Do something a little different today - not going to talk about tech policy, or mac-related news, or anything like that, we're going to talk about space stuff. because in addition to being an intrepid technology reporter, I'm also kind of an amateur historian and my area of passion is NASA in the the Apollo era. I've written extensively on the topic and interviewed a ton of the folks involved in sending people to the moon, from flight controllers to astronauts, and in honor of the 50th anniversary of the apollo 11 landing next month, and because you are all technology-minded folks, I wanted to come and do kind of a little presentation on some of my favorite bits of historical trivia and neat little facts that i've picked up over the years about how the Apollo project worked. This isn't intended to be a soup-to-nuts talk about how we got to the moon—more of a collection of neat little technical bits and bobs.

When we left Earth…

Fifty years ago, 23 people voyaged beyond low Earth orbit and crossed the gulf to the Moon.

12 of them set foot on the lunar surface.

It remains the only time in the history of humanity that we have traveled more than a few hundred miles from the Earth.

First, a bit of historical context. There were a total of nine Apollo missions that left earth orbit and flew to the moon. Each flight carried three astronauts, but three of those astronauts were lucky enough to make the trip twice on two different missions (Jim Lovell on Apollos 8 & 13, John Young on Apollos 10 & 16, and Gene Cernan on Apollos 10 and 17).

We retained the operational capability to put humans on the Moon for just four years.

Apollo 8
Liftoff: December 21, 1968

Apollo 17
Splashdown: December 19, 1972

And in spite of how grand Apollo seems, the actual flights took place across a remarkably short period of time.

Rather than get bogged down in a discussion about the political realities of Apollo and that kind of stuff, we're going to talk about the hardware that got us from the earth to the moon. Specifically, I'm going to focus up on three areas of interest—the ground, the rocket, and the two Apollo spacecraft. The idea here, especially with the spacecraft talk, is to illuminate a bit about how complex this machinery really was and why we were able to do what we did, even with technology that appears hopelessly, insanely primitive by 2019 standards.

Controlling the Missions from Mission Control

Johnson Space Center

- Originally the Manned Spacecraft Center
- Location of “Mission Control”
- Deeded to the .gov by Rice University (which got the land from the Humble Oil Co)
- Houston was chosen due to political wrangling first and foremost
- Geographic separation of national strategic assets played a secondary role

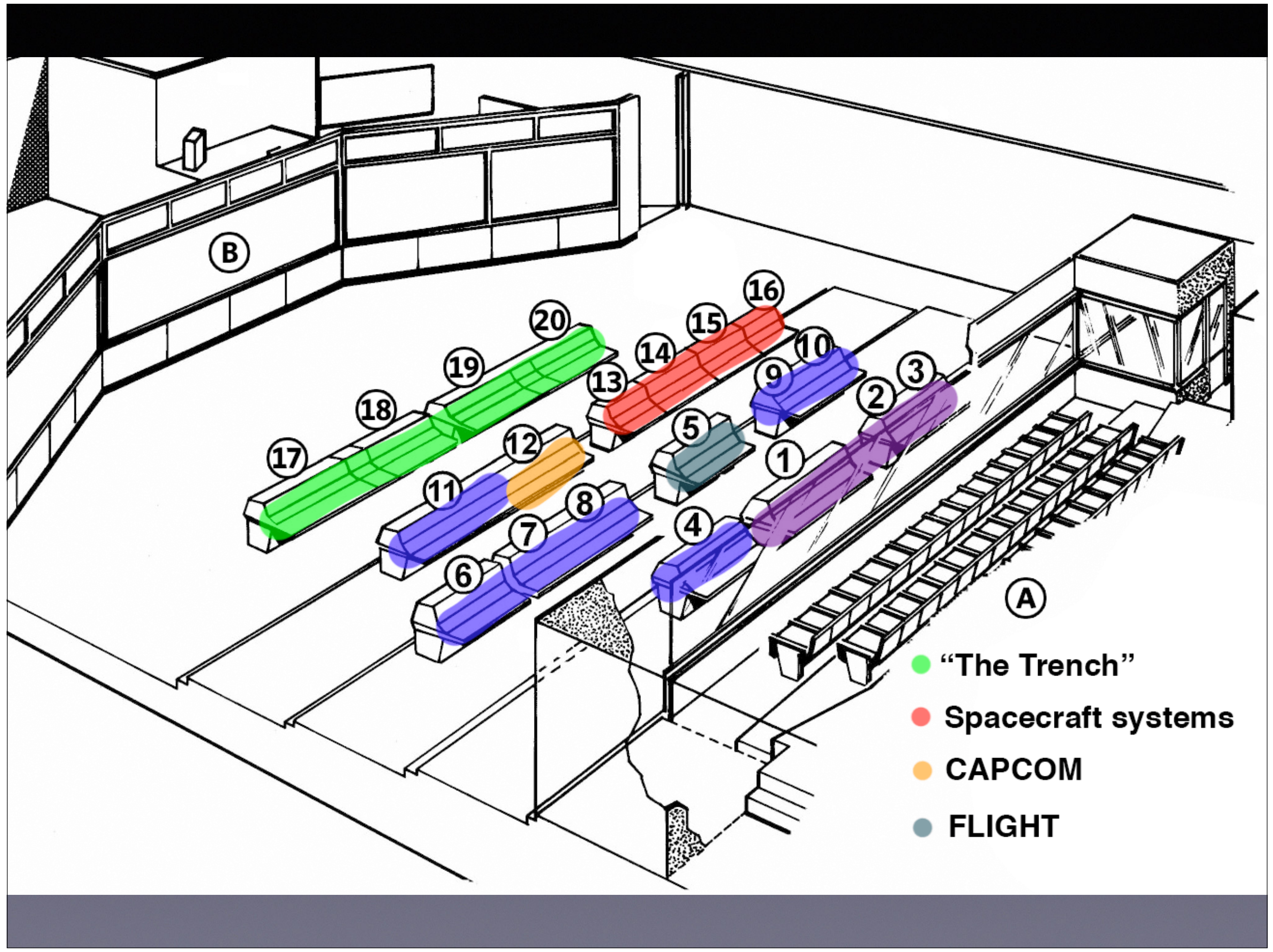
So we’re gonna start with mission control, which is located at the Johnson Space Center down in clear lake. JSC was originally named the Manned Spaceflight Center or MSC, and its presence in Texas is kind of an oddity. After Sputnik in 1957, the government turned to a small academically-focused organization called the National Advisory Council on Aeronautics to research human space flight options. N.A.C.A. was headquartered in Virginia, and the original Space Task Group was primarily made up of folks who came from or lived in the northeast. Things really got going in 1958, when N.A.C.A. was dissolved and re-chartered as a full fledged government agency you might have heard of, called NASA. Over the course of the next few years, as what would become Project Mercury unfolded, a lot of horse-trading went on about where to build the enormous permanent facilities that NASA would need to do more than launch tiny little 1-person spacecraft. There were dozens of proposed sites for NASA centers, and the proposed Houston site was no one’s first choice, especially not the Space Task Group folks in Virginia, but it came down to old fashioned politics—and here I’ll quote A&M historian Henry C. Dethloff: “Although the Houston site neatly fit the criteria required for the new center, Texas undoubtedly exerted an enormous political influence on such a decision. Lyndon B. Johnson was Vice President and head of the Space Council, [Texas 8th District rep] Albert Thomas headed the House Appropriations Committee, [Texas 22nd District rep] Bob Casey and [Texas 6th District rep] Olin E. Teague were members of the House Committee on Science and Astronautics, and Teague headed the Subcommittee on Manned Space Flight. Finally, [Texas 4th District rep] Sam Rayburn was Speaker of the House of Representatives.” — also geographic separation

“Mission Control” has gone by many formal names. During the Apollo days, there were two flight control rooms: “MOCR1” and “MOCR2.” Almost all Apollo missions were flown out of MOCR2, on the third floor of Building 30.

“Mission control” in general refers to the building where the mission control rooms are—the actual control rooms go by various names.

For Apollo, the MOCR was arranged in a theater-style layout with four tiers of consoles facing five large displays at the front of the room.

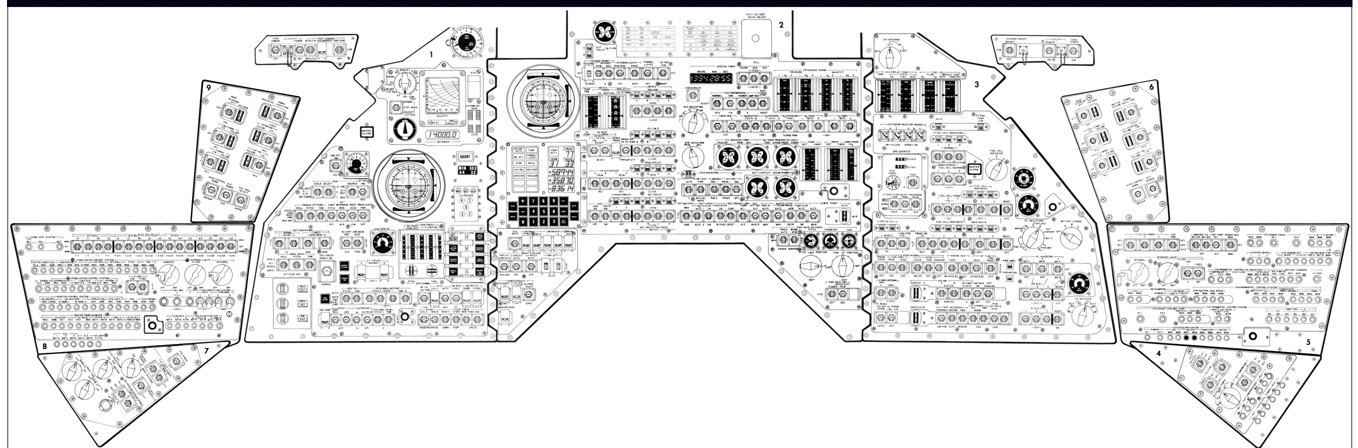
“Mission control” in general refers to the building where the mission control rooms are—the actual control rooms go by various names.



There are two chunks of consoles that were particularly important—the front row in green, and the second row in red. The green front row, called "the trench" for various reasons, was concerned with the launch, guidance, and return of the Apollo spacecraft. The right part of the second row, in red, were referred to as the "systems guys." Their collective role was to monitor all of the things on the spacecraft that the astronauts didn't have time to monitor, and that was most of the systems. Other important bits are position 12, CAPCOM, who was the only person normally allowed to actually speak on the radio to the astronauts, and position 5, the flight director who oversaw the entire mission. The other positions are support positions (recovery, surgeon, etc) and the back row in purple was reserved for high-up NASA management. The primary role of mission control during a mission was essentially to keep track of things. Keep track of where the spacecraft was and where it was going, to keep a constantly updated set of instructions ready to go in case the mission needed to be aborted at any moment, where the mission was on the timeline, what activities were coming up, whether something was taking too long, and most importantly, the health of the spacecraft itself. Because— (next slide)

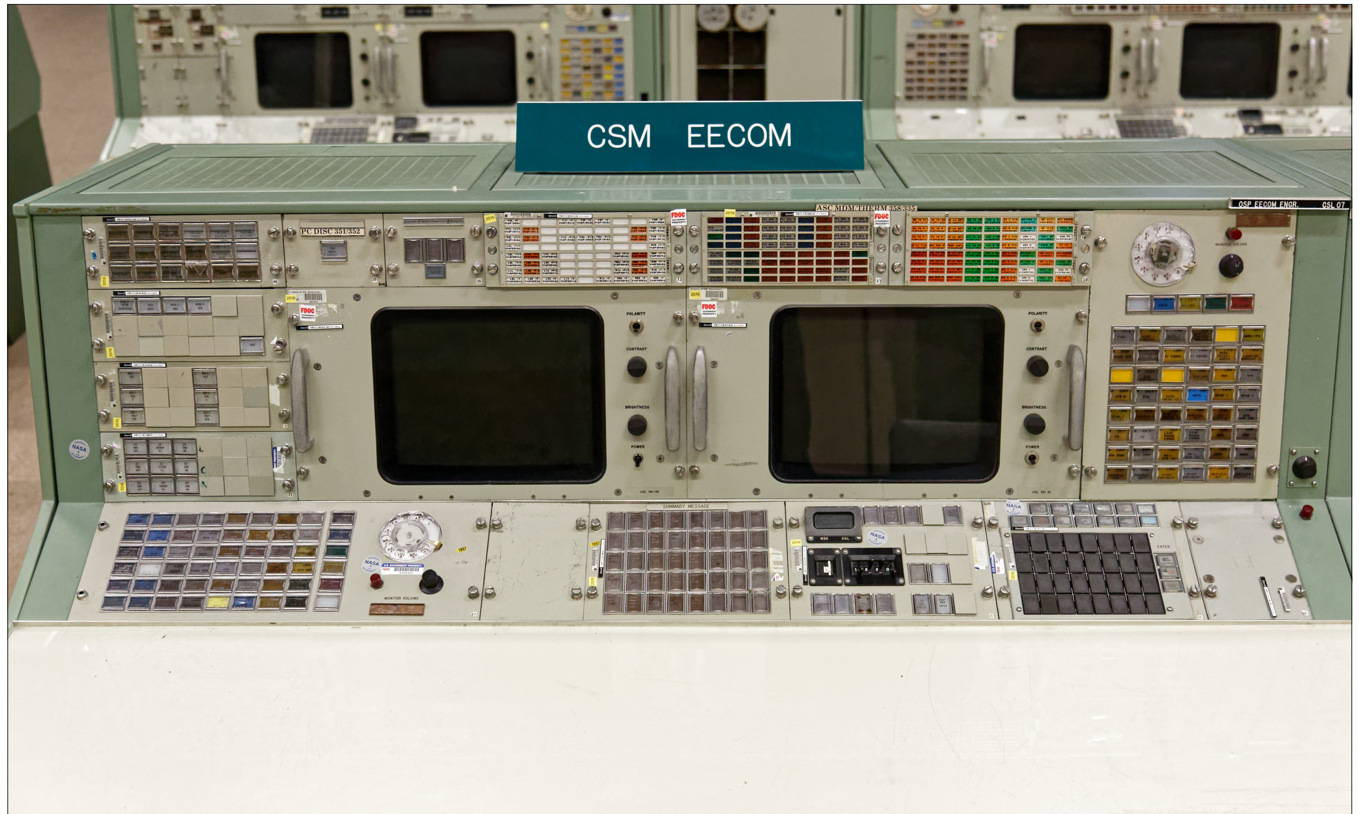
BOOSTER - RETRO - FDO - GUIDO
SURGEON - CAPCOM - EECOM - GNC - TELMU - CONTROL
INCO - O&P - AFD - FLIGHT - FAO - NETWORK
PAO - DFO - HQ - DOD

The three astronauts on an Apollo spacecraft were incapable of monitoring all of the capsule's systems. There was simply too much to keep track of.

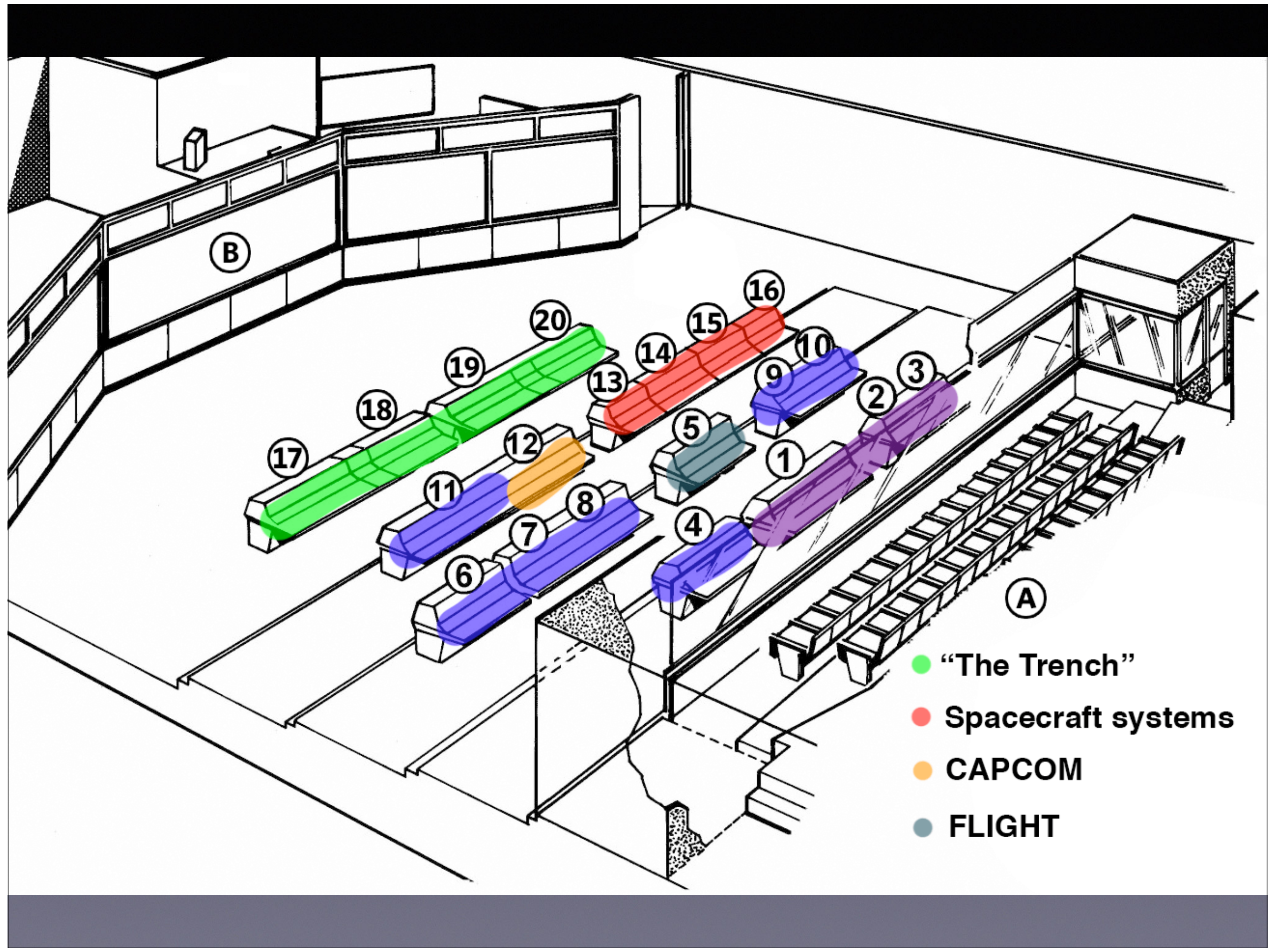


All these switches weren't even remotely enough to address all the spacecraft's functionality.

The apollo spacecraft was the most complex vehicle ever designed by humans up to that point (and the LM comes a close second). It was massively complex and had a tremendous number of interlinked systems. The decision was made, then, to chop up the workload. Astronauts would focus on astronaut-appropriate tasks, like flying, rendezvousing, docking, landing, and running experiments. They had some amount of control over their environmental and comms systems, and they could do all of their guidance and navigation independent of the ground if necessary. But their primary job was flying, landing on the moon, taking off from the moon, and keeping the science experiments and other mission tasks happening on the timeline.



Therefore, the primary job of Mission Control was to keep watch over all the things the astronauts couldn't. Each controller in turn had their own dedicated support staff to put more eyes on problems.



That watching was done by the consoles in red - 13 and 14 (EECOM and GNC) watched over the CM, and 15 and 16 (TELMU and CONTROL) watched over the LM. The consoles in green, on the other hand—the trench—monitored the Saturn V rocket during launch (the BOOSTER “super console,” which had extra people at it during launch), and then kept track of where the spacecraft was and where it was going, as well as continually computing up-to-the-minute options to abort whatever was happening and return to earth.

BOOSTER - RETRO - FDO - GUIDO
SURGEON - CAPCOM - EECOM - GNC - TELMU - CONTROL
INCO - O&P - AFD - FLIGHT - FAO - NETWORK
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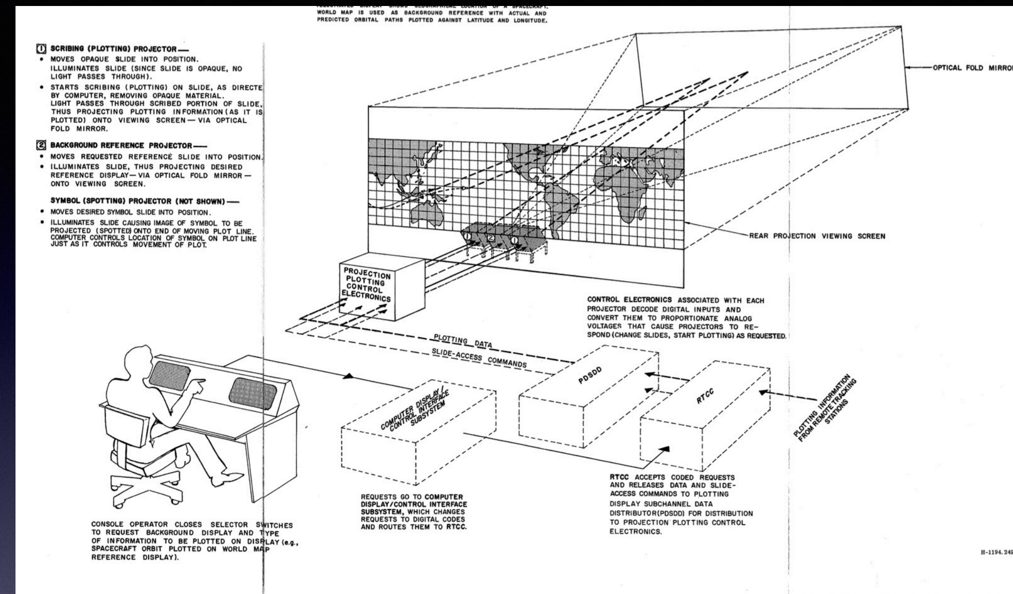


Figure 3-3-4-1. Typical Projection Plotting Display

And those screens were more analog than you might believe…

(explanation re: how displays were generated)

Source: https://www.hq.nasa.gov/alsj/MCCFamManual.pdf
“Mission Control Center Familiarization Manual”, NASA publication PHO-FAM001 (about 211MB)

When things go wrong…

- The key to Mission Control and the Apollo flights all working so well was simple: intensive training
- Controllers and astronauts spent hundreds of hours working through simulated mission, fixing simulated problems
- The best controllers could eventually identify individual transistor failures by looking at patterns of trouble behavior
- They got *so good* that they could even handle the most unexpected of issues…like the launch of Apollo 12

Play video after this - dropbox

From the Earth to the Moon clip, Apollo 12 launch
https://www.youtube.com/watch?v=SSN4MIsP_90

From the Earth to the Moon is basically *Band of Brothers* in space. If you've not seen it, it's very much worth picking up. It's available on DVD from Amazon, and a remastered BluRay HD version will be coming out next month and can be preordered here.

“FCE to auxiliary? What the hell is that?”

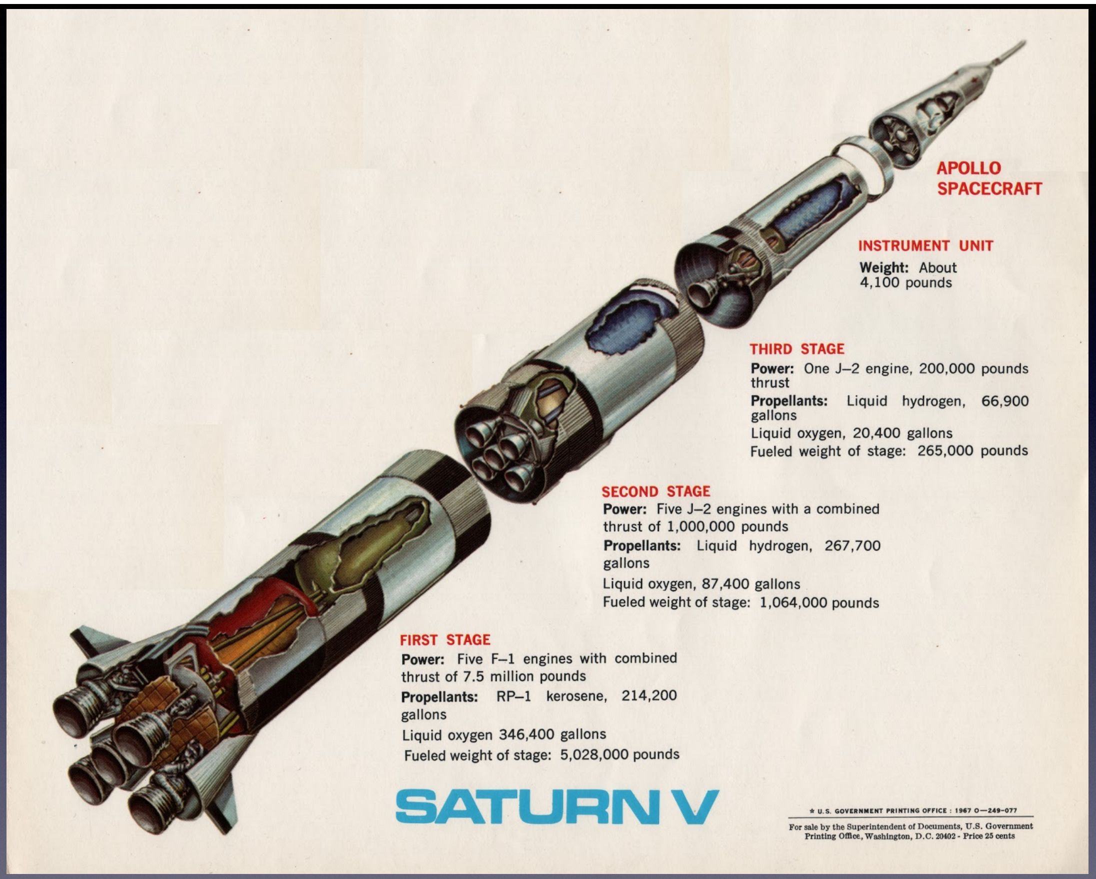
- “SCE” is the CM’s Signal Conditioning Equipment
- Responsible for translating raw sense voltage outputs from cockpit instrumentation into the right format for transmission to the ground as telemetry
- Lightning strike disrupted spacecraft’s AC power busses and drastically lowered power to the SCE, causing the telemetry feeds to look like garbage
- “SCE AUX” switch put SCE in low-power mode, enabled it to run on reduced power
- MOCR was then able to see telemetry feeds again, advise spacecraft on WTF to do next

So what the hell happened? The spacecraft was literally struck by lightning, twice, and the surge tripped breakers on the spacecraft and disconnected a whole buttload of systems from the spacecraft’s main electrical busses. The fix was to set SCE to Aux, but what does that mean? (read chart) John Aaron—who just spoke at rice this past week—was the best EECOM in the directorate. To hear the tale told by Sy Liebergot, one of Aaron’s EECOM peers, Aaron’s ability to recall tiny wiring and circuit diagrams was unparalleled, and when A12’s feeds went online, he stared at his console in silence for several seconds and then simply announced the fix over the loop. He later said he recognized the pattern of garbage on his screen from an exercise months before where a low voltage condition was being simulated. He was able to mentally look up that information under the stress of a launch and do it in seconds—and his quick thinking saved the mission.

The Saturn V

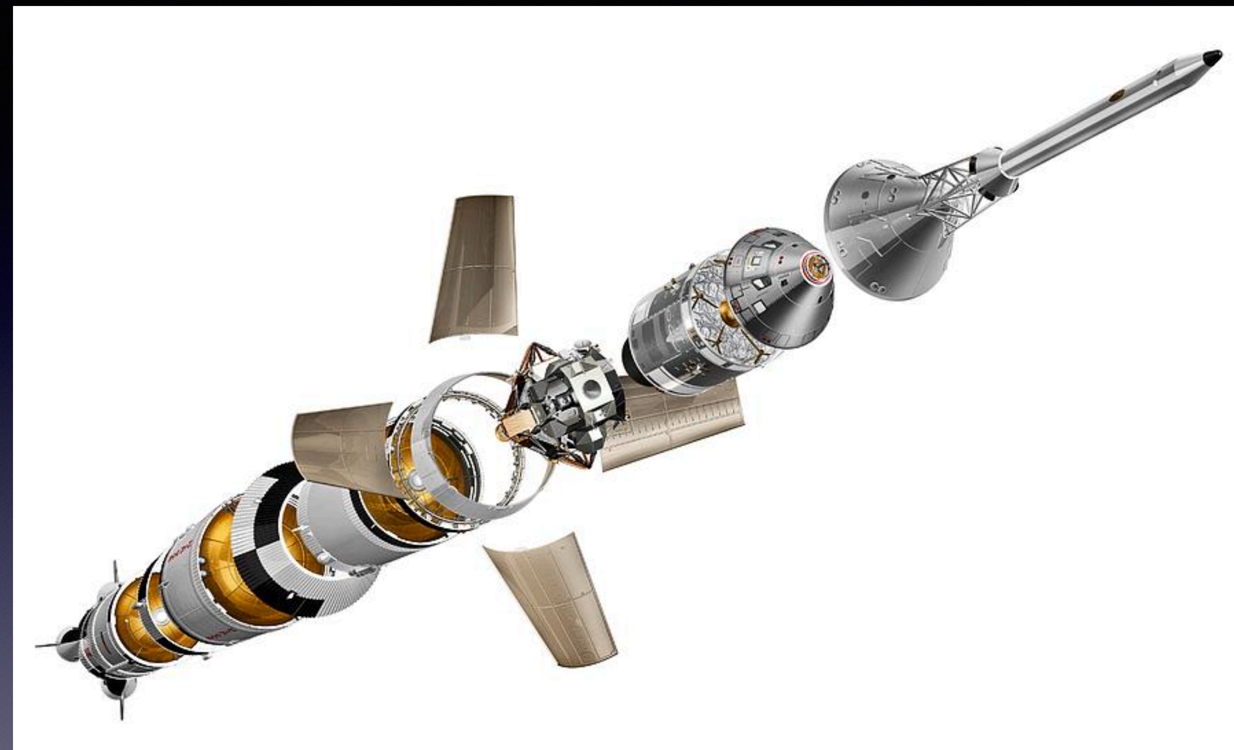
Largest successfully flown rocket ever built by humans

So speaking of launches, let's talk — just briefly! — about the launch vehicle. Every component of Apollo was critical to success, but it doesn't get much more critical than the rocket itself, because without the Saturn V, we'd never have gotten to the moon.



Three stages to the Moon

3 stage rocket - each stage had a different function. Stage 1 - thick part of atmosphere. Stage 2 - workhorse stage, delta V, most improvements. Stage 3 - multipurpose. final kick into orbit, and also cruise to the moon.



Exploded view: S-IC, interstage, S-II, interstage, S-IVB,
IU, SLA (opened), LM, SM, CM, BPC, LES

S-IC: the designation for the Saturn V’s first stage, manufactured by Boeing (more info)
Interstage: the load-bearing component that connects each stage together
S-II: the designation for the Saturn V’s second stage, manufactured by North American Aviation (more info)
S-IVB: the designation for the Saturn V’s third stage, manufactured by Douglas Aircraft Corp (more info)
IU: the Instrumentation Unit, where the rocket’s independent guidance and computers were located (more info)
SLA: Spacecraft/Lunar Module adapter (more info)
LM: Apollo Lunar Module (pronounced “lem”) (more info)
SM: Apollo Service Module (more info)
CM: Apollo Command Module (more info)
BCP: Boost Protective Cover (more info)
LES: Launch Escape System (more info)

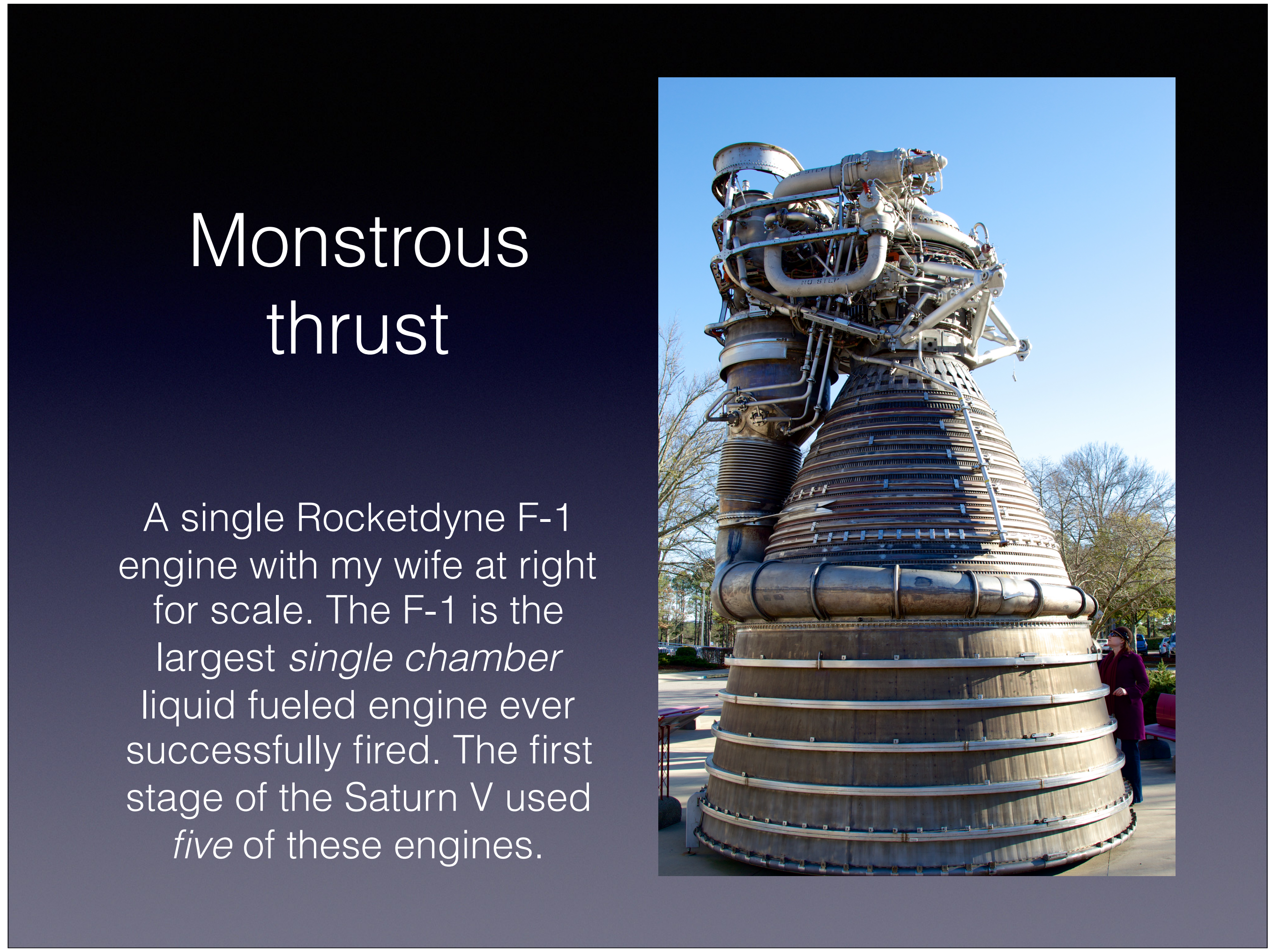
“Our Germans are better than their Germans!”

—The Right Stuff

Wernher von Braun in his office at the Marshall Space Flight Center in Huntsville, AL

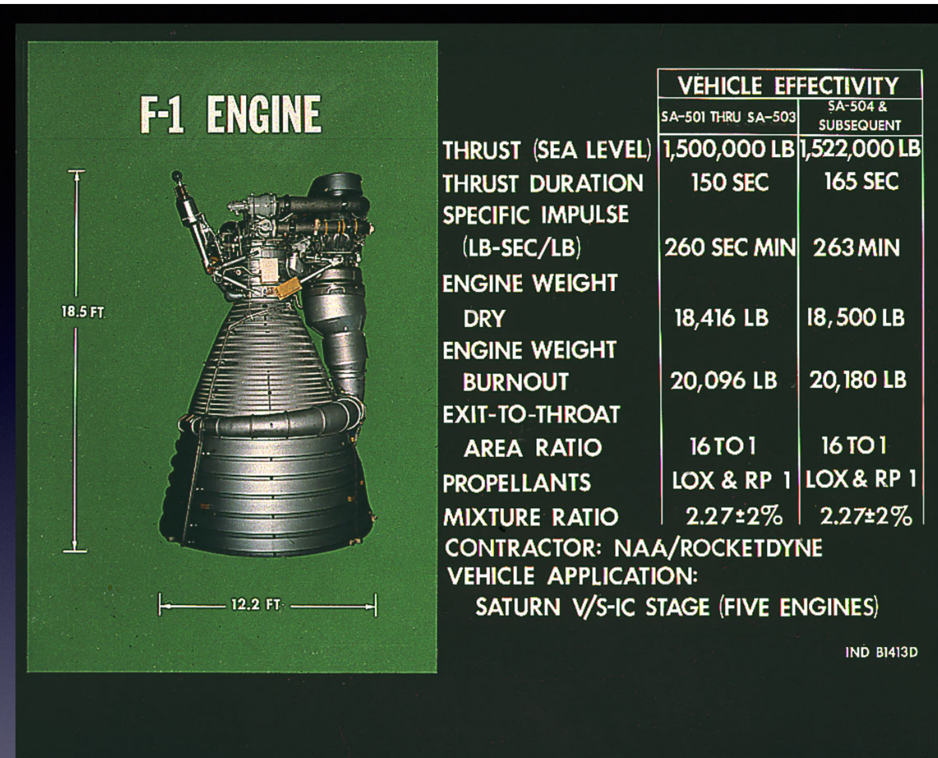
(Quote source: https://www.youtube.com/watch?v=rYco0UsWhLc)

The Saturn V was the magnum opus of Wernher von Braun, the foremost rocket scientist of Hitler’s Reich. I say that not to be inflammatory, but because it’s impossible to put von Braun in context without acknowledging that he was a member of the Nazi party—likely out of necessity in order to be able to hold the position of power he had over rocket design. von Braun had dreamed since he was a boy of flying rockets to the moon and to Mars, and had designed Germany’s V1 and V2 rockets. He was smuggled out of Germany after the end of WW2 in a joint CIA/OSS operation called “Operation Paperclip,” which is absolutely worth reading about, and sent to live in Huntsville with his team, working on human space flight concepts first for the Air Force and then for NASA. Freed from the constraints of making war machines, he and his team of expatriated German rocket scientists designed the Saturn series of rockets for NASA. With typical teutonic engineering conservatism, the design for the Saturn was over-engineered to the point that after the first few flights, the safety margins were scaled back from “insane” to “huge” and the rocket was able to be upscaled to carry greater weight with minimum design changes. von Braun’s design was so good that no Saturn V ever suffered more than a minor mishap during flight, and many of von Braun’s “over-engineered” decision—like giving the Saturn V its own independent guidance, in case it were ever to be flown with cargo instead of a spacecraft—paid dividends. Without that separate guidance, Apollo 12 would have been an immediate abort when lightning struck.



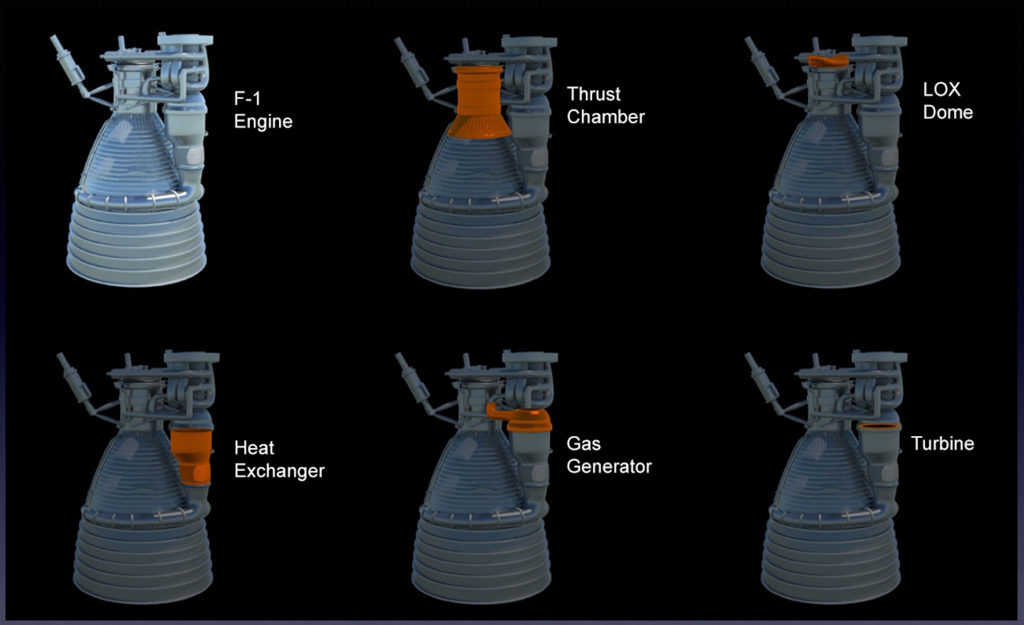
The most interesting (and visually imposing!) part of the Saturn V is the first stage, and the most ridiculous part of the first stage are the massive F-1 engines. There are five of them, and the numbers behind them are staggering.

Image source is a long piece I wrote on reviving the F-1 for present-day testing: https://arstechnica.com/science/2013/04/how-nasa-brought-the-monstrous-f-1-moon-rocket-back-to-life/



Almost twenty feet tall and twelve feet wide, the F-1 produced 1.5 million lbs of thrust and burned 1 ton of RP-1 kerosene and 2 tons of liquid oxygen *per second*.

And the Saturn V's first stage had *five* of them.



The F-1 is a “gas generator cycle” engine.
This means it uses the thrust from a small piggyback rocket motor (the “gas generator”) to turn the turbopumps to move fuel and oxidizer from the tanks to the thrust chamber.

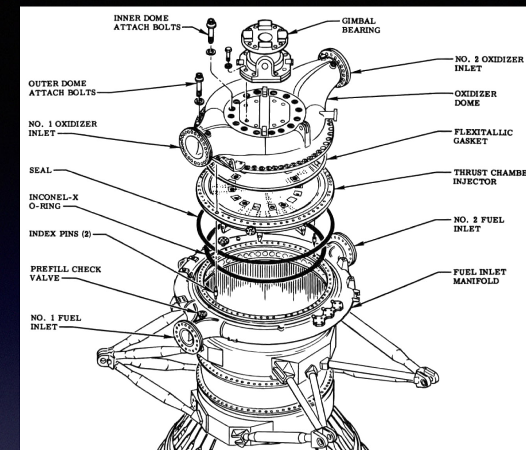
How a gas generator cycle rocket motor works (and some info on other types of rocket engine cycles): https://www.youtube.com/watch?v=jheMusS0JwA

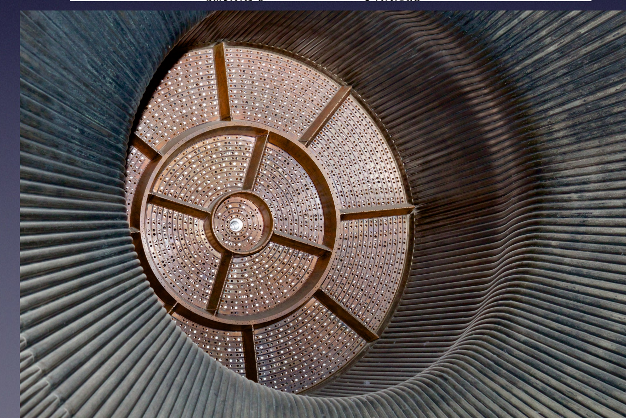
The gas generator itself develops more thrust than an F-16 at full afterburner. That power is used to turn the LOX and RP-1 turbopumps, which put out about 55,000 shaft horsepower.

This is a photo I took in 2012 at Marshall, when NASA decided to pull an F-1 gas generator off of an F-1 in storage and do some test firings to collect data on how the old engines functioned.

Source: https://arstechnica.com/science/2013/04/how-nasa-brought-the-monstrous-f-1-moon-rocket-back-to-life/

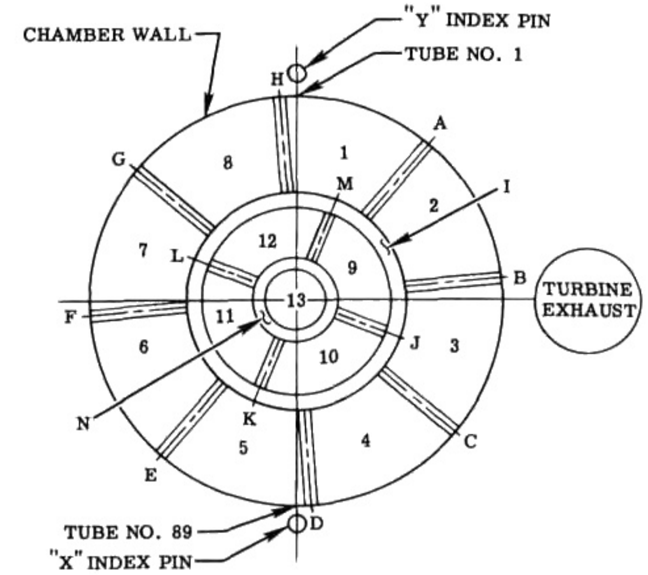
That power is used to shove three tons of propellent through a copper and steel sandwich called the "injector plate." The plate was drilled with over a thousand holes arranged in concentric rings. The holes delivered precisely-aimed atomized streams of LOX and RP-1 into the combustion chamber.





injector — 44" wide

More info:
http://heroicrelics.org/info/f-1/f-1-injector.html



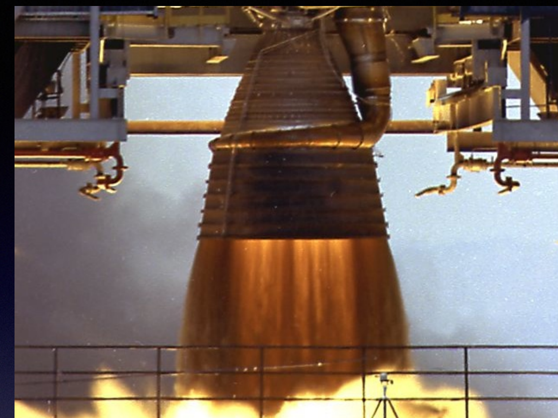
INJECTOR COMPARTMENTS INDICATED BY NUMBERS 1 THROUGH 13.
BAFFLES ARE INDICATED BY LETTERS A THROUGH N.

Thrust Chamber Injector Compartments and Baffles

What's up with those baffles?
They keep the engine from exploding!

Story re: baffle design and layout
More info: http://heroicrelics.org/info/f-1/f-1-injector-baffles.html
First-hand account of injector design process by some of the folks who worked on it:
https://www.youtube.com/watch?v=o39UlJlMce8#t=9m34s (skip to 9m 34s if the link doesn't automatically start there)

And that gas generator? You have to do something with its exhaust…



After the gas generator's exhaust has done its job, the plume is funneled through the finger-like manifold that wraps around the engine bell and then vented across the walls of the lower rocket nozzle, cooling it.

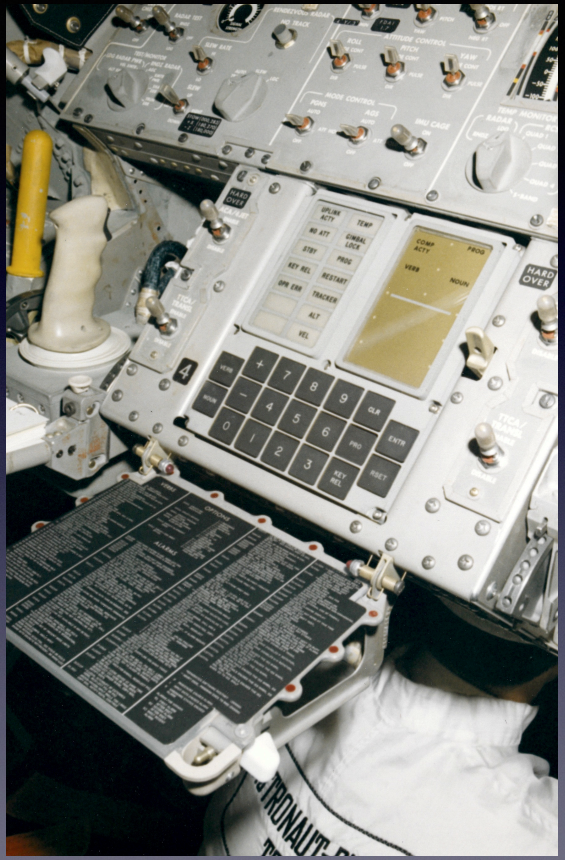
The exhaust is fuel-rich and takes a few seconds to completely ignite, thus providing the F-1's visually distinct dark thrust column.

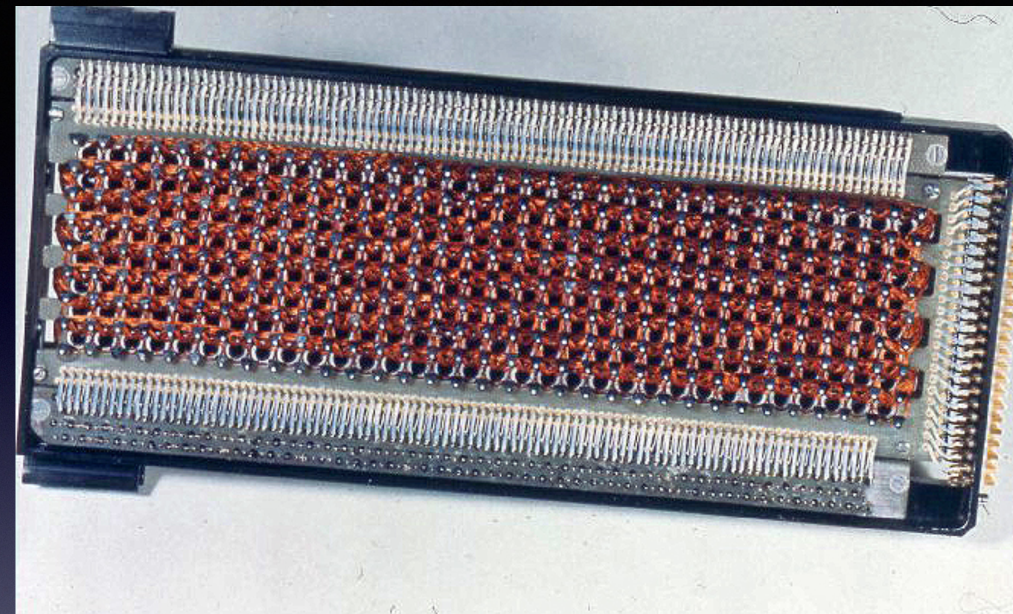
The Apollo Guidance Computer

Less powerful than a pocket calculator?
Well…sort of.

Let’s talk computers — space computers. So you’ve probably heard the old bit about how we flew to the moon on less power than a digital watch or whatever, and that’s…kind of sort of true, but it’s also a gross mischaracterization of what “computing power” means in different contexts.

- The AGC was the capstone of 1960s engineering achievement
- The MIT-designed software it ran was *literally* revolutionary
- The AGC effectively invented the entire field of real-time computing
- Not so much a computer as a sophisticated embedded controller with purpose-built peripherals





The AGC’s hardware was based on core-rope memory, with all the airspace in the the core-rope modules filled with epoxy

Complex and difficult to manufacture, but impervious to radiation effects, shock, G-loading, and pretty much everything else.

A great documentary on the subject: https://www.youtube.com/watch?v=xQ1O0XR_cA0

Block II AGC internals

- 16-bit datawords (15 bit wordlength + 1 bit parity)
- 2k-words RAM, 36k-words core rope ROM
- 4x 16-bit registers for general computing
- 2.048 MHz crystal clock for timing reference (but actual cycle time was 960ms, sort of)

Sounds primitive, but specs don't tell the whole tale.

Split-brained

- The AGC had a simple RTOS called the Executive that was responsible for batch job scheduling using primitive cooperative multitasking
- Also had a sophisticated interpreter (called “Interpreter”) that ran a “virtual machine” in software
- The Interpreter enabled the AGC to do complex math operations in software (including vector math and transcendental functions) that it couldn’t do in hardware

(read slide first) None of this sounds outlandish in 2019, until you realize that the software designers were making all of this up as they went along. They invented the concept of a real-time operating system without google or any existing best practice guidelines—they were CREATING the best-practice guidelines that we use today. It’s all well and good to implement emulation in software to do math you can’t in hardware today—it’s another thing entirely to INVENT the idea of doing that and then DO IT SUCCESSFULLY, for the very first time, without a blueprint.

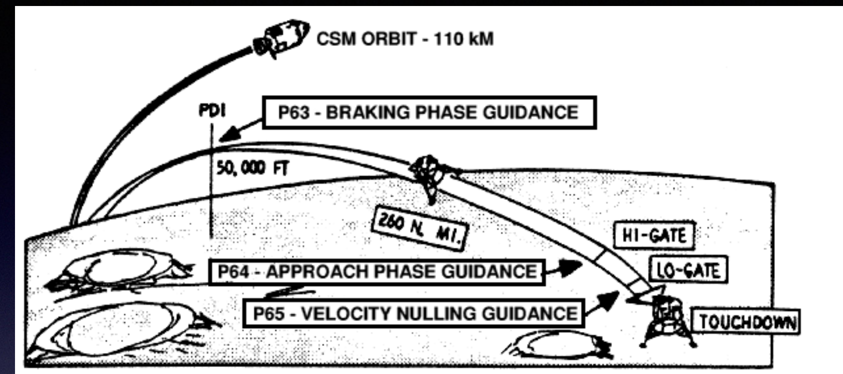


Fig. 3. Operational phases of powered descent. Design criteria: P 63 - Braking phase (PD1 to Hi-Gate), efficient reduction of orbital velocity. P 64 - Final approach phase (Hi-Gate to Lo-Gate), crew visibility (safety and site assessment). P 65 - Landing phase (Lo-Gate to touch-down), manual control takeover.

How well did it work?

Well enough to save the Apollo 11 landing.

Setting the stage real quick—this is how you land on the moon. There's no air, so you can't use wings or parachutes—you have to use rockets. This is why the Apollo landing process was called "powered descent"—they had to ride their own rocket's thrust down from orbit to the surface. Powered Descent was a complex and involved procedure, endlessly simulated by controllers and astronauts. There were tons of moving parts, and if anything went wrong, the only way to abort was to smack the "ABORT STAGE" button in the cockpit, which would blow the spacecraft in half, jettison the descent stage, and light the ascent engine. The astronauts would then have to locate and rendezvous with the command module for rescue. Powered descent was just about the worst possible time for something to go wrong, and so, of course, for the first lunar landing, that's exactly when things went very wrong. I'm goign to play you this clip from First Man, which dramatizes things a bit but which gets across both the seriousness of the situation and also the ridiculously FAST pace at which mission control resolved the problem.

First Man landing clip:
https://www.youtube.com/watch?v=TrvXqosqkls

[Seriously, this movie is *so damn good*. The filmmakers demonstrate both a tremendous respect for the source material, and also an almost uncanny attention to detail and accuracy. There are a few dramatic liberties taken to make things a bit more watchable and movie-like—a lot of space flight is just flat-out boring when things are going right—but the movie succeeds brilliantly in giving audiences a realistic look at not just the technology that got us to the moon, but at the people who flew there. And the quiet scenes Armstrong and his wife make a powerful counterpoint to the major action pieces. If you're a fan of human space flight and you haven't seen it, stop what you're doing and watch it.]

1201? 1202? WTF?

- The timeline is compressed and amped up with dramatic music, but that’s pretty much how it went
- What were these alarms?
- 1201 & 1202 are “executive overflow” alarms—the LM AGC was warning that it had run out of temporary storage space
- AGC program flow was carefully and painstakingly arranged so that this occurrence should have been impossible—the alarms were there for debugging and were NEVER expected to happen in flight

For a more in-depth explanation of the next few slides, please see the article I wrote on the 1201/1202 alarms a few years ago:
https://arstechnica.com/science/2015/07/no-a-checklist-error-did-not-almost-derail-the-first-moon-landing/

Or, if you really want to go down the rabbit hole, read Don Eyles even-more-in-depth explanation (which I used as the primary source for my article):
https://www.doneyles.com/LM/Tales.html

Eyles also has a book, which is a great time capsule of his work on the program as an MIT grad student in the 1960s. (In it I learned two major things: first, just how groundbreaking the AGC software was; and second, everybody at MIT writing the code was *super-duper stoned* for *basically the whole program*)

The alarms are commonly chalked up as the result of a “checklist error,” but this is not correct. The alarms stemmed from a *design documentation error*.

Before Powered Descent, Aldrin switched the LM’s rendezvous radar on to its “SLEW” mode, which energized the rendezvous radar.

This was done to give the crew one less thing to worry about if an abort were necessary (the rendezvous radar would be used to find the Command Module).

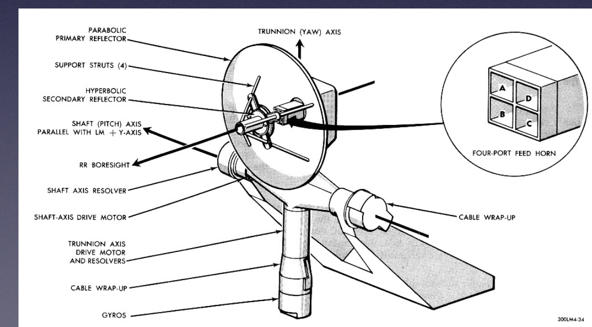
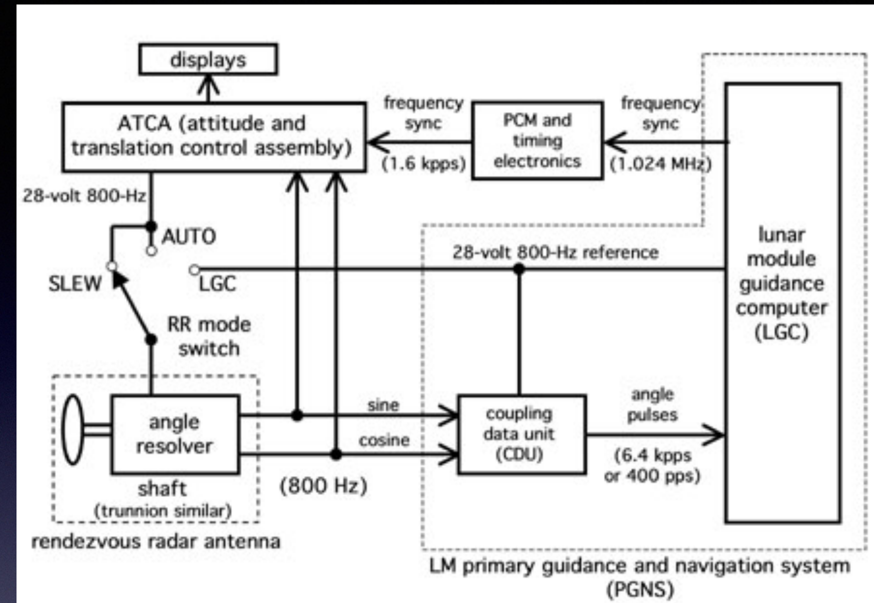


Figure 2.2-24. Rendezvous Radar Antenna Assembly

- This gets a little complex, but stick with me.
- The LM AGC connected to a piece of equipment called the ATCA (Attitude, Translation, and Control Assy), which provided the electrical interface for the AGC to steer the rendezvous radar's hardware.
- Similarly, the LM AGC connected to two devices called CDUs (Coupling Data Units) which allowed the AGC to read the position of the rendezvous radar's dish.
- The CDU read from the radar to the AGC, the ACTA sent commands from the AGC to the radar.



- The ATCA was powered by 800Hz, 28-volt AC
- CDUs had a separate 800Hz 28-volt AC synchronizing current.
- In order for everything to work normally, all of these 800Hz 28VAC feeds were supposed to be both *frequency locked* and also *phase-synchronized.*

…but due to a documentation oversight, the system was built without electrical phase synchronization.

The AGC was a digital device, but most of the LM's hardware was thoroughly analog. The ACTA and CDUs were both fed by separate 800Hz, 28 Volt AC currents, which they used for both power and timing reference.

(Again, if you want a more thorough explanation, this is presented much more in-depth on AGC programmer Don Eyles' site)

Rather than being phase-synced by design, the power to the ACTA and CDUs could be in phase or out of phase randomly, depending on the exact moment the rendezvous radar was activated by the crew.

The equipment expected all of its components to be in phase, and when they weren't…weird stuff happened.

120x Alarms: Cause & Effect

- The out-of-phase condition caused the CDUs and the ACTA to see each other's signals as garbage instead of as valid radar dish position data
- The CDUs began to frantically try to fix things by sending "MOVE THE DISH" interrupts to the guidance computer, as fast as it could generate them
- This resulted in 12,800 unplanned spurious hardware interrupts per second slamming into the computer

120x Alarms: Cause & Effect

- Interrupt handling requires some amount of computing power
- The 12,800 unplanned interrupts per second sucked up about 15% of the computer's processing time and broke the carefully-planned program flow in the guidance computer
- The computer was no longer able to service its joblist within its 960ms cycle time
- Temp storage areas normally emptied and available at the end of each 960ms cycle weren't being emptied because the jobs were lagging due to the extra 15% load

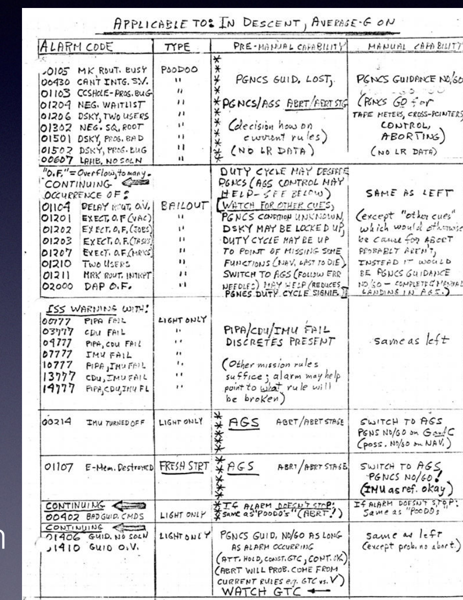
120x Alarms: Cause & Effect

- And here's where the genius of the AGC's design shone.
- When the overflow occurred, the computer displayed the "help, my temp storage is full" error code — 1201 ("EXECUTIVE OVERFLOW: NO CORE SETS")
- But rather than hanging or crashing, the computer automatically executed its BAILOUT restart routine
- BAILOUT simply flushed the temp areas and restarted the current job list — the spacecraft retained its guidance data and the flight continued uninterrupted

Here we get to see exactly how well planned the guidance computer's design was. Even though these kinds of alarms should have been impossible, the scientists and grad students at MIT who designed the software had built in the capacity for the computer to execute a soft-restart of itself, where it simply dumped all its work and started over on its tasklist. Because the overflow wasn't large, it took anywhere between several seconds and several minutes for it to recur. After a couple of occurrences, MCC figured out that the problem had to do with the radar and told the spacecraft that they'd monitor stuff and to not worry about it.

How'd they know so quick?

- During previous sims, controllers had been too quick to call an abort in response to computer trouble
- Flight director Kranz instructed GUIDO backroom controller Jack Garman to memorize every single computer error in case this happened during a mission
- So he did—and then it happened during a mission
- For his quick thinking, controllers began calling Garman as "GAR-FLASH"


APPLICABLE TO: IN DESCENT, AVERAGE-G ON

ALARM CODE	TYPE	PRE-MANUAL CAPABILITY	MANUAL CAPABILITY
00105 MK ROUT. BUSY 00430 CAN'T INTG. S.V. 01103 CCSHOLE-PROG. BUG 01204 NEG. WAITLIST 01206 DSKY, TWO USERS 01302 NEG. SQ. ROOT 01501 DSKY, PROG. BAD 01502 DSKY, PROG. BUG 00607 LAHB. NO SOLN	POODOO " " " " " " " "	PGNCS GUID. LOST, PGNCS/AGS ABRT/ABRT STG (decision how on current rules) (NO LR DATA)	PGNCS GUIDANCE NO/GO (PGNCS GO for TAPE METERS, CROSS-POINTERS, CONTROL, ABORTING) (NO LR DATA)
"O.F." = Overflow, to many - CONTINUING OCCURRENCE OF: 01104 DELAY ROUT. O.V. 01201 EXECT. O.F (VAC) 01202 EXECT. O.F. (JOBS) 01203 EXECT. O.F. (TASKS) 01207 EXECT. O.F. (MRKS) 01210 TWO USERS 01211 MRK ROUT. INTRPT 02000 DAP O.F.	BAILOUT " " " " " " "	DUTY CYCLE MAY DEGRADE PGNCS (AGS CONTROL MAY HELP - SEE BELOW) (WATCH FOR OTHER CUES, PGNCS CONDITION UNKNOWN, DSKY MAY BE LOCKED UP, DUTY CYCLE MAY BE UP TO POINT OF MISSING SOME FUNCTIONS (NAV. LAST TO DIE). SWITCH TO AGS (FOLLOW ERR NEEDLES) MAY HELP (REDUCES PGNCS DUTY CYCLE SIGNIF.))	SAME AS LEFT (except "other cues" which would otherwise be cause for ABORT PROBABLY AREN'T, INSTEAD IT WOULD BE PGNCS GUIDANCE NO/GO — COMPLETE MANUAL LANDING IN AGS.)
ISS WARNING WITH: 00777 PIPA FAIL 03777 CDU FAIL 04777 PIPA, CDU FAIL 07777 IMU FAIL 10777 PIPA, IMU FAIL 13777 CDU, IMU FAIL 14777 PIPA, CDU, IMU FL	LIGHT ONLY " " " " " "	PIPA/CDU/IMU FAIL DISCRETES PRESENT (Other mission rules suffice; alarm may help point to what rule will be broken)	same as left
00214 IMU TURNED OFF	LIGHT ONLY	AGS ABRT/ABRT STAGE	SWITCH TO AGS PGNS NO/GO on G and C (poss. NO/GO on NAV.)
01107 E-Mem. Destroyed	FRESH STRT	AGS ABRT/ABRT STAGE	SWITCH TO AGS PGNCS NO/GO! (IMU as ref. okay)
CONTINUING 00402 BAD GUID. CMDS	LIGHT ONLY	IF ALARM DOESN'T STOP: same as "POODO's" (ABRT!)	If ALARM DOESN'T STOP: Same as "POODO's"
CONTINUING 01406 GUID. NO SOLN 01410 GUID O.V.	LIGHT ONLY	PGNCS GUID. NO/GO AS LONG AS ALARM OCCURRING (ATT. HOLD, CONST. GTC, CONT. OK) (ABRT WILL PROB. COME FROM CURRENT RULES e.g. GTC vs. V) WATCH GTC ←	same as left (except prob. no abort.)

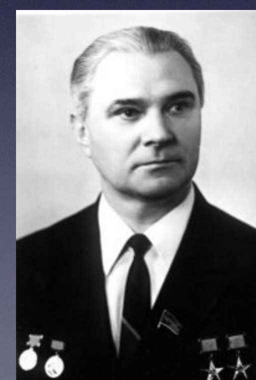
Optional fun activity: the actual sync'd mission audio

https://www.firstmenonthemoon.com/

(We can do this now if you guys want to experience how this went down in real-time!)

Lastly:
What about the USSR?

The Soviet space program was locked in a push-pull war between two chief designers,**Valentin Petrovich Glushko** (left) and **Sergei Pavlovich Korolev** (right). It was a bitter and acrimonious rivalry that effectively destroyed any chance the USSR had to mount an effective response to Project Apollo.



capitalist approach vs. communist approach

Cryogenic propellants are things like liquid hydrogen and liquid oxygen. They are very cold and difficult to store and transport because they must be kept at hundreds of degrees below zero and they're constantly trying to boil off. You cannot leave a cryogenically fueled rocket sitting on the pad for very long or its fuel will evaporate. Hypergols, otoh, are easily storable and don't require massive insulation; they can be left in a rocket for days (or more), doing away with having to fuel and de-fuel a rocket multiple times. On the other hand, the chemicals we use as hypergolic propellants are MURDEROUSLY TOXIC and HIDEOUSLY CORROSIVE. They are incredibly dangerous in the short term and if they don't kill you in minutes, they'll give you cancer later. A rocket burning H_2+O_2 produces steam and water vapor; a rocket burning DNT+Hydrazine produces cancersmoke. Spilling cryogenic fuels is a pain in the ass to clean up; spilling hypergols is a legit evacuate-the-surrounding-area-immediately emergency.

We out-spent them. It was yet another area where Apollo was a strategic victory against the USSR.

This wikipedia article is a good jumping-off point if you want to fall down the Soviet space rabbit hole and spend a few hours reading about stuff.

Do you want to know more?

- *Apollo: The Race to the Moon*, by Charles Murray & Catherine Bly Cox
- *A Man on the Moon*, by Andrew Chaikin
- *How Apollo Flew to the Moon*, by David Woods
- *Flight: My Life in Mission Control*, by Chris Kraft
- *The Apollo Guidance Computer: Architecture & Operation*, by Frank O'Brein
- *Chariots for Apollo: A History of Manned Lunar Spacecraft*, by Brooks, Grimwood, & Swenson
- *Challenge to Apollo: The Soviet Union and the Space Race*, by Asif Siddiqi (see presenter notes for link)
- *Ракеты и люди* ("Rakety i Lyudi," or "Rockets and People"), by Boris Evseyevich Chertok (see presenter notes for link)

Siddiqi's work is available in two volumes from Amazon (part one, part two) or as a pair of PDFs for free from NASA (part one, part two).

Chertok's work is available as a four-volume set from Amazon (here) for free from NASA (here).

"If we die, we want people to accept it. We are in a risky business, and we hope that if anything happens to us, it will not delay the program. ***The conquest of space is worth the risk of life.*** *Our God-given curiosity will force us to go there ourselves because in the final analysis, only man can fully evaluate the Moon in terms understandable to other men."*

–Gus Grissom