NASA JOHNSON SPACE CENTER ORAL HISTORY PROJECT
ORAL HISTORY TRANSCRIPT

BEDFORD F. COCKRELL
INTERVIEWED BY JENNIFER ROSS-NAZZAL
HOUSTON, TEXAS –28 MAY 2019

ROSS-NAZZAL: Today is May 28th, 2019. This interview with Butch Cockrell is being conducted for the JSC Oral History Project in Houston, Texas. The interviewer is Jennifer Ross-Nazzal. Thanks again for taking some time to meet with me this morning. Really appreciate it.

COCKRELL: Glad to be here.

ROSS-NAZZAL: I wanted to ask you about your memories of Sputnik.

COCKRELL: Sputnik was probably one of the catalysts that got me in the business. I was a sophomore in Beaumont High School [Texas], and I already had an interest in space kind of things. We used to get a thing called the *Weekly Reader*, came out every Friday, and it had little articles in it. There were articles in it about putting things in orbit, and I was curious about that. [But I] didn't understand how it worked.

I went to the high school physics teacher, and he said something to me, said some words, and I didn't understand it. I didn't understand it till later. In the fall of '57 I was 16. I was a sophomore in high school and already had a love of math. By the time I was a sophomore the only science class I'd had was biology, so I hadn't had chemistry and physics yet. I was taking math courses, of course.

My dad wasn't a ham radio operator, but he was interested in radio. He had a shortwave radio, so he could get weather. It had a band on it that could receive the signal from Sputnik. The Beaumont newspaper published articles about when it was going to come over, and we would get the radio on and listen to it beep. My dad was a blue-collar guy, didn't have a college education, but he was fascinated by things like that all his life. In fact, I remember when I was working at NASA I spent many days talking to my dad about how things worked.

I went on through high school and took physics and chemistry and all the math courses, made good grades, and I got accepted into Texas A&M [College Station] in 1959. I thought I was going to be an electrical engineer, majored in electrical engineering, and I realized after two semesters that the engineers had to take labs. They were usually in the afternoons, and the math majors and the physics majors only had lectures in the mornings and no afternoon classes. I switched my major and majored in math physics.

[The way I got my job at NASA was luck. When] I was a senior at A&M, [in the spring of] 1963, my last semester of my senior year, I almost had enough credits to graduate, so I was double-registered as a graduate student as well as an undergraduate. I was also by obligation in the ROTC [Reserve Officer Training Cadet] program. At that time, unless you were medically exempt, you had to be in the Corps at A&M. You had to take ROTC. I was on the way to getting a commission.

I was grading papers for a physics professor. His name was Jack Kent. He got a contract with NASA to come down here every Thursday and teach orbital mechanics. NASA had just opened a facility up on the Gulf Freeway at a place called the Houston Petroleum Center. People who were here then may remember. There was a yellow oil derrick out on the freeway in the parking lot next to this place. It was just before you get to Wayside Street on the Gulf Freeway.

The Langley [Research Center, Hampton, Virginia] people had moved here the year before. They were hiring, and some of the new hires had various degrees in various disciplines. John [P.] Mayer, the guy who ended up being my boss for a lot of my life, he was Chris [Christopher C.] Kraft's deputy. They had an organization there; it was called the Flight Operations Division. Chris Kraft was the division chief and a guy named John Mayer was the assistant chief for Mission Planning.

John Mayer realized that a lot of these new hires didn't understand orbital mechanics well enough, so he hired this professor at A&M to come down every Thursday and teach a class on orbital mechanics. I was grading papers for him, and I was his lackey. Every Thursday we drove down here in an A&M Pontiac station wagon. I carried the viewgraph machine and the viewgraphs and the handouts and came with him.

As we did this, all spring semester in 1963, one day a guy named Paul [G.] Brumberg approached me and said, "You've taken all this stuff. You know all this stuff. You need to fill out an application."

I said, "Well, I can't, because I'm due to be commissioned the day I graduate. I'm going to get a degree, and I'm going to get a commission. I got an Army tour to do, a two-year Army tour."

He said, "Don't worry about that. We'll get you assigned to NASA."

I did. I filled out an application. They hired me. I graduated on Saturday in May of '63, and I went to work on Monday.

ROSS-NAZZAL: Wow! They worked fast.

COCKRELL: I showed up at the Houston Petroleum Center facility there on the Gulf Freeway. It's a one-story building, a whole bunch of little buildings all connected with breezeways. Apparently it had been built at some time for some petroleum group, and they were leasing it out to the people moving here to NASA. I start working there, and the Personnel Director, a guy named Bill Forsyth, said, "I'm going to fill out an application to appeal to the Army to have your military assignment assigned to the Manned Spacecraft Center."

I said, "Great."

I went to work, and Army said no. I lasted about three months, but it was invigorating. We had a contractor. I was put into a branch called the Math Physics Branch in that division, Chris Kraft's division. The branch chief was this Paul Brumberg. His deputy was a guy named Emil [R.] Schiesser. I think you interviewed Emil.

ROSS-NAZZAL: A couple of times.

COCKRELL: Emil is the math physics guru; he's the one that we all know. When people talk about math physics and navigation, they talk about Emil. I went to work for Brumberg. Brumberg left before I left that summer, and Emil became actually the section head. The branch chief became a guy named [James F.] Dalby.

That summer, I worked with a guy named Sam [Samuel] Pines, who was a contractor. He had a little company called Analytical Mechanics Associates, AMA. He had four employees. He was a genius about computers. The computers we had in those days were not nearly as sophisticated as the ones we have now, even the mainframes.

We were trying to solve problems. When you're numerically integrating a function, if it's a straight smooth function like a straight line, it's easy. You can take big steps in your integrator and not make errors. Think, for example, if you have a line starting at the x-axis and going up at 45 degrees. You can take a point at the start and a point anywhere out there, measure the length of the bottom, and measure the length of the side, and you get the area. It's perfect, [but] that's only for straight lines.

If the line is curved and you're trying to compute the area, which is what integration is, you got to take smaller and smaller steps. If you take small steps, it takes more computer time. We wanted to find out how to integrate the functions that we were integrating. These are orbital mechanics problems. You want to take a known position and velocity at a point in the orbit. You want to propagate it ahead in time so you'll know where you'll be in the future so you can plan things. That's what mission planning is. [If] I want to be over Corpus Christi at a certain time of day when the Sun is shining so I can take a picture I got to plan all that; that's what orbital mechanics does. We wanted to find ways to pick the integration step size so that it was small enough to minimize the error but large enough to not use up a lot of computer time. That's mostly what I did that summer.

We found some solutions. For example, when you're in Earth orbit, the orbit is pretty curvy. It's shaped like a circle or an ellipse and so you have to take relatively smaller steps than you do when you're on the way. When you're on the way to the Moon, the trajectory is fairly smooth and fairly linear, fairly straight. We came up with a scheme where we changed the step size based on the shape of the trajectory. Then I had to go to the Army. The good thing about the Army was that's where I met my wife.

ROSS-NAZZAL: Always nice.

COCKRELL: I went to Letterkenny Army Depot [Pennsylvania]. I was ordnance officer in the Ordnance Corps of the Army, which I had chosen, and I got sent to the Ordnance Officers' Training School which was in Aberdeen, Maryland. I was there for about nine weeks. Then I had a choice to make. They said, "You want to go into tank automotive or supply?" I picked tank automotive because that sounded more interesting than supply. They assigned me to supply.

ROSS-NAZZAL: Of course, that's the way it works, right?

COCKRELL: Of course. Sent me to Supply School. I went to Supply School at Fort Lee, Virginia. Then I got my full-time duty assignment, which was at Letterkenny Army Depot in Pennsylvania. It's about 20 miles from the Gettysburg battlefield near the Maryland border. Army depots store ammunition and precious metals. They have these bunkers full of ammo, powder, and everything you can think of.

At this depot, we had 5,000 civilians and about 30 military officers of which I was one. The Depot Commander was a light colonel. He called me in when I first got there. He said, "I noticed in your resume that you programmed computers at the Manned Spacecraft Center. We've got a computer project down at building so-and-so-and-so-and-so, and there's a first lieutenant down there that's leaving in six months. I want you to go down there and take over his job and finish this software project."

I said, "Okay." I went down there. They were building a payroll program in COBOL [Common Business-Oriented Language].

ROSS-NAZZAL: Quite different from what you were working on.

COCKRELL: I was programming scientific equations in Fortran [Formula Translation], and they were doing a business language. I didn't have any business background. They had all these civilians that were doing the work that were contractors. I basically was a little 21-year-old second lieutenant that managed 25 programmers. We built a payroll program and put it in play at this center. In fact, I went around to other centers. Part of my job was I had to go educate the other centers on how to use it, because we built it, then we provided it to them, and they had to go show them how to use it. We did a test program.

One funny story about that. One day I sent out a memo to all employees, and there were 5,000 civilian employees that we paid with this payroll. I said, "You need to give us an address where you want your check mailed. You can send it to your bank. You can send it to your house. Whatever you want to do." I didn't give them any other choice. I got a bunch of complaints. There were 27 men at the depot that didn't want that check mailed to their bank or their home. They wanted it handed to them like it had always been.

I asked a guy who was a GS [General Schedule]-15 civilian that I worked with. I said, "Why is that?"

He says, "Those guys haven't told their wives in years what their pay is." As they got pay increases, they didn't tell their wives. They were cashing their checks and going home and keeping money for hobbies. I had to reprogram the program and have it sort bank, bank, bank, home address, and then we had this private that drove around in a jeep and handed them out every other Friday.

I finished that tour. While I was there I met this young woman working in a hotel there, and we got married there on the base. Came back home, and I came back to NASA. When I first hired in that summer I was a GS-7, and I was making $6,666.66. Somebody must have taken an equation and divided by three or something. The salary was $6,666.66. I told myself if I ever made $10,000 I'd have succeeded. This is 1963.

ROSS-NAZZAL: That sounds like what my father-in-law told my mother-in-law. When you make $10,000 that's [his dream].

COCKRELL: Ten thousand will be like hog heaven.

ROSS-NAZZAL: Yes. You were about the same age.

COCKRELL: After I did my Army tour, the branch chief was now a guy named Jim [James C.] McPherson. He hired me back, and he gave me a GS-9. I went to work, and this was 1967. I came back, and I bought a house on the GI Bill in Clear Lake City, Camino South, the same house I'm still in. It was the third house built in Camino South. You can sit in our front yard, and you could see the Clear Lake Movie Theater, which is now a Chinese restaurant behind a Valero.

ROSS-NAZZAL: Is that the 888 Bistro?

COCKRELL: No, it's no longer a Chinese restaurant, it's vacant now. But there's a two-story building right across from the Firestone store.

ROSS-NAZZAL: Oh yes, the Oriental Gourmet I think is what it used to be.

COCKRELL: It used to be, but it went out of business. The Valero wasn't there. That was the movie theater's parking lot. We could sit in our front yard and see the theater, and we could get in our backyard and watch planes land at Ellington [Air Force Base]. There were no houses between my house and Ellington, and no houses between my house and the Clear Lake City Shopping Center down by the theater. It was 1967, February.

Everybody on my street was somehow affiliated with NASA. It was a cul-de-sac and at one time there five of the women were pregnant at the same time, so we had all these kids growing up together. We had block parties. We put a barricade at the cul-de-sac and on Halloween night we would show movies outside on garage doors, have bobbing for apples. Everybody would make doughnuts and cookies and had a big party in '67, '68, all building up to Apollo.

When I came back, I was put in charge of maintaining the constants. It was a navigation group, and there's a lot of constants that you have to use. The idea was that we wanted everybody to use the same ones, so we wouldn't have somebody in Baltimore running a trajectory program that used a set of constants that were different than the ones here at the Manned [Spacecraft] Center. My job was to document these constants.

There was a document that was agreed to by all the NASA Centers that these are the ones we will use. I basically put that document together, and it went around for everybody to use. When you model gravity, the Earth's gravity is not spherical. The Earth is fat in the middle. It's bigger at the equator than it is at the poles. That's because when the Earth was cooling it was spinning, and centrifugal force brought more mass out at the equator. As you look at the Earth, it's oblate. That means the gravity is different. As you go around in orbit, the gravity force is not constant, it's affected by the shape of the Earth. There are constants in that; there's a Taylor series function that has coefficients that model that misshaped gravity. Those constants were part of it. Later on, if we get to it, I'll have a horror story I'll tell you about me and the Russians during ASTP [Apollo-Soyuz Test Project] agreeing on constants.

Also in Apollo, we had to have a coordinate system to keep track of everything. The coordinate system we used was the orientation of the Earth at the beginning of the year. In fact, it was the nearest January. It was called the nearest Besselian year. That means roughly January. What we did is at the moment, at some date near January 1st, the Earth was oriented some way with respect to the stars. The z-axis went through the spin axis of the Earth, through the North Pole. The x-axis was where Greenwich meridian was at some time of day. The y-axis completed it.

The other job I had was that we had star charts that the crew used on the flights. We had about 50 stars in the computer, and we had catalogs of where the stars were located in a system that was the same kind of system, but it was based on 1950. Since the stars are moving a little bit, I would calculate how much they had moved since 1950 and put them in that year's system. If we flew a mission, say Apollo 8, [which] was in December of 1968, the January we used was January '69. It was the nearest January. If you launched after July it was the next one, if it was before July it was the previous one. I had to move all the stars into the system that was defined by the orientation of the Earth, January 1st, 1969.

Then they built star charts. They were plastic charts where the star patterns were on. The crew could look at those, and during the flight they could look out—when they aligned the navigation instruments, there's a thing called an inertial measurement unit [IMU], which is a bunch of gyros and accelerometers. You have to know its orientation with respect to the stars, so when it senses stuff it senses it in that coordinate system. The crew would look through the sextant and point at two different stars, identify the stars, and the stars' locations were stored in the computer. Once he looked at two stars, software calculated what the orientation was. That's called a star alignment. We did those. We still do it. They did it on the Shuttle.

I also built venting tables. The third stage of the Saturn V when it was in Earth orbit, just one orbit, even though it had finished its burn, was going to be used again. The third stage of the Saturn was the end of the launch to get it into orbit, and then they coasted around the Earth one time and then they lit it again to do a burn called the translunar injection [TLI] burn. That's the burn that kicks you out of Earth orbit on the way to the Moon. It's about 3,400 meters per second.

During that coast around the Earth, the S-IVB, the Saturn third stage, was venting fuel. It had liquid hydrogen and liquid oxygen, and they couldn't store it as the pressure built up. They had to open the vent. The venting was based on the position of the Sun. When the Sun shined on the tank it heated it, which made it vent. They modeled that vent thrust. When we propagated the state vector or the position and velocity around that orbit, we took into account the misshaped gravity, atmospheric drag, and the vent of that nozzle. I modeled that and put that in the ground computers. Then when the Saturn third stage fired itself and kicked the stack on the way to the Moon, it continued venting because it didn't burn all, they overloaded it. On the way to the Moon it was venting.

What we did after Apollo 11—8, 10, and 11 didn't do this. They targeted the stack to go in front of the Moon to go into a retrograde orbit around the Moon. As the Moon is coming around the Earth, the stack approached the Moon in front of it, got to the Moon, and then went around behind it and went into what's called a retrograde orbit. After Apollo 11, we used that vent for the

S-IVB engine to push it into the Moon. On Apollo 12, 13, 14, 15, 16, and 17 we crashed the S-IVB into the Moon. They had planted seismograph sensors on the Moon, so they were trying to measure [the impact]. They created an earthquake by impacting the thing, and they measured the vibrations, like the oil companies do when they go out and blow up dynamite to determine where the oil is in the seismic tests.

I also was involved in the navigation for the lunar orbit rendezvous. We built a thing called a Kalman filter in the Lunar Module [LM] and there was one in the Command Module. We worked with Draper Lab at MIT [Massachusetts Institute of Technology] in Boston. They built the software and the hardware. They built the computers for the Apollo spacecraft. They also programmed the computers. But we helped them with the equations and we had an input into what they were. My counterpart was a guy named Bill Robertson at Draper Lab, MIT, and he was the constants guy and the star guy and all that, like me. We were cobuddies.

For the rendezvous we had to build a filter. The way you do navigation—I may be saying more than people need.

ROSS-NAZZAL: No. I think a lot of people, when they read these, they might not understand what some of these terms are, so I think it's always helpful.

COCKRELL: The way you do navigation is you have some way to take measurements of something. Suppose you're on the Earth and you have something in orbit around the Earth. You have a ground station, maybe it's measuring the range from the antenna to the vehicle. Maybe it's measuring some angles like elevation and azimuth. What you do is you guess where you are. You have a pretty good estimate of where you started. You try to pass mathematically a trajectory around the Earth. You think this is where I think I am.

Then you take these measurements. Say the vehicle goes across radar and the radar takes these measurements. What you do is you go back and you say, "Okay, if I was where I thought I was this is the measurement I should have taken." You calculate what the measurement should be at that time. Then you get the real measurement, and they're different. The reason they're different is because your trajectory is not perfect, you don't model gravity perfectly. The station has errors. It doesn't have a perfect range measurement; it's got errors on it.

What you do is you pass this through a range of measurements, and there's a bunch of what's called residuals. These are the differences between what you thought you should get and what you got. Then you go back to the beginning and you change your position and velocity vector a little bit and you pass it through again. You keep doing that over and over and over until these differences are the smallest. It's called least squares. It's the square of those differences become the minimum. That's called a Bayes filter. That's what we used all the way through Apollo in the ground programs.

But on board we couldn't store that much information in the computer because the computer was too small. So we built a filter that was called a Kalman filter. The Kalman filter did that one measurement at a time. It basically said, "Take a measurement, compare it to what you got, see what the difference is, and adjust your trajectory." You do that every minute as you're measuring.

In Apollo, the stuff I worked on was the Lunar Module. The Lunar Module had a rendezvous radar that measured range, range rate, and two angles. This Kalman filter, I had to monitor it during the flight. I sat at a console on the second floor in a back room. As they took measurements on the front side where we could talk to them, we could find out if the differences were big or small, how things were going. Of course when they're on the back side, we had no comm, so we'd have to wait. After the flights were over, I would interview the crew about what their experience was with this residual.

The crew had the ability to reject a mark. If the rendezvous radar took a measurement and the crew thought that the difference was too big—a flag popped up to tell him, "Okay, this is big, do you want to take it or reject it?" I remember talking to Pete [Charles] Conrad after his flight which was Apollo 12. He said he had no problems at all, everything worked great.

I had to go in on the landing day because one of the aborts we had—if the vehicle didn't land, it had to abort the landing—it had to go back and do a rendezvous. Us rendezvous guys had to be on console during the landing so we could be there in case there was a rendezvous. If everything was successful, then we were on call for whenever the last day when they left the Moon and we did the rendezvous. We were on consoles for all that.

I guess the crowning glory for navigation guys was Apollo 12. When we went to the Moon on Apollo 8, I told you earlier that the Earth's shape is misshapen which causes the gravity field to be warped. You have to calculate gravity wherever you are. The Moon was worse. We got to the Moon and went into lunar orbit. The ground trackers would track the vehicle, and when it went behind the Moon they knew where it was when it left, so they propagated the state vector around to when it appeared again, and it came around the Moon, it was like 5,000 or 6,000 feet further downrange than we thought. We knew it was the gravity model. But we had very little data, because all we had was Apollo 8.

There was a Boeing project called Lunar Orbiter back in the '60s that we had some data from. I didn't work on this much, but JPL [Jet Propulsion Laboratory, Pasadena, California] and the guys at MIT and another group in the Math Physics Branch—I was in the onboard soft navigation and there was another group that did the ground. That's where Emil was. They came up with this idea that the Moon was like raisin bread. It had what's called mascons. There was this distribution of the regolith but there were concentrations of probably iron ore or nickel or something like that that were buried around in the Moon at various places. They were called mascons which really means mass concentrations.

As you flew around the Moon, if you flew over one of these, gravity was different than what you thought it would be. We had a very very very poor knowledge of the gravity, and we couldn't propagate a state vector around the Moon very accurately. We discovered after Apollo 11 landed—10 was the same thing but 10 didn't land, 10 just went to the Moon, did a rendezvous, and came home. But we got more data because they were in orbit for a while.

When 11 landed the navigation system onboard the Lunar Module thought it knew where it was. We wrote that down. It sent back data, telelinked the data back what its position and velocity were on the Moon. They took photographs while they were there on Apollo 11, and then we compared those photographs to Moon maps. The Lunar Module on Apollo 11 was about 5,000 feet different than we thought it was. The error was almost a mile.

ROSS-NAZZAL: That's a big difference.

COCKRELL: Lo and behold, George [M.] Low whips in one day and he tells [Robert R.] Gilruth that they want to take Apollo 12 and they want to go to an existing lander called the Surveyor. There was a Surveyor that had landed on the Moon prior to us going there, so they said, "We're going to go to the Surveyor crater. We're going to land next to the Surveyor, and we're going to get Pete Conrad and Al Bean to go over and take a picture of it and cut a piece of metal off of it and bring it home."

Here we were in July of 1969. We'd just found out that our error in landing was a mile. They couldn't walk a mile. If they landed a mile away from the Surveyor they couldn't have gotten to it. George Low is saying, "We're going to go land next to the Surveyor." The nav [navigation] group went into business. We flew that mission before Christmas. I forgot the date, but Apollo 12 was before Christmas that year; it was July, and it was three or four months.

It's fascinating what we did. It turned out from the photographs we knew that there was a crater near the landing site that was called Cone Crater. It had a distinctive shape, orientation, looked like an ice cream cone. It was round and tapered like an ice cream cone, and it was very near the Surveyor. We had a map location.

The other thing that happened that saved the day, there was a guy named Bill Lear. Unfortunately he's dead now. You'd love to interview him. The Apollo vehicles, both the Lunar Module and the Command Module, had two systems for doing the guidance, navigation, and control. It was called PNGS and AGS. PNGS was primary navigation and guidance system, PNGS. The abort was called the abort guidance system. They had two inertial measurement units, two sets of accelerometers, two sets of gyros. But we only had two.

The question became if you have two answers, say you're taking a temperature measurement with two thermometers, one of them says 50 and one of them says 80. What do you do? You don't have any third choice. Bill Lear came up with an idea. We track the vehicle when it's in orbit with a radar called S-band radars. There were three of them on the Earth. There was one at Goldstone, one at Madrid, and one in Canberra, Australia, these huge 70-meter dishes. What they did is they sent a signal out to the vehicle at a known frequency. It was called S-band frequency. Basically the vehicle had a mirror, you could think of it as a mirror. It basically took that signal and it sent it right back.

The transmitter sends out a signal of a known frequency. If the frequency that you get back is higher frequency, that means the vehicle is coming towards you. It's called the Doppler shift. Have you ever sat at a train and heard a train go by? It goes whee oom. When it's approaching you the frequency of the whistle is compressed and higher frequency. And as you're going away it stretches out. Same thing in that.

We measured a light-of-sight velocity to the vehicle and could calculate its velocity to about a centimeter per second. We did that from three points on the Earth. Any time there would be at least two of them that could see it. What we did on Apollo 12, we knew we had a downtrack error because the gravity model is like an energy error, and it causes you to not know the energy and so you're too far downtrack.

… [The LM had done a deorbit burn behind the Moon. After it was acquired by our ground trackers, Bill Lear's program computed the downtrack error. This] was a keyed input by the crew. What it was was a downrange error which we calculated on the ground. The LM has separated from the Command Module, it's coming around the horn, it comes into comm view. We see it, we start tracking it. It's coasting around to about 8-nautical-mile perigee, and then it lights its engine and lands.

If you update the state vector by a mile in position you have to change six numbers. The coordinate system has an x, y, z for position and x-dot, y-dot, z-dot for velocity. He would have to punch in 12 numbers. We knew our error was all going to be along the track. We said, "Okay, when we calculate what the error is, the crew will type in in feet the downrange error. So we lie to the guidance." What we did is we moved the target.

We had a landing site we were targeting for. The vehicle was looking for it. The guidance was trying to steer it to it. But we knew we had an error here, so we moved the target so that when the vehicle kept doing what it was doing it would get to the right place.

On the rev prior to the deorbit of the Lunar Module, we did landmark tracking. The crew, while they were still attached to the Command Module, pointed the sextant at the Moon and took measurements across the Moon of the Cone Crater. We got the plane down pretty good, and we adjusted the plane of the trajectory. Then we got the downtrack error with this S-band radar tracking.

We landed, and I remember I was sitting down at my console, and I heard Pete Conrad say, "Guess what I see." He landed, and he could see it. We were like 600 feet from the Surveyor. If you ever talk to an Apollo nav guy like Emil or anybody else, Apollo 12 was our glory day, it was our highlight.

I guess the other story that I can think of about Apollo, I was involved in 13. Let me tell you one more story about 12. Apollo 12, we had launched. Just as the Saturn cleared the tower lightning struck the vehicle. You may have heard this story before. There's photographs of it. The Saturn V stack, the engines are right at the top of the gantry or the tower. Right about the time the lightning strikes, the Saturn V, at the top of the Command Module there was an escape motor which is a long skinny tube, and it struck right on the top of that. It sent shock waves down through the vehicle.

What it did, it popped a breaker in the Command Module between the inertial measurement unit and the computer doing calculations. Basically what happened is the Command Module equations that we wrote to propagate the state forward in time weren't getting the measurements of the engine thrust, because that's what the accelerometers measure. When the Saturn V was on the pad, the inertial measurement unit is running. There's a [sensor]—it's called a pulse integrating pendulous accelerometer.

You remember when [boys hung] a pair of dice from the rearview mirror? … When you hit the accelerator, the dice move. They move because the acceleration or the thrust. That's what these do. They're little wheels. They have a weight on one side, and if you're sitting in the room, that wheel, if the weight was here, it would try to roll like that so the weight would be down.

When it tried to move, it set up a [current] in an electric motor winding, so it sensed that it was being rotated, so it would send a pulse to send it back. Every pulse that it took to send that wheel back to its normal place was worth 1 centimeter per second of change in velocity.

When you're sitting on the pad, the Earth is pushing up on the vehicle, and the accelerometer is measuring that. Newton's law says you're falling toward the center of the Earth at 1 g. When you're falling at 1 g and you're being pushed at 1 g and they equal out, you sit there.

We took off, and the Earth is pushing, and then you add the Saturn V's millions of pounds of thrust, and the accelerometers were sensing that. They said, "Okay, we're lifting up, we're lifting up, we're lifting up, we're walking away." Pow. Lightning strikes. The breaker disconnects the IMU from the computer. The computer kept running and kept downlinking. But it wasn't getting any IMU data.

What Bill Robertson and I saw on our console was the state vector go up to about 300 feet and then it started dropping. It was dropping. We thought the vehicle blew up. It's falling back to the Earth. … The calculation kept going. Newton's law was dropping it to the center of the Earth. We got a divide by zero and the whole system went belly-up.

Fortunately, during launch the Command Module computer had nothing to do with guiding the vehicle. The Saturn third stage S-IVB had a computer in it that was built by Marshall [Space

Flight Center, Huntsville, Alabama] that basically took us to orbit. We didn't use the Command Module computer until we got on the way to the Moon. It was just there for a backup, but Bill and I thought the vehicle had crashed and blown up. Our software wouldn't work. It said divide by zero. We're crazy. We were just looking at numbers. We didn't have a view.

Of course then I heard CapCom [capsule communicator] talking to the crew and they were go for TLI. Something's dreadfully wrong. Turned out they found out what it was. Popped the breaker. Put it back online. Did the translunar burn right on time and went to the Moon. That's my Apollo 12 story.

ROSS-NAZZAL: That must have been a huge relief when you heard the crew talking to CapCom.

COCKRELL: Oh, it was.

ROSS-NAZZAL: I imagine.

COCKRELL: It was. Apollo 13, I was home, about 10:30 at night. They were on the way to the Moon. They had done the translunar injection burn. I get a call from my Branch Chief Jim McPherson, probably about 10:30 at night, said, "You got to come in."

I had been watching it on TV. I knew that they had an event. I heard them say that they had. I didn't know what it was. I got out there. I didn't go to the Control Center. I went to my office because they wanted me to run some software.

What had happened, the oxygen tank blew up. A heater in it malfunctioned and caused it to blow up,; the oxygen tank blew up. When it blew up, there was a lot of ice particles that were in the vehicle that were floating around in the vehicle. When Jim [James A.] Lovell and Fred [W.] Haise got into the Lunar Module, they powered down the Command Module because they didn't want to use the batteries anymore. The oxygen tanks were fuel cells that made electricity for the vehicle. All they had was batteries now in the Command Module, so they turned everything off, moved into the Lunar Module, two guys did, Lovell and Haise.

They powered the LM up, pressurized it. They were in suits of course. They got it up. It's inertial measurement unit had not been aligned, so they had to align it. Jim Lovell looks through the sextant. All he saw was millions of particles. He couldn't see stars because there were ice crystals floating.

What they asked me to do—I told you earlier that I created these positions of the stars in the computer. They were stored in the computer. We also had the ability to put in the computer what's called a unit vector, which was the location of the Sun and the location of the Moon at any given time. I came and I calculated those positions at a future time about 45 minutes in the future, created those numbers, and we uplinked those numbers to the computer.

What they were going to do if they had used it, Lovell was going to shoot a sextant on the Moon and the Sun. You have to have two stars to align the platform, so he was going to shoot the Sun. He had a filter. He put the crosshairs on the Sun, put the crosshairs on the Moon, took the mark. That gives you a crude alignment. It's crude because the Sun extends about a half a degree of space. Even if you get it right in the center you're not like a star. A star is a point. They were going to do a crude alignment, align the platform, do a little burp with the engine to fly away from the ice crystals, and then do a fine alignment.

It turns out by the time my stuff got up there, they had found another way to get it done. I heard him say, "I see Canopus." Which is a star he knew and could identify. He went ahead and shot stars. What I did they didn't use.

But my star charts got used, not for stars. The way they scrubbed the air in both vehicles is they had a thing called lithium hydroxide. What lithium hydroxide does, the crew breathes oxygen, the vehicles had pure oxygen. When they breathe oxygen, they exhale CO2. If you keep doing that long enough, you'll get nothing but CO2 and you die. You got to scrub it.

The way they scrubbed it, they had a thing called lithium hydroxide. The cabin air was sent through a filter which was embedded with lithium hydroxide, and the lithium hydroxide reacts with the carbon dioxide, basically takes the carbon out and passes oxygen through. It scrubs the carbon dioxide out of the air and gets it back to more oxygenlike.

The canisters that were in the Lunar Module were different size than the canisters in the Command Module. They didn't have enough canisters in the Lunar Module to go six days. What they did, a guy named John [W.] Aaron came up with the idea of making ducts out of the crew charts. They took crew charts that were nonflammable plastic and made tubes, taped them with duct tape, and they arranged where they could get the cabin air to go from the Lunar Module through the canisters in the Command Module and back into the LM. They used my star charts for one of those tubes. That was my contribution to Apollo 13.

ROSS-NAZZAL: That's funny.

COCKRELL: I computed the state vector to the Sun and Moon, which wasn't used. My star charts weren't used, they were used for ductwork. But the crew survived. We got them back.

I guess the flights 14, 15, and 16 were fairly uneventful for me. Everything worked fine. We had no problems. I remember watching John [W.] Young kick a million-dollar experiment's wires loose. They set up this box on the Moon. He's walking around. He pulls out a bunch of little wires and destroyed it. I remember him saying, "Oops."

There's another story I guess I can tell. If you want to edit it out later you can.

ROSS-NAZZAL: That's your call.

COCKRELL: I'll say it. We can decide.

ROSS-NAZZAL: Okay.

COCKRELL: John Young and Charlie [Charles M.] Duke were in the LM, and they did about three different EVAs, extravehicular walks, on the Moon. They went out and did a walk, came back, got in, repressurized, then they had a sleep cycle.

One night they were in the LM. They had repressurized and taken their suits off. The normal downlink that's supposed to be suppressed got out to the press. I have a copy of it at home. John Young is talking to Charlie Duke and he says, "Charlie, I got the farts again. It's that goddamn Gatorade." They were worried about the crew getting low on potassium, so in the suits they had a little tube from the backpack, and they had Gatorade. If they got thirsty they would reach over and suck on this tube and get Gatorade. Young was convinced that that was causing his gas problems. Charlie didn't say much. He said, "Yes, okay." That's my Apollo 16 story that

I remember. I wasn't much involved with [it]. I don't know if you want the Internet to have the word fart on it or not.

ROSS-NAZZAL: Oh, no, that's perfectly fine, if you're fine with it, I think it's okay.

COCKRELL: A lot of people know that story, so it won't be disputed. There's a teletype downlink that people have.

ROSS-NAZZAL: Yes, I was going to say that sounded familiar.

COCKRELL: You've probably heard that before.

ROSS-NAZZAL: I have. I think somebody told me it was orange juice, some other people.

COCKRELL: It could have been. He may not have said Gatorade. It was something. It was a mixture. It was like that. It was pumped up with potassium, a fruit drink. Apollo went fine. I don't remember anything happening after we got to going. I do remember Bill [Howard W.] Tindall who was in charge of the software. We used to have these software control boards, and every mission we would go, "We got to change this, we got to change that."

The computers were hardwired. They were called ropes. They actually hired women who had small fingers. They worked at Raytheon, and they were former seamstresses. They sewed for a living, and they got the job. They called it weaving. They would take a wire and connect it at two points in this battery of network. To change the software you had to move those wires around. Like on Apollo 11—another story I didn't tell about 12.

After Apollo 11, we thought we had a better knowledge of the lunar gravity model, so we put together a change to go change the gravity model in the Command and Lunar Module. I remember that was between July and November we did it.

ROSS-NAZZAL: Yes. Short time.

COCKRELL: We did it. We figured out the code, changed the constants, put the code together, they programmed it, verified it with their verification system, and it went through. We flew it. In the last years I was working on the Shuttle, it took one year to make a change to the computer software in the Shuttle.

Bill Tindall was in charge of this board that decided whether we were going to do those things or not, and I was in a division called Mission Planning and Analysis Division that had an advantage because he was our deputy division chief, so we could go see him ahead of time and do an end around. This guy named Baxter Clifford and I went in with our code that we had checked out, and we said, "Bill, we want to change the gravity model in the Command and Lunar Module software." It was called COLOSSUS and LUMINARY. Command Module software was named COLOSSUS, and the Lunar Module software was named LUMINARY.

Bill, he's a really personable guy. He's the best boss I ever had. He looked at me and he said, "Butch, I thought Newton did that 200 years ago." I said, "Changed the gravity." But he laughed, he knew what it was. He had already been prompted, so he approved it.

As we were working up to Apollo 15 Bill Tindall told everybody, "Boys and girls, this is the last set of ropes we're going to make. We're going to fly 16 and 17 with the same ropes that we fly 15." Everybody went, "Oh my God, you can't do that. We've got all these special things we need to do." He held to it. He held to it. He basically laid off Raytheon, and we flew the same code.

There was a thing called erasable load, which is E-memory. That was the kind of stuff I used, like on Apollo 13 when I sent up those little vectors to the Sun and Moon. That went up in the erasable memory of the computer. But you didn't change the basic core memory because that was hardwired. They had a little of that that he approved, but nothing else. Then we flew the same software for three years.

I remember that as being risky days. I came into work the same month that MA [Mercury-Atlas]-9 flew, the last Mercury flight, [M.] Scott Carpenter's flight landed about two weeks before I hired on. I basically missed Gemini because I went to the Army. By the time I got back Gemini was over and we were getting ready to fly Apollo 7. I was gone during the Apollo 1 fire.

I remember when John [H.] Glenn went up—this isn't my experience, it's stuff I read. John went up on a Mercury-Atlas for his flight. Six months prior to his launch Mercury-Atlas blew up on the pad. They put it together, put him on top of it.

Gemini 6 and Gemini 7 was a rendezvous, and they launched two Geminis days apart. One vehicle was already up there. I remember Wally [Walter M.] Schirra and somebody else were on the pad. It was a Titan. The engine lit and then shut off. They're up on the top. There's an escape system but they don't trust it. There's a ring that Schirra could pull. It would pop the vehicle off, but the power to that was coming from the ground power system.

Gemini has a timer. The first stage burns for a certain amount of time, and when it lights a timer starts running in the vehicle. When that timer gets to the end it blows some explosive bolts and separates the stage. It's the timer. The timer was running. They're sitting on all this kerosene, and if the timer goes off on time, it blows the vehicle up. They said, "Cut the power."

They cut the power, which stopped the timer. But then someone said, "No seats." Because if he didn't have power he couldn't pull the escape ring. They basically made a choice, no power, we're not going to blow the thing up. They sat up there for a while. They brought the gantry back out. They climbed out, went down the elevator, went back to the motel. Seventy-two hours later they lit that vehicle, and it went up to orbit. That would not happen today. It would not happen today.

ROSS-NAZZAL: Why do you think that's the case? You mentioned the same thing with Shuttle. Taking so long to make decisions about software changes.

COCKRELL: One of my experiences in my life was when Mission Planning and Analysis Division died—or it was basically just killed by a manager at NASA—I got sent to a division called System Engineering. It was an experiment that didn't last but about two years.

There was an engineering director. What was his name? He's an old guy from Hallettsville, Texas.

ROSS-NAZZAL: I think you said it was Henry [O.] Pohl.

COCKRELL: Henry Pohl. Henry Pohl was the directorate chief. He decided that we needed to have a System Engineering Division because the Shuttle had gotten built and it didn't have really good system engineering. He gave us an example. There's a thing called a flash evaporator on the Shuttle. What it is, after you get to a certain altitude, you're cooling things on the Shuttle by boiling ammonia, but you can't do that forever.

When you get to orbit, they have a thing called a flash evaporator. They pump water through all the systems that make it get hot, like the avionics, and it gets warm, and it goes back to this flash evaporator. The flash evaporator basically opens a door and lets this hot water basically vaporize. It goes out in space.

The flash evaporator was located in the very center of the bay back by the engines. It was about 4 feet from the wall. There was this tube that went to the wall. When it flashed, the tube froze, iced up. If it iced up enough it couldn't flash.

The way they solved that problem is they wrapped a coil around it and heated the tube. You were getting rid of heat with the flash evaporator, but you were sending it through a tube that had to be heated to get rid of the heat. Henry Pohl said, "The way you solve that problem is you move the flash evaporator right next to the wall." But they didn't think of that, because it was not system engineering.

Long story short, one of the things I learned in system engineering was a phrase called better is the enemy of good. You may have heard that before or other people may have said it.

Modern engineers have so much computer capacity, so much capability to study things analytically. You've probably heard of the programmer that says, "I want to make one more test. I want to make one more run. I got a bug somewhere in there. I got to find it. I'm not going to release my software yet because I got to make it perfect."

I think what happened as the Shuttle came along, the Shuttle started out with this mentality of we're going to have a redundant everything. We're going to have three of everything. Nothing can ever fail. Shuttle would fly a perfect mission. Nothing would go wrong. All the systems are being monitored during the whole flight. I remember Jay [H.] Greene one time saying that when the Shuttle landed at Kennedy [Space Center, Florida] after a perfect flight with no anomalies in any of the subsystems, NASA declared the vehicle unfit for flight. They really did.

ROSS-NAZZAL: How was that?

COCKRELL: Every subsystem, they took it over to the Horizontal Processing Facility, and every subsystem manager, the IMU guy, the star tracker guy, the computer guy, the hydraulic pump guy, all went out there and they had to take it apart, look at it, study it, and put it back together. It took months to fly the Shuttle again. Even though it landed, its software told you everything was working fine. We could never get past that point of overchecking everything. I think the Shuttle software was the same way. They decided change is a bad thing to do. If we change something we got to be damn sure that it's right. We got to check, check, check, check, check everything we do over and over and over.

Whereas in the earlier days, something broke, they thought they figured out what it was, and they went out and did it again. It was more risky. I think it's probably less safe.

John Glenn's flight was probably less safe than any of the Shuttle flights in terms of risk, probability of stuff like that happening.

ROSS-NAZZAL: Speaking of computers, you were talking about the computing capability at that time. You were using mainframes. Can you talk about how you came up with this idea and how you used those computers? I know for instance you guys had cards. Which is very different from today. People just use PCs [personal computers] now. Some people just use a tablet. Some people might be interested in learning more about how all of that worked. How did you get the cards ready and submit them, and how long did that whole process take?

COCKRELL: Apollo, after we got going, it was pretty rapid. Of course we had a lot of prep. I was working on the onboard software for Apollo in 1963. We were building the Apollo Control Center computer. At that time the Control Center was in Florida. They flew Mercury out of a Control Center in Florida. Basically they had a big contractor that did their nav and their propagation stuff.

We were building stuff for the first time. In the building I was in up there on the Gulf Freeway we had a computer called a 1620, and it was about as big as this table in a room. It used punch cards. The way we programmed computers, we had a coding sheet, which was a green piece of paper about this long. It had a little place over on the left-hand side where you could make comments. Then you had a number. Programs in those days, you had a number, one two three four five. You may say, "At three go to five." Five was a code.

It had 80 columns, and we wrote the code into the sheets. Then we gave them to these math aides. We had a group that was a section in Math Physics Branch. These women keypunched the cards. They would take these coding sheets. They had a keypunch machine, which is like a typewriter, and they would type our code into the machine, and the card would get fed in. It would punch holes in the card at the right place for that code. Then we would take that program and put it into the card reader and run the program.

We had a printer in the room. Your output was a print. We had to sign up for it. One person at a time could use it. We'd go there, and you'd sign [up]. I want to have the computer at eight o'clock. So we worked a lot of funny hours then, because I remember the mentality was we were fighting with Russia. Russia was the enemy. They scared the hell out of us with Sputnik, and we were going to beat them to the Moon.

I remember our big computers, the 7090s, were over at the University of Houston in the building where Channel 8's studios are now. There's a big field next to that facility, and we would go over there on Saturdays to run our programs. We would go in and submit a deck, and it took maybe an hour, because there was so many of them.

We would go back out on that lawn and play football. I remember me and Emil Schiesser and Jim Blucker and Ivan Johnson would go out there and play flag football and then go in and check our runs on Saturdays because we could get more turnaround on our runs.

The onboard computers, you have more capability in your iPhone than the onboard computers had. We had in my office in the Houston Petroleum Center Friden calculators on the desks, mechanical Friden calculators. They were electric, but you could add, subtract, multiply, divide, things like that on the Friden. We did a lot of that offline.

We had a computer at one time in Building 30 that used punched paper tape. That's how I got data from Marshall. Marshall would send me the heating timeline for the S-IVB. They sent that on a paper tape. I'd have to take that paper tape and convert it to a card and then put my software in to calculate what the vent thrust was going to be and what level it would be at what time, during that Earth orbit.

I remember this guy Bill Lear showed up one time from California. He was stationed in California at TRW for a long time. He flew in one day, and he had a Hewlett-Packard HP whatever the first one was.

ROSS-NAZZAL: Wow.

COCKRELL: By that time we had calculators that could add, subtract, multiply, divide, but they didn't have science functions. He had an HP calculator that cost about $95, which is way expensive for most of us, that did math, trig, logarithms, sine, cosine, tangent, all this stuff. He showed it around, bragged about it. TRW had bought it for him. It wasn't long before we got—I probably got one of my promotions because I got involved with small computers in the '80s. I bought an Apple II+. Apple II+ used—they were called floppy disks. They were really floppy. They were about this big, and you could bend them. It was a magnetic thing. It had a hole in the middle, and you put it in the Apple II+.

Before there was Excel, there was a program called VisiCalc. I coded software in BASIC on an Apple II+. Using VisiCalc and BASIC software, I did the treasurer's report for my church. I sorted pledge units. That's when I remember I got mad at women who used a different last name than their husband, because a lot of times in the church the pledge unit would be Brenda and Butch Cockrell. I could find Cockrell, and I knew that pledge unit.

Some of the women had kept their maiden name, but they were married. They pledged different. If they pledged different, it didn't matter, because they would be two pledging units, the husband and wife would pledge different. But if they pledged as a couple, I couldn't sort on both their names because they were different. So I had to write special code to do all that.

But my division chief, who was a guy named Ed [Edgar G.] Lineberry found out about that, and he started having me do things at work on early Apple computers that we only had two or three of in the division. I got one of the first ones. He took me out of Math Physics and put me in a little staff office next to his office to basically do that kind of stuff for him.

Then it wasn't long before we populated everybody with computers, and by the end every engineer had a computer. I remember my engineers, I had a guy named Jerry Condon working for me. He complained to me one day. He said, "Butch, you got to upgrade my computer." I was the branch chief. He says, "Let me show you something," and he goes to his computer. I'm standing behind him. He says, "Okay, watch this. I want to update this trajectory." He goes enter. It goes poof. It's like 4 seconds. He knew somebody at IBM that had one that he would hit it, and it would be there. He said, "We're behind."

I was thinking back when I was playing football next to the computer, running inside, with punch cards, waiting for 2 hours to get my run back so I could check something and submit it again. My engineer is complaining about the delay time in updating a trajectory on his desktop computer. It was in his room in front of him.

I also found out something interesting. I encouraged my engineers to write papers, and I noticed one day that all my old engineers' references were old references. They'd go all the way back to the '50s and '60s and reference papers and documents. My young engineers never referenced anything prior to about 1986. I discovered what that was.

My young engineers didn't ever go to a physical library, they only used references that the Library of Congress had converted to digital. If a paper had been written after 1986 it was probably stored in the archives in the computer. But Isaac Newton's paper in 17 so-and-so hadn't been copied yet into there. My young engineers never referenced things that they couldn't get to at their desk. My old engineers would go over to the library and pull it out and look at it, like I did. We had card catalogs. We'd go to a card catalog and find the name of the book and then go find it. It's different. It's passed me by. …

A lot of the stuff that we did, we didn't want the computers to have to do, so we tried to find ways that the computers were less stressed. Like I was saying, we would take big steps if we could on flat functions, and we'd take small steps when we had to.

This is sort of complicated. Whenever you propagate an orbit around the Earth or around anything, you model stuff. You model gravity, you model drag, and things like that. A guy named Kepler figured out something back in the 1600s. It's called the two-body problem. If you have a central body with gravity field and you have a vehicle in orbit, he came up with the math equations that could tell you, if you know where that particle is at some time, what its position and velocity is, he can tell you where it'll be at any other time analytically. In other words, it's just like solving an equation. You punch in time and you get XYZ. It's perfect, makes no errors.

The problem is orbits aren't two-body. They start out being like that, but then gravity messes them up because it's not central perfect gravity, not spherical gravity. There's drag, and there's the gravity of the Moon, the gravity of the Sun, the gravity of Jupiter, all these things happening that affect it.

We came up with a scheme that summer that I was working there called the Encke. One way you can do the problem—and I told you about numerical integration. It's when you take a function and you take little bitty steps along the way. The change in x causes a change in y. You're plotting a two-dimensional curve. It's in x and y. You take a little bitty x, and what does that do to y? If the function is smooth you can take big steps and not make errors. If it's curvy you got to take small steps.

The Encke scheme said, "Let's take the two-body part and solve it analytically." What I do is I say, "Okay, I want to propagate my state ahead from here to here." I do the two-body first analytically and I get a perfect answer, if it had been a two-body. Since it's not a two-body there are perturbations through the two-body, so the only thing we numerically integrated was those changes to the two-body. The two-body is 95 percent of the mathematics of the motion, and the small percent that's not two-body we did by taking these little bitty steps.

They were small numbers, because drag is small. The changes to gravity from the central gravity is tiny, compared to what the central gravity is. That saved time.

But now computers are so fast and so sophisticated that my engineers now, they can run a trajectory to Mars and back in seconds and conclude everything. They don't bother separating the two-body part from the perturbation part. They just numerically integrate everything, because the computer has got so much memory and so much CPU capacity that it's just simpler. In fact it allows mathematicians to be lazier, because you just code up an integrator and say, "Run a code, a fourth-order integrator, and make the step size a half a second, and go," and it'll do it.

A lot of the problems we solved too were guesswork. What you would do is we had a thing called an iterator. Let's say we wanted to get to the Moon, and we wanted to hit a target behind the Moon at 60 nautical miles so that when we got to the Moon we would be 60 miles above the Moon.

We're at the Earth. We're going to light an engine, and the engine is going to produce 3,400 meters per second of change in velocity. We're going to take off. You don't know everything perfectly, so you guess. I think it ought to be this. You get there, and you're 90 miles [out]. So you go back and you change a little bit of this. There's a formula for changing it, and you iterate on this difference.

What happens is you shoot a trajectory out there, and it's off. You try it again, and you keep correcting, and making it better and better and better and better and better, until you get down to some threshold of what you want. That's called iteration, and that can be done very very well.

In the Apollo Program, the onboard computer had the capacity to compute a trajectory back to the Earth. If they were at the Moon and they had to do a burn, and the ground communication was gone, they were by themselves, the onboard computer could calculate the burn you needed to do at the Moon to come home, and it did it by iterating.

It would have to take the trajectory, guess a burn at the Moon, and hope it came back and hit a corridor at the Earth where the trajectory was such that you hit the Earth at the right angle. That took 10 minutes per iteration in the onboard computer. If it took five iterations, it would take an hour. You're stranded at the Moon, and you got to run the computer for an hour to get a burn time and a burn direction. Probably wouldn't have worked. They would have probably had to come home quicker.

The other thing we did in Apollo is we knew we couldn't get it right, so we had midcourse corrections. We shot the thing to the Moon with the translunar injection burn, and then we tracked the vehicle as we were going. As we get about a day out, we say, "Well, let's see. We're a little off." So they did a midcourse correction. They would burn a small engine just a little bit and get back on track. They did that going out and coming home.

There was an error in the movie *Apollo 13* that I caught. When you're coming back to the Earth from the Moon, there's a thing called the entry corridor. You probably heard entry guys talk about this. You're coming back to the Earth. The Earth has an atmosphere around it. If you come straight in, you'll burn up and crash. If you come in too shallow, you'll hit the top of the atmosphere, and you'll go on by. There's a little corridor that the velocity vector has to be pointed at the Earth so it's not quite tangent to the Earth but just a little bit off tangent so that it hits it at this angle. It's only about a half a degree of flexibility there. That's all based on the trajectory, nothing to do on board the vehicle.

During Apollo 13, they're coming home, and they're moving things around in the Command Module. There's another property of entry. The Command Module is a cone-shaped thing, but the center of gravity is not at the center of the vehicle. It's offset. When it gets in, if the heat shield is flying along the velocity vector, there's a little bit of offset gravity, which causes it to have lift.

You can take this vehicle, and you can bank it around like this. If you're coming in too steep you can point this lift vector up and you'll raise the trajectory a little bit. If you're coming in too shallow you can point it down and steer down. That's how the guidance works in entry. It guesses where it ought to be at any time. It says, "I should be getting this accelerometer measurement at this time. If I'm getting too much acceleration, that means I'm deeper in the atmosphere than I thought I would be, so I steer up. If I'm not getting as much acceleration as I should be getting, I must be too high. I steer down."

That's based on things in the vehicle. In other words, to have that gravity offset, you have to move material away from the center. While they were coming home, they were moving things around in the Command Module and in the lockers to keep the c.g. offset, because they thought they were going to bring rocks back, and they didn't have any rocks. They had to move cameras around and stuff like that.

They're doing all this, and some guy on the ground says, after they move stuff around, "We're back on the corridor. Moving stuff around in the Command Module doesn't change the trajectory, which is what defines the corridor. That changes the lift capability of the Command Module when it gets in the atmosphere. It's called the L/D, the lift-to-drag ratio.

I can say a little bit more about mission planning. When we went to the Moon, some examples of things mission planners have to deal with. I am prejudiced about mission planning because that's where I lived most of my life. I started working for John Mayer from the get-go, and he was the mission planning guy from Langley.

NASA had three kinds of organizations. They had engineers who built stuff and bought stuff, the physical stuff. They had Mission Operations, who flew it. In other words, they were the ones that knew how to fly it, what to do during the flight. Then they had Science Directorate. The Science Directorate basically did science and human factors, stuff like that, and analyzed the rocks.

We had engineers, we had operators, and we had science. What MPAD did, MPAD was in the middle. We were the bridge between the operators and the engineers. For example, if we were going to build something, how big an engine do you need to kick yourself to the Moon? That's what we did. We said, "Here's the delta-V you need to produce in Earth orbit to get to the Moon." It's 3,400 meters per second, say. The engineers knew then that they had to buy an engine or build an engine that could produce that much change in velocity with that much mass, Command Module, Lunar Module, S-IVB.

When we got to the Moon, the crew wanted to land with the Sun behind their back. The reason was they didn't want to look at the Sun, and they wanted the Sun to create shadows. If you landed at the Moon at noon, everything would be washed out and white, couldn't see shadows. You don't want to land at night, all you'd have is earthshine for seeing. They picked an angle of 13 degrees. They wanted to come in such that the Sun angle was 13 degrees from the east at the Moon, which produced the right kind of shadows.

Then we had to pick when do you leave the Earth. For one thing, the Earth is rotating like this. The Moon is going around the Earth. You're at the Cape [Canaveral, Florida]. You got to wait till the Cape rotates around and gets in the plane of the Earth-Moon trajectory. The Earth-Moon is in a plane. You launch from Kennedy in a window of time that allows you to steer into the plane of the Earth-Moon system. If you launch at a different time, you'd have to do a huge plane change maneuver, which are very expensive.

You got to calculate what day you can launch in a window of days so that when you get to the Moon, if it takes you three days to get there, the day you land, Sun will be shining on the Moon at 13 degrees.

The other thing we did, it was all fortuitous I guess, because of that we chose to go retrograde, which means that the orbit that the Command Module and the Lunar Module were in when they were going around the Earth was opposite the Moon's rotation. On the Earth, the Earth rotates toward the east. If you're at the Cape, when you launch from the Cape, if you launch due east out of the Cape, you're already moving 1,400 feet per second because the Earth is rotating at that rate.

If you were to launch from the Cape and fly back toward Texas, it would take more propellant and a bigger engine because you're going retrograde. You're going against the Earth's rotation. The Moon doesn't rotate very fast, so it wasn't a big deal. But by going retrograde, we could land from east to west, with the Sun behind our back.

The other good thing about it was when we got there, the Moon is going around the Earth, [from east to west. As viewed from the Earth. We arrive coming from west to east and] get captured by the Moon [after] a burn. You capture yourself, so you're in [a retrograde orbit going east to west].

When I get ready to leave, the Moon is going [west to east]. When I get ready to leave, I do a burn [on the backside of the Moon] that is a retrograde burn with respect to the Moon's motion. … When I leave, when I do a burn that slows me down at the Moon, I'm taking energy out. I'm basically tied to the Moon and the Moon's orbit around the Earth. To come home, I need to slow down, so I do a burn against the Moon's direction of motion, and [at the same time] that causes me to [escape from] the Moon. Not only do I leave the Moon because I'm pushing away from it, but I'm slowing myself down with respect to the Moon's orbit with the Earth, and I come back, fall back to the Earth. That's what we did. That's what we figured out.

The last 15 years of my career I was a branch chief, and it was basically what was left of mission planning. It was in the Engineering Directorate, but I had engineers that were doing mission planning. We worked with Doug [Douglas R.] Cooke and others on doing advanced missions, planning missions to go back to the Moon, go back to Mars, and do things like that. In fact my branch is still doing that. They're working on these asteroid missions and this lunar space station, these halo orbits at the Moon. Fascinating stuff.

ROSS-NAZZAL: What were your hours like when you were working? Then you got married when you came back. What was that like?

COCKRELL: It's amazing. I loved my job so much that I remember getting up and wanting to go to work. I remember thinking about work at home a lot. I brought work home a lot. I was young. When Apollo 11 landed I was 27. I coached Little League teams. I coached girls' soccer teams. I had a darkroom at home, I had a photography hobby. I was the star guy for Apollo, so I got interested in stars. I had a telescope, and I would get up at three o'clock in the morning and go out and look at a certain star that was up then.

We went camping every spring with the kids. I was active in my church. I played softball on a softball team at NASA. Math Physics had a team called the Bandits. I generally got to work about 8:30, and I stayed till about 5:30. I'd go in a little bit late. There was a disadvantage to that in that you didn't get a good parking place. There was a gravel lot across the street from Building 30, and I had to park over there nearly all the time. Most of the guys in Math Physics except for Emil, me and Bob [Robert T.] Savely and all my other buddies, we would get there about 8:30, but we'd stay late.

Of course when we had a splashdown party, we partied. We partied. We used to have a party before every Shuttle flight and after every Shuttle flight. We'd go out to the Gilruth Center and drink beer.

There's a bunch of things that had to get loaded on the computer, all this software that we were responsible for. All that got loaded, and it got the final check. We were done, so we'd go out to the Rec Center, and somebody would buy hot tamales and beer and we would drink beer and then go watch the flight.

I remember after [Robert L.] Crippen and Young's first flight we had a party at my house. I got a keg of beer, and all the guys in the nav group came over there, and we celebrated the first Shuttle flight. I had a lot of fun in Shuttle days. We're probably getting close to time. I had an ASTP story I could tell you.

ROSS-NAZZAL: Do you want to save that for next time? I got a couple of other Apollo questions that I thought you might want to talk about.

COCKRELL: Okay, go ahead, let's stay on Apollo so we don't break the trend here.

ROSS-NAZZAL: One of the things that you had talked about was the fact that your engineers were writing technical notes, technical memorandums. I noticed that you had written several for Apollo that had been released. I wondered if you would talk about that, and that whole process and how that worked, being a young mathematician and putting that together, getting it reviewed, and publishing that.

COCKRELL: One of the things I can say is that we had a lot of help from technical editors. I remember there was a woman. This is kind of a sad story about women. There was a woman named Cathy Osgood who went to Virginia Tech [Blacksburg], graduated with a math degree. She got hired by Langley but they told her she couldn't be an engineer because she was a woman. They said, "You're a math aide."

It probably wasn't until in the '70s that she got in the engineer track. Like I said, we had math aides that keypunched the cards, read the coding sheets. We also had technical editors. We would write our papers in script, ink pens. We had secretaries. The branch had two secretaries, and I remember probably during Apollo they had IBM Selectric typewriters that had a little ball. The ball had little letters on it.

This ball would do that. Each key, the ball moved around. It was electric-assisted. The secretaries would take our stuff, and they would come back and say, "I can't read this word." They would type it up, and they would give it to us. They issued us these pens that had red lead on one end and black on the other. You could go in there [and edit].

I remember Emil was my section head. Every time I would write a report or a paper or a memo Emil had this habit. The way he managed, he would redo what you did. In other words, you would go in his office, and he'd say, "Did you do this?" He would go to the board and he would start thinking here's what I would have done. He tells you what he would have done, and you'd say, "Yes, I did that."

I remember his habit. When I would walk in his office with a memo for him to sign, he had to concur on it, he'd reach in his pocket and take out that pen with the red ink, like he knew he was going to do something, and usually he did. Usually he would find something or other.

My favorite story about Emil, about documents. He wrote a memo one time. Bill Tindall was the directorate chief. One day Bob Savely and I and Emil went to Bill Tindall's office for a meeting about something. Emil had let this slip through him. His secretary, instead of typing the word mathematical formulation, she typed mathematical fornication. Tindall saw it. He's this real human guy, he's just the greatest guy in the world. He says, "Emil, I want to know what this is. Can you explain to me what mathematical fornication is?" Emil, if you know his personality, he turned bright red, he couldn't speak. He was humiliated. It was like the worst thing that had ever happened to him. We were all laughing.

We would write memos, they would type them for us, and if it was more than a memo, if it was a technical note or—what were they called?

ROSS-NAZZAL: Technical memorandums, TMs?

COCKRELL: TMs and technical notes. Technical notes took a little bit more review. They were published pretty wide. I think they go in the Library of Congress. They're kept. Technical memorandums and technical notes were a little bit less. But they're all women, and they were good at English, and they would correct our mistakes and fix it for us.

Also, if we had graphs or plots, they were manually done. We didn't have pen plotters then. If I ran a program and I created a graph of something, like maybe the vent force from the S-IVB during the Apollo 11 parking orbit rev, it would be this curve. I would get the data, and these math aides would get graph paper, they had real good penmanship, and they would put the labels on there. In fact some of them were typed and stuck on with little sticky tape. They would draw the curve with French curves. I'd have points on there, and they would draw the curve and put the labels on it and make it pretty, put it in the document. It took a while. You didn't write a memo or technical note and have it out the next day. It was two or three weeks.

What I was going to say about women, when I joined NASA, it was called the Manned Spacecraft Center. Nobody ever even thought, well, so what. Then they changed it to Johnson. The other thing I remember was in the Engineering Directorate there was a division called the Manned Systems Division. They did the seats and the displays and switches, how the crew interacted with the vehicle. Now that's called crew systems.

I remember because a lot of women majored in math and physics, not so much engineering. In the '60s, in the Math Physics Branch when I joined it, there were four women engineers doing programming and doing engineering work. They were not math aides. But we had 12 math aides.

ROSS-NAZZAL: Who were the women engineers? Do you remember?

COCKRELL: There was a woman named Sissy Phillips. Her name was Laura Phillips. There was a woman named Sue Shafer. She could beat me in tennis. I thought I was a good tennis player and she just beat me. She was good. Sandra Yates. This was 1963. Cathy Osgood was not in the Math Physics Branch. She was down the hall in the Mission Planning Division. She was an engineer.

ROSS-NAZZAL: Her name I've heard quite a bit, and we've interviewed her.

COCKRELL: She's still alive. You could probably interview her. She's from Langley. She started at Langley.

ROSS-NAZZAL: She's actually working on a book. She's working on a book, she told me.

COCKRELL: She's working on a book.

ROSS-NAZZAL: She's working on a book, yes.

COCKRELL: I had a lot of respect for a lot of the women I know that—when I was able to hire, the times that I was able to hire, we could only hire co-ops, and you could only hire straight A co-ops. There were so few positions. I hired a woman from Virginia Tech. … [Her name was Michelle Monk. One of my best engineers. She is still with NASA at Langley. She went home to be near her parents.]

I had 25 people, and 4 of them were female. Some of the old guys never got it. I remember one time. We had a meeting that was held before every Shuttle flight called the aerodynamics panel. All the aero guys—those are the guys that do the wind tunnel testing and they worry about the Shuttle when it's in the atmosphere, when it's flying. During launch there's a concern about you can't go too fast too soon because you'll break things.

If you've ever heard Shuttle launch tapes, they have a thing called throttle up. *Challenger* [STS-51L] was right after throttle up that they blew up. They throttled back automatically to get through the thick atmosphere. When they get to the thin atmosphere they throttle back up. These guys do all that, they know when to do that.

This old guy hadn't gone to an aerodynamics panel in months and years, he was a manager then. He decided one day to go back, and he gets in there. His engineer told me this story. He gets in there and he says, "Why are there so many secretaries here?"

ROSS-NAZZAL: Oh, ouch.

COCKRELL: They were women engineers.

ROSS-NAZZAL: Right, things had changed.

COCKRELL: Who were doing aerodynamic work. He thought there's a lot of secretaries here.

ROSS-NAZZAL: Oops. I think this might be a good place for us to stop. There's more Apollo questions that I have for you. But as long as you have time to come by and do some more sessions.

COCKRELL: Sure, yes.

[End of interview]