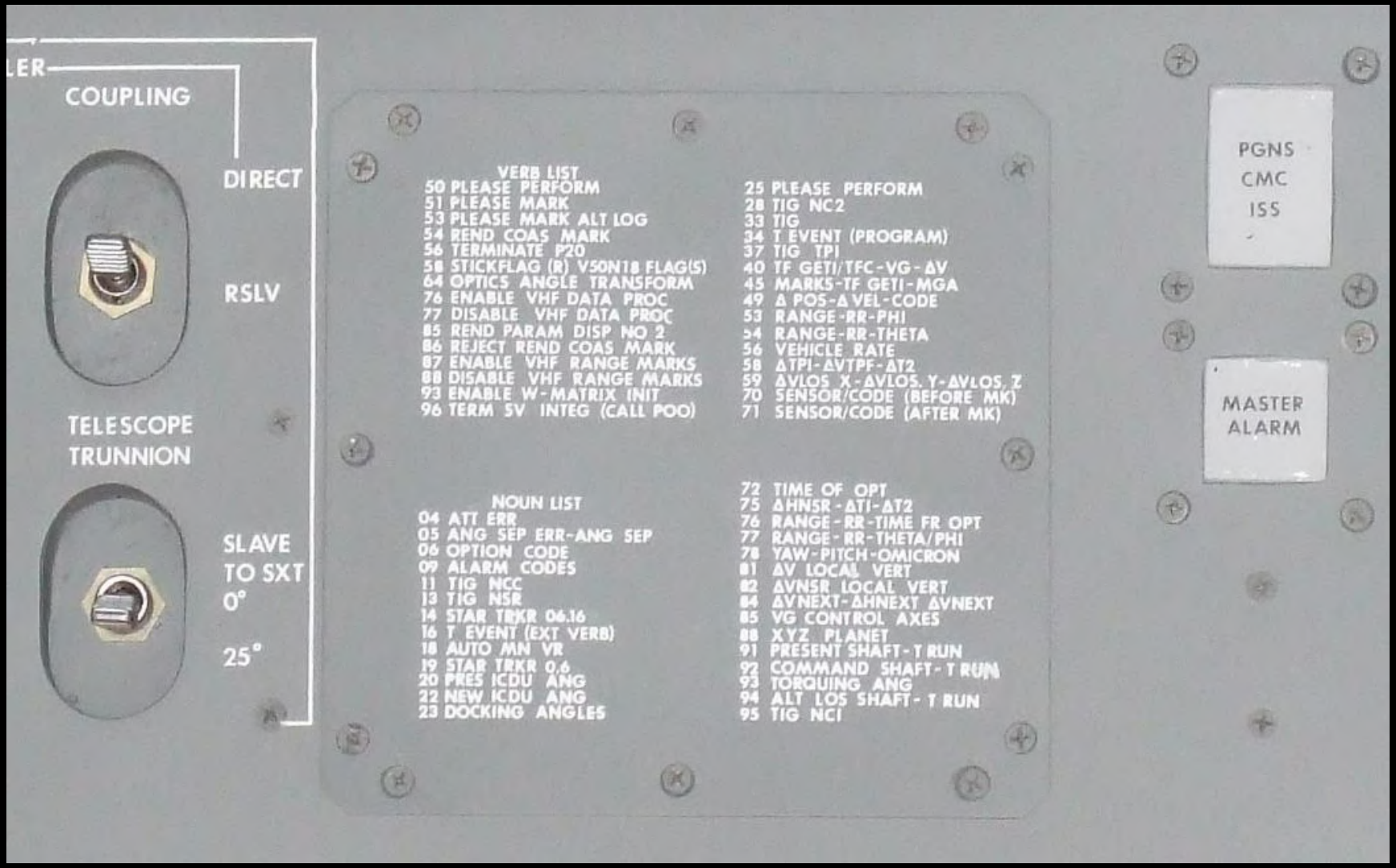
- 36 - mission-elapsed time (3 components)
- 47 - spacecraft weights (2 components)
- 64 - g-force, velocity, range to splash (CM)

Sample DSKY Operations

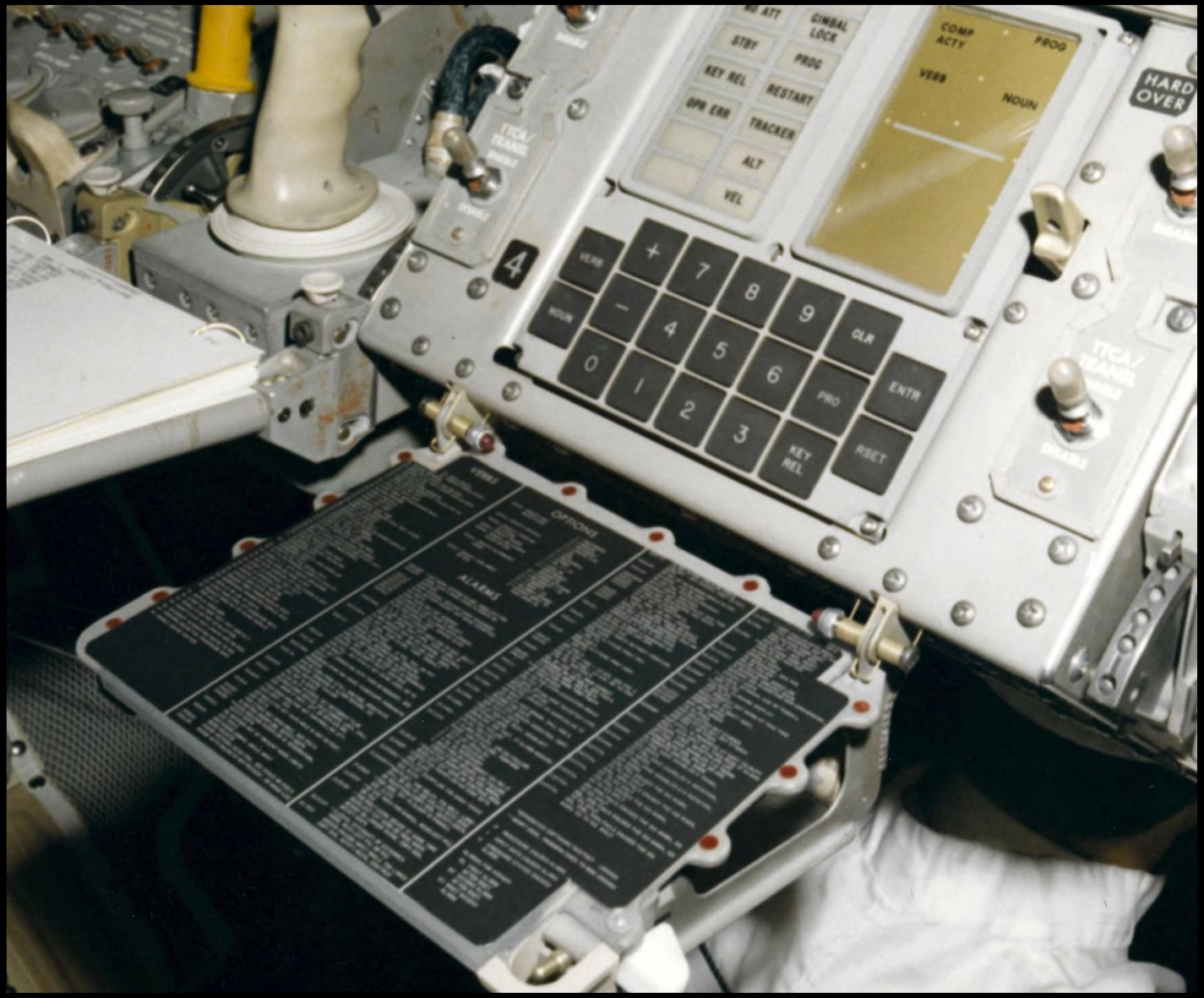
Sample DSKY operations:

1. Lamp test
2. Display the current mission time
3. Display and then change weights of both spacecraft
4. Put computer in standby mode

DSKY Cheat Sheets (Command Module)



DSKY Cheat Sheets (Lunar Module)



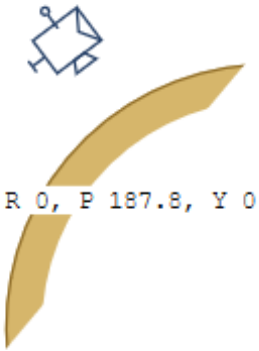
FLIGHT PLAN

LM

CDR	LMP
P20 RENDEZVOUS NAVIGATION	V32 - MARKS = 5
ACQUIRE AND TRACK CSM	
MAINTAIN RR	V32 - MARKS = 10
TRACKING ATTITUDE	RCS TEMP/PRESS/QTY CK
SLEW STEERABLE ANT	AFT OMNI, PCM LBR
ANT P 58, Y -38	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
MAINTAIN RR AND	V90 OUT OF PLANE
VHF TRACKING ATTITUDE	
	V32 MARKS = 10
	P30 EXTERNAL ΔV
	V90 OUT OF PLANE
P41 RCS THRUSTING	
	LOAD AGS ΔV
RCS, PLANE CHANGE	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

What About Serious Stuff?

- Programs to execute entire mission phases
- Programs to perform ad hoc maneuvers

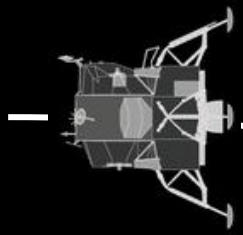
Landing on the Moon

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 program

BRAKING PHASE

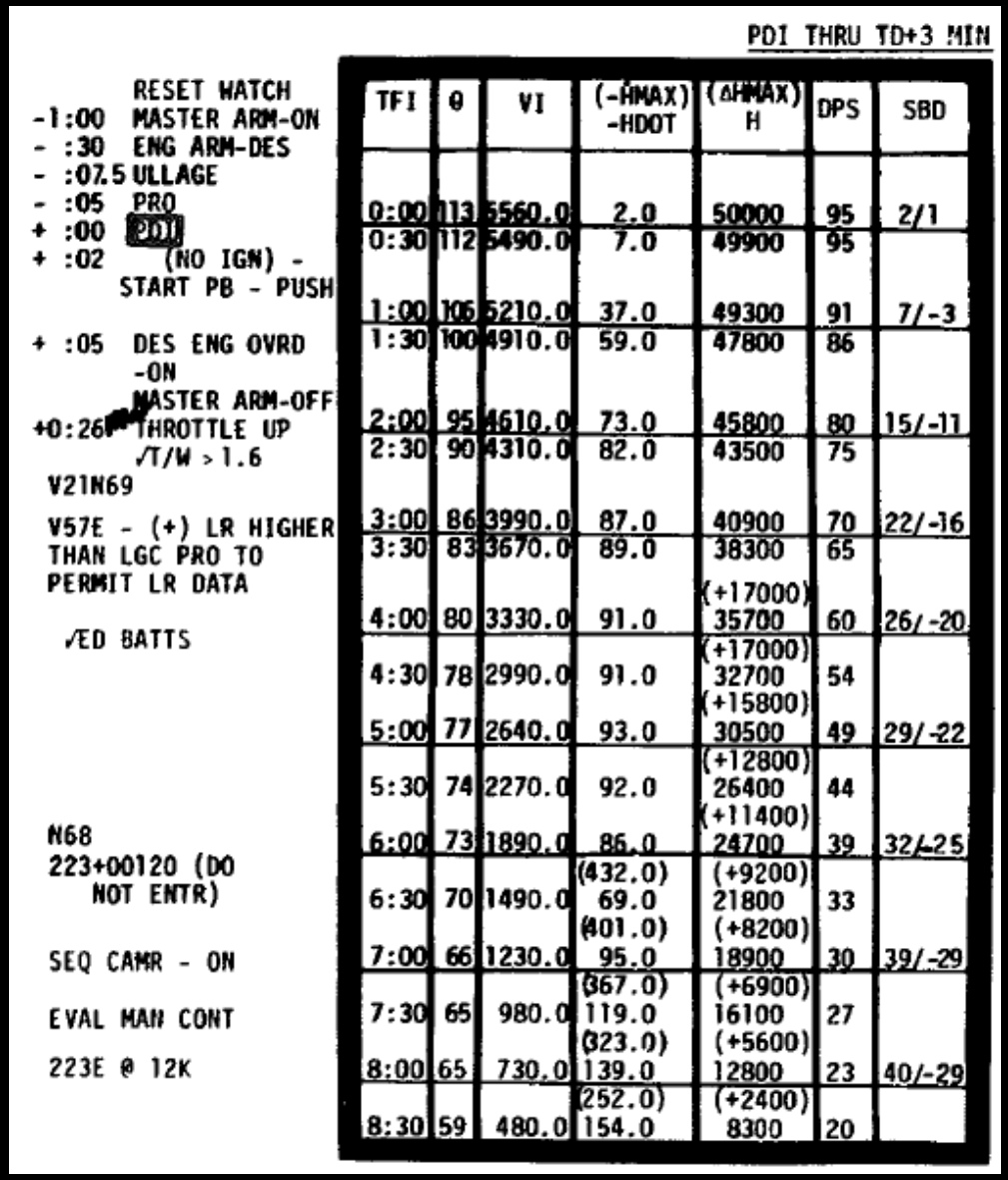
P63



ENGINE IGNITION
50,000 feet altitude
240 miles from site
3,777 mph

7,000 feet altitude
477 mph
2 miles to go

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

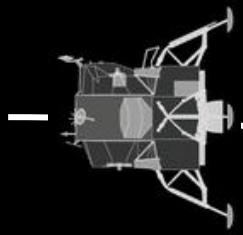
EVAL MAN CONT

223E @ 12K

TFI	θ	VI	(-ḦMAX) -ḦDOT	(ΔḦMAX) Ḧ	DPS	SBD
0:00	113	6560.0	2.0	50000	95	2/1
0:30	112	6490.0	7.0	49900	95	
1:00	106	6210.0	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

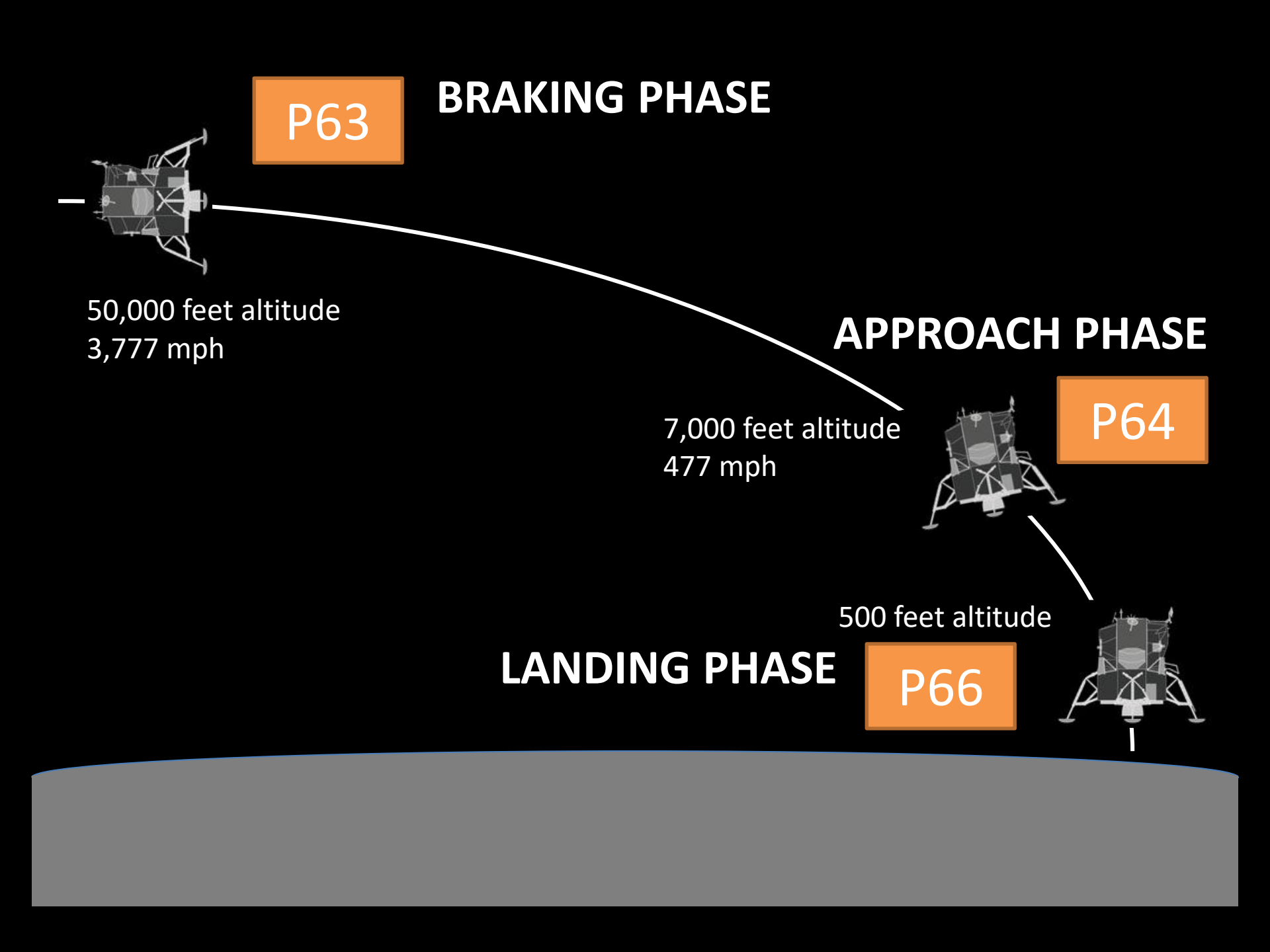


50,000 feet altitude
3,777 mph

APPROACH PHASE

P64

7,000 feet altitude
477 mph
2 miles to go


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

Ride Along with Apollo 12

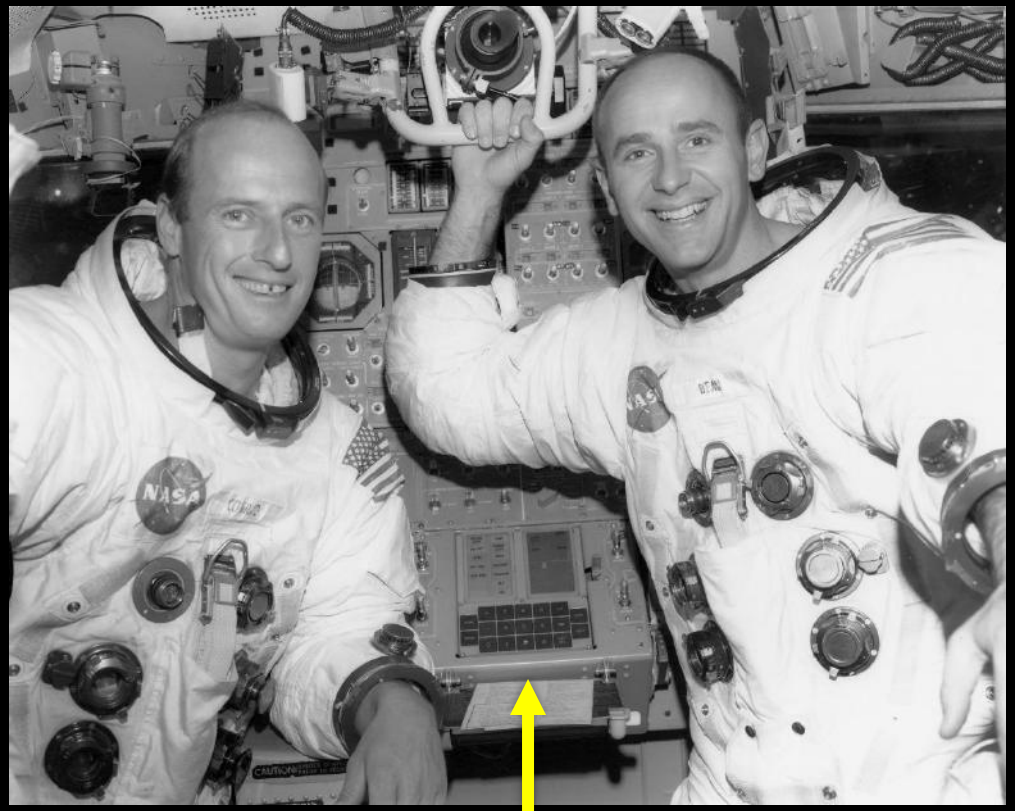
Apollo 12 Landing

- 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

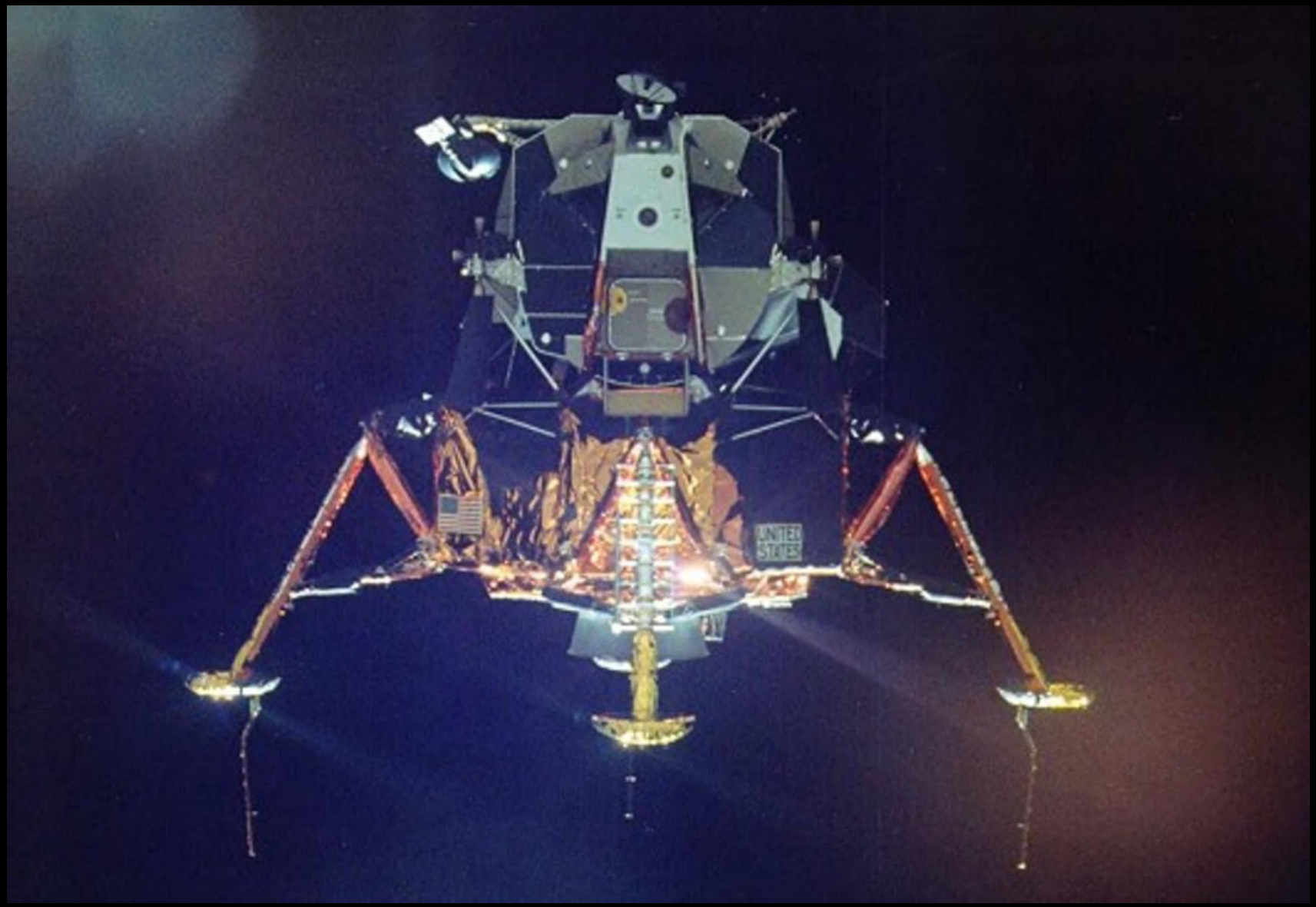


Al Bean

LM Pilot

Apollo Guidance Computer

Demo



Legacy

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

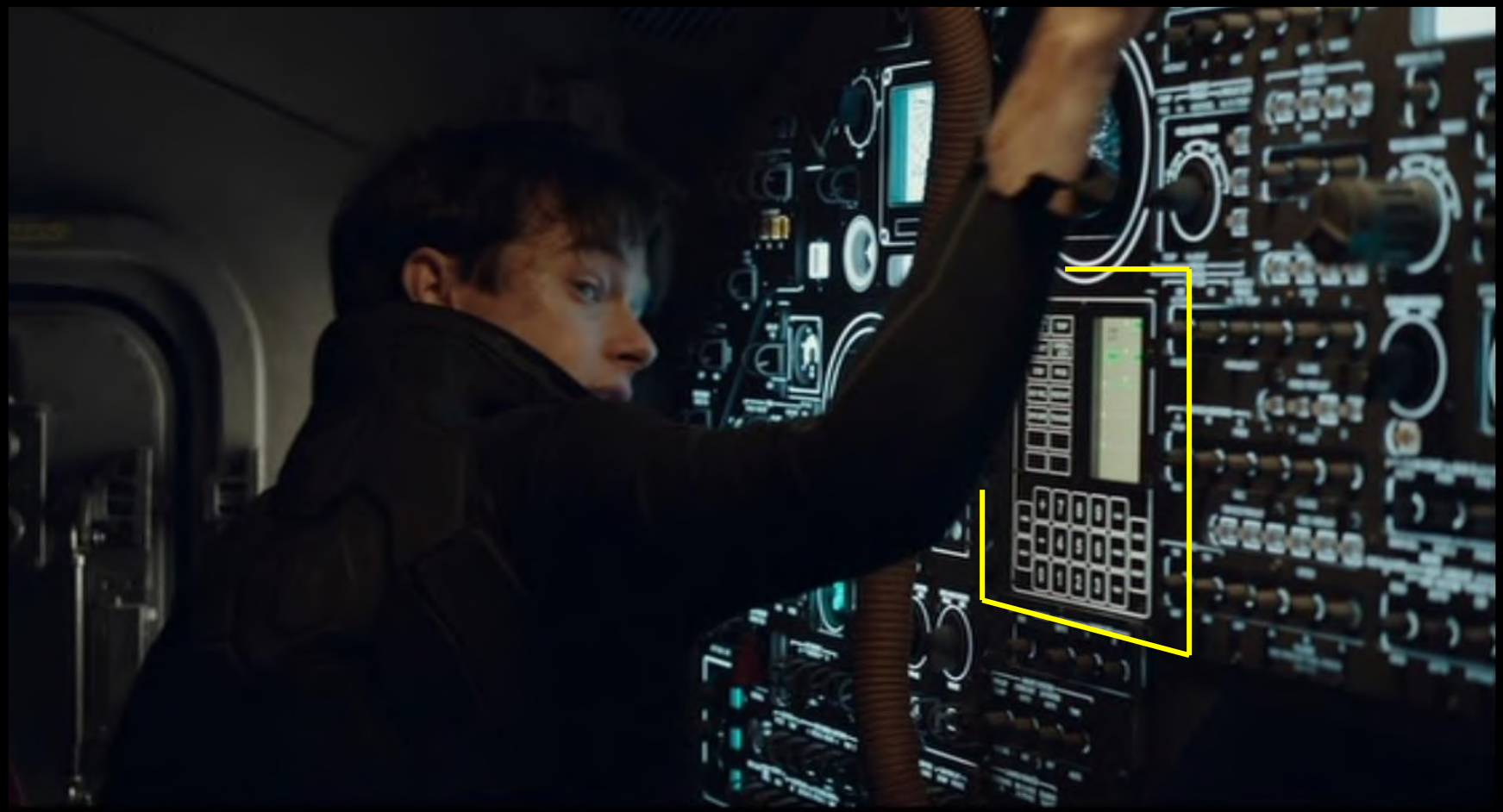
1995

Apollo 13

Valerian and the City of a Thousand Planets

2017

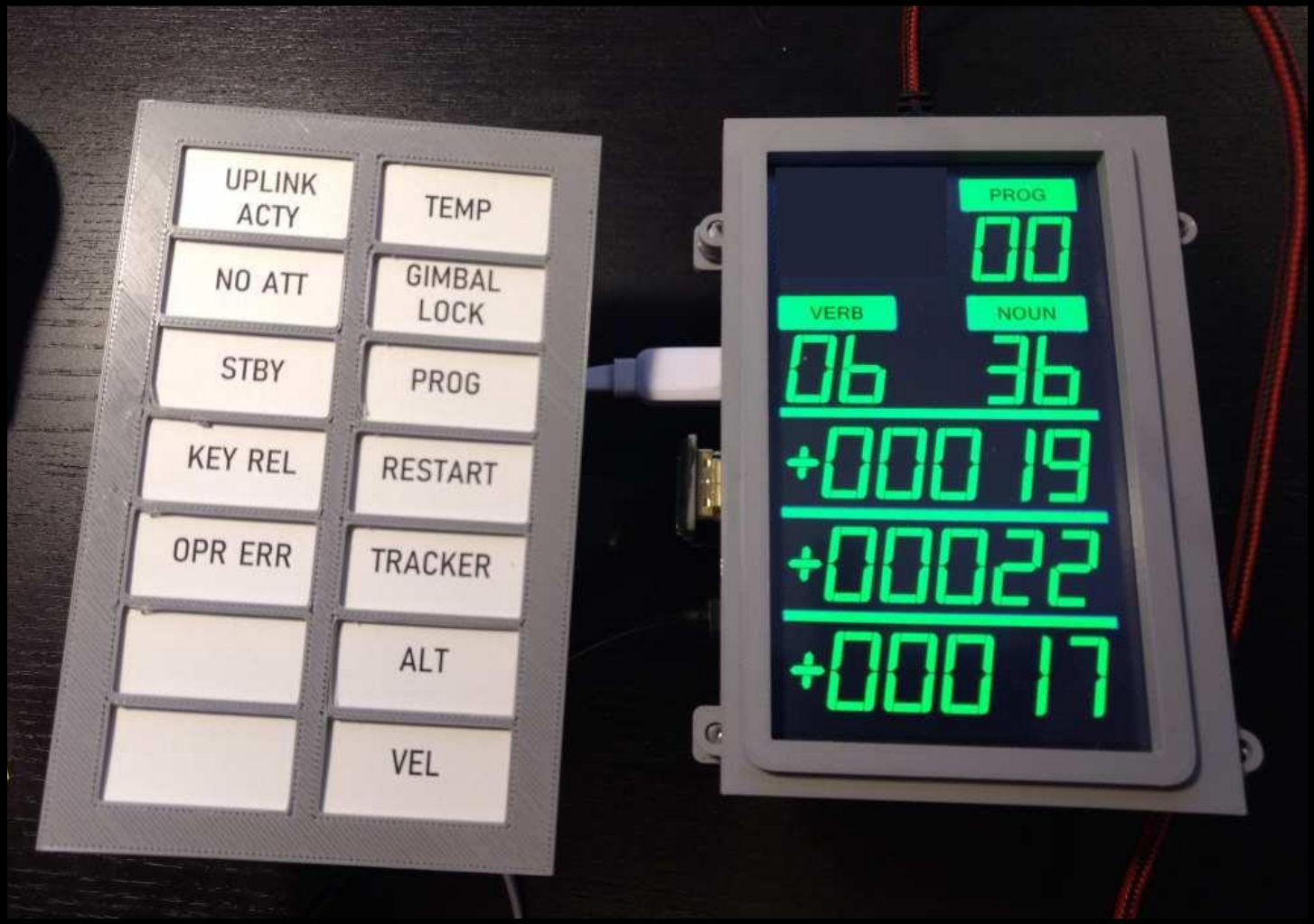
Valerian and the City of a Thousand Planets



Reproductions

Reproductions

- Still a ways to go ...

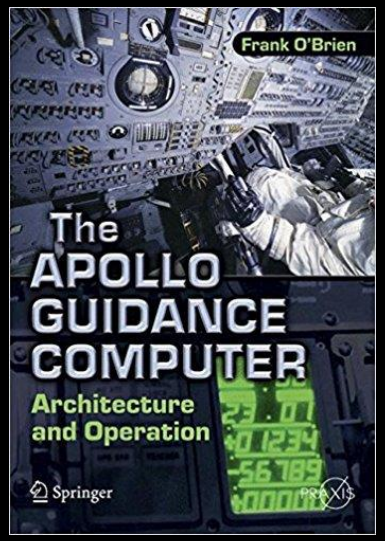


Working AGC

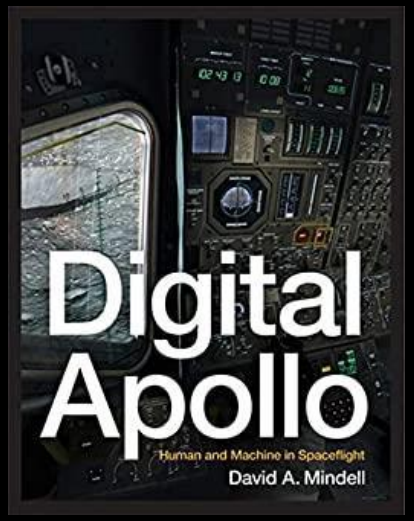
- Only a single working AGC exists
- Restored by YouTuber CuriousMarc

Explore More

- *The Apollo Guidance Computer*
  by Frank O'Brien



- *Digital Apollo*
  by David Mindell



- AGC source code
  `https://github.com/chrislgarry/Apollo-11`

- Virtual AGC
  `http://www.ibiblio.org/apollo`

Questions?

Computers to the Moon

Mark Schulman
Central Florida Computer Society

marks@schulmans.com