Oral History of Myron Kayton

Interviewed by:
Dag Spicer

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Dag Spicer: Welcome. It's August 5, 2006 and I wonder if you would tell us your name, sir, and just spell it out for us.

Myron Kayton: Myron Kayton; K-A-Y-T-O-N.

Spicer: Okay. And you were the assistant program manager, I believe?

Kayton: Well, I think it was deputy.

Spicer: Deputy program manager.

Kayton: Deputy manager. I don't think it was called program manager, because most of my work was technical. "Deputy manager for lunar module guidance and control" was my title.

Spicer: Right. And this is part of the Apollo program, but of course you did some work before then and after that, and we're going to talk about that. Let's talk about you a little bit; about when and where you were born. When you grew up, what kind of things you were into and formative experiences; things that led you into a career in science and computing.

Kayton: Well, I was always curious about science. I built model airplanes like most boys did in my day, flew them; gasoline powered and gliders. And went to the Bronx High School of Science, which was a good start. And one interesting thing you mentioned that I hadn't thought about in decades; I used to visit the local public library a lot. It was about a ten block walk. I'd take books out. And I took a book out, it was black, it was about this big and it had black stripes on it. I have no idea who wrote this book on calculus. And I taught myself calculus. I was about 11, 12. And I could do integrations and differentiations, and I could fill up cones, calculate the rate of height rise with constant volume of water flowing into cones and things. I thought it was really fun. And I'd never thought about it as being anything special. It's just something you do. It's like reading all the other books that I read.

Spicer: So you were a precocious child.

Kayton: Yeah. And when I got to high school, I realized that they weren't studying that yet. So there must be something special about it.

Spicer: Right. What did your parents do?

Kayton: Well, my father had a grocery store and my mother was a legal stenographer. So I learned to type early; that's why I have such lousy handwriting.

Spicer: Did they encourage you in a life of the mind and to read a lot?

Kayton: Yeah. Yeah they did. They did. They did. They thought that was really important.

Spicer: So the Bronx High School of Science - is it High School of Science?

Kayton: Bronx High School of Science.

Spicer: Yeah. Is of course a famous school; what we would call a magnet school today.

Kayton: That's right.

Spicer: And tell us a bit about what that was like-- your classmates and your teachers.

Kayton: Well, it was good. We were fortunate, I didn't know it at the time, we were fortunate that The Depression had just occurred, and a lot of very competent people couldn't find jobs, so they went into teaching. And so by the time I got there, they were already in 20 years or 10 years, and they didn't want to change. They were just going to stay until they retired. So we had a superb group of teachers. Really good. I remember an English teacher, I remember science teachers, I remember physics teachers. And math teacher; we had one math teacher who got into trouble with the McCarthy [HUAC] Committee. Superb teachers. I mean, really superb teachers. And I commuted by subway or bus. It was too far from home to get to otherwise. But I either went by subway or bus. But I was very pleased. It was a good school. I even donate to the alumni association as we speak.

Spicer: Right. Any famous teachers that, say, the average person would know?

Kayton: No.

Spicer: Yeah. Just solid…

Kayton: Solid teachers.

Spicer: People that were probably more qualified than they needed to be to be teachers.

Kayton: Because of The Depression.

Spicer: Right. Right. So you graduated from high school. Do you have any special courses that you enjoyed? More chemistry or physics or math?

Kayton: Well, all of them. I mean, we got two years of physics. I don't think I took the second year of chemistry. It was available. I wasn't that interested in chemistry. But I took the regular year. And I took lots of math. Took all the math they offered. And I took some shop courses to build experimental equipment, you know, and to do experiments. That was fun too. I always like hands-on things. So that was-- I'd say most of the graduates, just for your interest, did not go into the sciences. Most went into medicine and law. I had never seen the statistical breakout, but I bet you far more went into medicine than into the sciences.

Spicer: So when you're in your senior year in high school, did you have an idea you would like to go on or did you have any career ideas or dreams?

Kayton: Yeah. My parents told me I wanted to be an engineer since I was five. I had an erector set; one of my uncles bought me an erector set. And it kept growing. I kept getting more add-ons and parts. And I built everything with it. Stuff that was in the book plus new stuff. You know, the book had suggested projects and plus a lot of others. And so my parents told me I always wanted to be an engineer since they could remember. And it didn't change. I would have made more money if I didn't go that way. But that's okay.

Spicer: You've got to follow your dreams.

Kayton: That's right. But it was a delightful career.

Spicer: Well, tell us a bit about that. And where you went to college.

Kayton: Well, I went to Cooper Union in New York City. I was offered a - I won second prize in a high school math competition, New York City-wide. I was offered a scholarship at New York University math department, which is very good. It had-- what was his name? I say Conit [ph?], that's Harvard. Courant was there. And a number of other of these really top mathematicians with their-- but I really wanted to be an engineer. So I went to Cooper Union and passed their test. They had an entrance exam at the time; their own special interest exam and an interview process, and I passed it. So I went there. New York University probably would have been my second choice, and then probably City College as a backup choice, because my parents weren't that rich that I could afford to go to MIT or Harvard or anyplace like that.

Spicer: Right. So walk us through your college education.

Kayton: Well, Cooper was a typical tough school. I think it still is. They loaded you with 23 units the first year to see who can do it. Because if you couldn't, then why-- they told you at the orientation, make room for somebody. If you can't handle it, they want you out early so they can make room for somebody else. And that's how it worked. And your load lightened as you went on and I think you got down to about 18 units by senior year. The first year was a killer. And the next year was pretty rough. But I picked mechanical engineering. It was a choice between mechanical and electrical, and I don't even remember to this day why I picked mechanical rather than electrical. But I did. And just loved it. It was just really interesting stuff, taught by guys who were really involved; totally involved in engineering. Many of them were outside consultants and we would hear about all their outside projects of bridges and tunnels and engines and material analyses and so on. So it was a fun place to go.

Spicer: What year did you graduate?

Kayton: 1955.

Spicer: Okay. For our reference point.

Kayton: Yeah. My bachelors in mechanical engineering was in 1955.

Spicer: Okay. And what happened after that?

Kayton: Well, I went to work for Ford Instrument Company for a long summer. I graduated early. And Ford was a fascinating company. They made analog computers for naval gunfire. Invented by Hannibal Ford, not Henry, in about 1905 or so. And they were called gun laying computers that were carried on ships, and you would optically track your target with a telescope and estimate the range either with a range finder or just using the Navy's-- they didn't have radars, of course. And the ship speed was input to the computer, and the computer would calculate the lead angle of the gun; how far ahead of the ship you have to aim, the elevation angle and the azimuth angle. And I worked on that as a very junior engineer on the most trivial aspects of…

Spicer: These were completely analog systems?

Kayton: Completely analog. Now, the interesting thing is Ford never went digital. They later got bought by Sperry, who did go digital. And Sperry just took whatever technology they needed and closed the place up. It was also a subway ride from home, so I could get there. I'd read lots of books on the train. So the train was the place to catch up on reading.

Spicer: So after this summer…

Kayton: Then I went to Harvard. I decided I wanted to learn electrical engineering someplace and I don't know why I picked Harvard. Because they had - they were not especially strong in electrical engineering. But everything was happening there. It was a school where I knew that every visiting scholar and every visiting important dignitary would give lectures there, and I was always interested in attending them and listening. So I went there, and I was right. I mean, you saw everybody. Everybody in the newspaper showed up.

Spicer: Any particular people that stand out?

Kayton: Well, when I get to MIT I'll tell you a few. I don't remember any who stood out at Harvard. But I did talk to Howard Aiken in his computing lab. I was thinking of doing a thesis there. I got kind of turned off. I asked them what they were doing. He showed me around. And they were re-calculating the trigonometric tables digitally and finding errors in the sixth and seventh decimal place. And I kind of decided that wasn't what I wanted to do. There was more than that, but I wasn't imaginative enough to see forward the other things I might do with it. It never went anywhere; Howard's computer lab closed. I think it was part of the politics of the classics professors at Harvard that didn't want these upstart, dirty hands computer people competing with them. I really think there was a lot of that in it. But I didn't. I decided it was time to leave and go to work. So I went to work for Avco. And then went to MIT two years later.

Spicer: Now, Avco is an aviation company?

Kayton: Well, it was. Yes, the name was Aviation Corporation. But the division I worked for was building nose cones for the brand new ballistic missiles that were just being invented. And my job was to design an attitude control system for the nosecone as it re-entered the atmosphere to keep it from tumbling or wobbling or getting out of shape. So I did it on a lot of computer by simulation.

Spicer: Is this a Minuteman [missile]…?

Kayton: No. It was actually the Titan nose cone; way back before Minuteman. There was an Atlas and then a Titan and then Minuteman.

Spicer: Did that involve spinning the nose cone?

Kayton: Yeah. Spinning the nosecone and then damping the oscillations. The big thing was damping the oscillations. And then it turned out later I found that the aerodynamicists had worked out a way to do it without active controls. So they never used the control system that I worked-- that I so painstakingly worked on. They never used it. That's what I heard afterward. I have no confirmation of this. No confirmation that the aerodynamicists were able to shape the body and put the right little strengths [?] or whatever on it to get it to damp out passively, which is always better, since you don't need to worry about batteries and cold gas. Yeah. Mine was a cold gas. I didn't design the system. I did the simulations. Somebody laid out before I got there, my boss did, a fellow named Herb Wexler, very bright guy, taught me a lot. He laid out the cold gas system with the valve deporting gas out the corners. And he said: 'now take that and go calculate the forces and the torques and find out how much the moments of inertia are. Do something with it.'

Spicer: Yeah. Complex.

Kayton: So I did. And analog computers were fun anyway. They're very physical. They're very hands-on. You can do things with them. And the company got a digital computer, an IBM 650, partway through the project and Herb asked me to submit one case to the digital computer so that they could run a check run against my analog solution. And I remember that was slow and painstaking. I never got to see the computer.

Spicer: The 650?

Kayton: Yeah. The 650. It was done by a priesthood that, you know, intermediate between you and god (the computer). You gave the data to the people at the counter, and they massaged it, punched the cards in the computer. They didn't let you punch your own cards. And then pass back and it didn't run, of course, and they'd fix it up and submit it again and eventually you got a run.

Spicer: Now, because we're in mid-50s…

Kayton: '50s. Mid-50s.

Spicer: I'm going to say mid-50s, '56, '57, and of course '57 was a really famous year for space flight. There was one particular event which occurred which really perhaps triggered the space race, if you like.

Kayton: Was that…

Spicer: Sputnik.

Kayton: Yeah.

Spicer: And I wonder if you could reflect on that.

Kayton: Oh yeah. I'll reflect on it, because after Avco…

Spicer: How did that change things?

Kayton: …I applied to MIT. I decided I needed to know more about these events, techniques, and I was accepted to the aero department. The aero department insisted on the MIT rule that you had to demonstrate proficiency in two languages. There was a whole list of languages. The aero department says any two of Russian and German will do. Because of the Sputnik, the Russians became ten feet tall and we had to learn Russian. And that's closed book, they give you two papers to translate, closed book. One in a field I didn't even understand; nuclear physics, and one in aeronautics that I understood very well, so I could translate that one. The other one I think they were very nice in letting me pass. Somebody was a kind reviewer who let me through. Because I didn't even understand the paper in English, much less understand the Russian. And so the Russians were ten feet tall. And they could do no wrong. And we were forced to sort of learn about them. And all the published papers were entirely theoretical. We were publishing papers on how things work, and they were publishing papers on abstractions; the openau [ph?] functions and theoretical optimizations and the-- nothing. No clue as to what hardware they were building or how they were doing things. And of course, in the bigger picture, the Russians had large boosters, because they had poor guidance systems. They had very poor electronics. So the guidance systems, this has been-- it's not my idea. I've seen this through other people. Their guidance systems were so poor, they had large CEPs [Circular Error Probablity—a measure of a bomb's destructive power]. So they had to build big boosters to lift heavy bombs to destroy things. Circular probability. And so electronic guidance wasn't important to them. Their idea was on, I think it was John Ruble [ph?] once said "More rubble for the Ruble", you know? They just needed big…

Spicer: Bigger bombs?

Kayton: Bigger bombs. And we were, particularly with the Minuteman program, we were going with very precise guidance, very small warheads, very light, small missiles which later couldn't even lift a man. When it came time to put a man in space, the Russians could lift 15 psi bathyspheres of the kind they used to drop underwater. You know, they could throw one up in the air. We couldn't because we had gone for these very precise, small missiles. So we had to start over on another program to make bigger ones that would be big enough to carry a man-rated vehicle.

Spicer: And that's a common trade of Soviet versus American military development. It's almost always been like that. Massive numbers and simple technology versus smaller numbers but very high technology.

Kayton: That is correct. I was climbing around a Russian fighter that I was supposed to get a ride in, but the pilot didn't show up that day at Ohio University. And their gas gauges are floats in the tank with little sticks that stick out the top of the wing, and you look to see where the markers on the sticks are, and that tells you how much gas is in the tank.

Spicer: Unbelievable.

Kayton: And the gear lowering is a one-time bottle. And they gave you three bottles up in the nose so you could lower the gear three times. They didn't have a hydraulic-- that is, we have a hydraulic system. There'd be a hydraulic pump on the engine which would pump up a reservoir. In fact, there'd be two of them, because you want redundancy. And you'd have two hydraulic systems, two reservoirs, and you could port the hydraulics into the landing gear anytime or use it for flaps or use it for other things. The Russians were very simple. Very easy. Everything I've seen of Russia, and I occasionally look at Russian technologies, are utterly simple in a smart way. They don't go in for high tech. They can't, at the time. I went to a Russian factory that was trying to promote technology that was at least 25 years old, and thinking that it's the latest stuff. And I really tried to explain to them that nobody-- they wanted me to help them export it to the west. Nobody's going to buy it.

Spicer: Okay. So at the time, when Sputnik-- did people really understand that fact?

Kayton: No. No. Ten feet tall. The average person, particularly, thought the Russians could do all sorts of things. And on Apollo, the Russians-- our schedules were open. And the plans were open.

Spicer: Publicly accessible.

Kayton: Public. That's the word. Right. And so the Russians would read the newspapers. And they would say oh, there's a two-man spacecraft going to go up on such and such day. So we'll do it first. So-- and then there's going to be a three-man spacecraft. So we'll do it. And they always beat us by three or four or five or six weeks. Apollo, for example. There, there was going to be a three man spacecraft. So what did they do? They took the Vostok, which I think was a one-man spacecraft, and they had an ejection seat in it. And they took out the ejection seat, and they stuffed two more couches in. And they flew these guys-- no data gathered, no purpose to the mission at all except…

Spicer: Publicity.

Kayton: Publicity. Yeah. Nothing except-- our flights were all designed and a sequential thing; you learn about how to do extravehicular activities. You learned to keep a guy in space for 14 days. You learned how to rendezvous with a dead target. Then you learn how to rendezvous with a live target. Then you learn how to dock with a target. It was a buildup plan. And you learned to reenter without accuracy restraints, then you'd peg an offset CG [center of gravity] and you roll the spacecraft and you gradually reduce the landing errors from 250 miles down to a mile, which is literally the exact numbers of what happened. The Russians didn't do any of that. And the Russian landings, you know, they're parachute. As you probably know, in the Vostok program, there were parachutists, not pilots. The spacecraft would come down by parachute and then the crew would bail out and land on parachutes. Because the spacecraft would hit so hard that it would crush itself. So the pilots' main skill was parachuting. That's where Valentina Tereshkova came from. She was from a sport parachuting club. She never learned to fly.

Spicer: That's interesting.

Kayton: She didn't have to. And so the Russians had a very simple, straightforward, really publicity-oriented program. And I don't think they really did an attempt to have a-- I mean, they're a planned economy, and we're the free enterprise economy. And yet we're the ones who did the planning for a series of 20 years worth of flights. And they're the ones who just took potshots at getting a…

Spicer: A quick sort of short-lived publicity…

Kayton: Yeah. Demonstrations. Like their trial of Buran, the Russian copy of the U.S. space shuttle. They flew one flight, never to be seen again.

Spicer: I wonder if that helped. This is just speculation, but maybe it helped the US space program. You know, increased the pressure since in the public sphere it seemed like we were far behind.

Kayton: Yes. Our intelligence people never took up on this. They never-- at least not to me. Maybe high up they did. But at the level I sat, I saw a little bit of intelligence stuff. They never reported that what the Russians were doing was a kind of a show. And that there was nothing behind it. The average public, including the engineers, thought boy, the Russians were really strong and they were doing all these things, and they had plenty more in the barrel waiting to take out and fire. And in fact, it wasn't true.

Spicer: Like President Kennedy's famous "missile gap," which never was, later on.

Kayton: Which never was. That was part of the story. The missile gap was an intelligence failure as well.

Spicer: Right.

Kayton: It could be everybody. So they could have more. Yes, they could, but they didn't.

Spicer: Yes. And I guess they wanted to assume the worst.

Kayton: Yes. We were thinking worst case.

Spicer: The safe thing to do.

Kayton: Yeah.

Spicer: Right. Okay, well let's start with-- let's go back to the start of the Apollo program, and you can go back to precursor missions if you like, like Gemini and so on.

Kayton: Yeah. Mercury.

Spicer: Mercury. So why don't we just pick up that and the objectives of the program. And like you say, it was a 20 year long sequence of missions and programs.

Kayton: Yeah. Well, Mercury was just an attempt to get a guy in space and find out what he could do when he gets there. And there were hand controllers and there were optic ports, and there were modes, there were attitude hold modes, there were rate hold modes, there were angular acceleration hold modes. And all kinds of-- on doing this, because there were hand controllers that did this all. And in each flight, there would be instructed to roll the spacecraft, point to the star, look at a landmark, try to spin the spacecraft up around and on its principal axis; whatever they wanted to do. There were all kinds of experiments devised on the ground. And these guys would do them. The first Russian Vostoks had no controls at all in them. They were just manned ballistic missiles. The crew just sat there. And they just were fired and dropped back into the ocean again. I think our suborbital flight I think was the-- the first guy who flew, was it Scott…

Spicer: Shepherd [ph?]?

Kayton: Shepherd [ph?]. The first one, I think was like that. Like a ballistic missile flight. And the Russians de-orbited and de-orbited automatically and dropped to start the spacecraft back home. Our guys had all kinds of backup schemes. And you had the right angle for-- you didn't de-orbit horizontally, you de-orbited at a slight angle to optimize the descent trajectory, and you had stopwatches. You had an onboard procedure for calculating the time to de-orbit. And in case you lost radios, then the ground would update you the current value if you could get communication. And then you fired your three engines and de-orbited. And so the Mercury program was an attempt to find out what everybody could do on board a spacecraft. And that was Mercury.

Spicer: Under basically manual control.

Kayton: Manual control.

Spicer: And then they would watch USAF as the input…

Kayton: These were pilots, remember. Automatic. The Russians were heavily into automatic control. Everything was done for the crew and the crew were kind of like observing pilots. The US program was run by test pilots out of Edwards Air Force Base and out of Packs River [ph?]. And they wanted everything done manually. I heard a lot about that when I was at NASA. The crew had to be able to-- if you had an automatic mode, it was okay, but there had to be a manual alternative in case the automatic didn't work.

Spicer: Yeah. And I actually want to ask you about that a little later with respect to Apollo pilots, you know, who are used to that.

Kayton: Yeah. Well, Gemini comes next. And by the time of Gemini, President Kennedy already announced there was going to be a moon program. So people said the moon flight's going to be about two weeks long. So you've got to keep a guy in space two weeks and make sure he doesn't get sick and his bones don't turn to mush and everything else. And then there's-- the spacecraft is going to be too heavy. You can't launch it in one piece, so you're going to have to have a rendezvous so you've got to learn how to rendezvous in space. And then the guy's going to walk on the moon, so you've got to build some space suits, and you've got to test them in orbit, earth orbit, where people get out of the spacecraft and wander around. And then you've got to learn to do precision entry. Because the Mercury entries were 200 mile errors, generally. And understand that we're landing in the water. The Russians are landing on land. They're a land power. They didn't have a navy at the time. So they're landing on land, and they're parachuting out at the beginning, and then they learned to put a rocket on the bottom so the spacecraft comes down and a rocket fires and slows it down enough so that they don't hit too hard.

Spicer: Pulverize.

Kayton: And pulverize, yeah. Later on, they learned that. We were just landing in the ocean. And we'd have two navies out. There'd be an Atlantic navy and a Pacific navy, because there was always a primary landing site, and then in case of weather you had to land in the other ocean. So the whole US Navy was out there every time there was a mission. And it's expensive. And if you land 200 miles off, a destroyer at 20 knots will take ten hours to find you if he heads straight for you and…

Spicer: **if** he can find you.

Kayton: …and can find you. This was a major worry that a spacecraft would sink with its crew. When the spacecraft landed, an HF antennae popped out of it, out of the top and sent out…

Spicer: A beacon?

Kayton: A homing signal; a beacon. So that the ships could home on the beacon.

Spicer: Right.

Kayton: And of course the ships would then, when they got close enough, would send a helicopter ahead to check up on the spacecraft and maybe drop a raft for the crew to get out into. One spacecraft did sink. I forget which, but the crew got out.

Spicer: Yes.

Kayton: One sank and was lost. But all the others were recovered.

Spicer: Did they just recover that one off Florida a couple years ago?

Kayton: I don't know. Might possibly be. I don't think the-- the landings were not off Florida. The landings were way out in the middle of the ocean.

Spicer: The Pacific?

Kayton: The Pacific was usually the primary target because there's more space. It's the longest runway in the world. 2,000-3,000mile long runway. You can't miss. But that was an exciting time. And I'm trying to think of the continuation of the Gemini issue; Gemini got these 200 mile errors down to about a mile. In fact, Gemini got it to less, Apollo got it down to a mile. Gemini got it down to two or three miles. Though Apollo 13, 14, 15 were down in the 0.6, 0.7 mile area. They were actually that good. Really precision entries. And you did that by offsetting the center of gravity. But that's a long story. I don't want to go into that here. But you offset the center of gravity and you roll the spacecraft so that there's a lift vector. And you control which way the lift vector points. As the spacecraft rolls, you can take a lift vector if you want to stretch the glide, you put the lift vector up, and if you want to pull the glide in, you put the lift vector-- if you want to turn left to right, you put the lift vector sideways. And you're constantly rolling the spacecraft slowly into control the landing point. The first Geminis didn't have offset CG, but the offset CG was introduced in Gemini and was used throughout Gemini and Apollo. Very effective and I'll bet it gets used in this next post-- the new return to the moon program. We'll probably do the same thing. We'll probably land in the water. With controlled entry. I don't know. I'm not on any of those committees.

Spicer: Alright. So we're up to maybe the end of Gemini and start of Apollo. Why don't you tell us how you got involved with that program?

Kayton: Well, one of my MIT classmates who was a navy commander called me one day when I was working at Litton and said "We're starting a new spacecraft called the lunar module, and we want somebody to run the guidance system. How would you like to come?" And I said "Cliff, what day do you want me to start?" You know, was my response. And so I left Litton and drove cross-country to Houston.

Spicer: What year was this?

Myron Kayton: 1965.

Spicer: Okay. So the…

Kayton: It was Memorial Day. I drove over the Memorial Day weekend.

Spicer: Just back up a second. So you graduated MIT with a PhD?

Kayton: Yes.

Spicer: In which year?

Kayton: 1960.

Spicer: **19**60. Okay. And then you worked at Avco?

Kayton: At Litton. No, I had worked at Avco before, and then I decided to go work for Litton in California. I had a summer job with them in '59. And they were working on inertial navigation systems for airplanes. A bright idea at the time, because all the money was going into ballistic missiles. All the inertial navigation money was going into Minutemans and Titans and Tridents--well, Trident; too early. Polaris is one. They were all going into that. MIT was pushing ballistic missile inertial navigation systems.

Spicer: Right.

Kayton: And some of the engineers at Litton decided that it could be done for an airplane. And so they set up a company and got some funding. And it was small. And I worked with them for a summer. And then I decided it was an interesting team. I liked them. And so I went back.

Spicer: This is a spin-off of Litton?

Kayton: It was Litton.

Spicer: It was Litton.

Kayton: The original Litton. Yeah. Different division. The original Ltiton were the microwave oven guys here in the bay area. And then this was a, I guess in a sense a spin-off out in southern California of guidance and control people. And it was a very nice outfit. Very marketing oriented, I might say, but nevertheless they did good engineering. They're still around. They're still the number one of the two biggest airplane inertial navigation companies in the world. Honeywell and Litton are still the neck and neck leaders in that business.

Spicer: Right.

Kayton: It's narrowed down to just those two with a few small stragglers behind. With a few stragglers kind of holding on with their fingernails.

Spicer: Very high barriers to entry…

Kayton: Yeah. All that at this point I guess. Very expensive to get in.

Spicer: R&D, production…

Kayton: Yeah. Machinery and people. Knowledgeable people. It would be virtually impossible to start a new one up. And the people with these older ones that are still trying to hold on are having-- my understanding is, are having some difficulty.

Spicer: Right. Okay. So '65, you move to Los Angeles.

Kayton: Well, from '65, I worked for Litton from '60 to '65 in Los Angeles, then I moved to Houston…

Spicer: Oh, Houston.

Kayton: With NASA.

Spicer: Okay.

Kayton: And then I started work just as the Gemini was gearing up and the Apollo work was in engineering. And I was, of course, on the Apollo team. But I did try to stay as much as possible up on Gemini. Gemini was very closely kept at the time. I don't know why. It was hard to get information.

Spicer: Even within NASA?

Kayton: Even within NASA. Stuff was supposed to spill back and forth, but it wasn't easy. For one thing, you were so busy on meetings on Apollo, you don't have time to go to the meetings on Gemini. And I think they had the same problem. And the Apollo command module was a different contractor. Mercury and Gemini were done by McDonald in Saint Louis and the Apollo command module was done by Rockwell in Los Angeles. And they had to learn the space capsule business from scratch. But fortunately I was on the _______ side, which was done by Grumman who had some unmanned space experience. They had done some observatories; optical observatory work. But they were also-- it was, I mean, it was first of a kind. A spacecraft to be used only in space. No ability to come home, you know, built out of light, flimsy foil.

Spicer: Yeah. So tell us.

Kayton: It was fun.

Spicer: Let's start from, you know, day one when you started there. And you don't have to go day by day, but some big milestones would be good.

Kayton: I hardly remember the-- from the spacecraft top end, there were questions of fuel cell versus battery. They picked the battery. I had nothing to do with that. That was on the spacecraft side. The issue of landing with legs and compressing on the spacecraft side.

Spicer: So the lunar excursion module?

Kayton: It started as the lunar excursion module, and then in about '67 was changed to lunar module.

Spicer: Lunar module; okay.

Kayton: Since it didn't do any excursions.

Spicer: It didn't move once it landed.

Kayton: Yeah. So they changed its official name. And then the excursion module was really the LRV; the lunar rover vehicle, which was carried on the back of the lander, lifted off by the crewmen and then driven around the surface. That was the excursion.

Spicer: Neat.

Kayton: So they changed its name officially.

Spicer: So tell us about some of the design challenges that you faced on that.

Kayton: Well, the issue of having a separate abort guidance system was one of my major efforts. The command module had only one guidance system. And for the landing on the moon, we thought a separate system would be in order to go find the command module in the event that the lunar module's primary guidance failed during the descent. See, if the command module fails, you just keep going. And you'll eventually get back to earth and you can make yourself a manual entry. You're not dead. But if you're landing on the moon, and the primary guidance system fails, you're quite dead if you have no alternative.

Spicer: That is, once you're on the moon…

Kayton: Once you're on the way down.

Spicer: Oh, once you're on the way down.

Kayton: Yeah. Once you're on the moon, you could probably-- the plan was if you were on the moon, and had a guidance failure, you would do a manual climb out into a lower orbit, and then the command module would come down and get you. And there was an actual plan prepared for that. It was never used. To my knowledge was never used.

Spicer: So tell us about this computer that you're talking about. This is not the same as the Apollo guidance computer.

Kayton: This is a different one.

Spicer: This is the abort guidance computer.

Kayton: Abort guidance computer with its own sensors. The Apollo system.

Spicer: Why was it called abort guidance computer?

Kayton: Because it was only for purposes of abort. I fought many battles at many meetings where the contractor would come in and say let's expand it a little bit, and you'll have a dual way to land. You'll have two landing computers. And I said no, no, no, no, no; we want just an abort computer. It's only purpose is to abort and go back to the command module. It has no landing equations.

Spicer: At what point does this abort computer kick in?

Kayton: Anytime.

Spicer: So even-- there must be a point of no return, though. Once…

Kayton: No. As long as the engine is working.

Spicer: Okay.

Kayton: As long as the engine-- the one thing of single point failure was always the engine. And if the engine goes out, they're permanently going to live on the moon. The crew's just going to be permanent inhabitants if they push that ascent button and the ascent engine doesn't bite. Those are single point failures. But the-- even the descent engine is not a single point failure, because you could use the ascent engine for the abort. But the primary guidance computer could become a single point failure if it failed during the descent. You then have to get back out. And so the abort guidance computer solved the problem of getting you into an orbit that was sufficiently good to either find the command module or get into an orbit well enough to establish-- it could find you.

Spicer: Right.

Kayton: And it had no landing abilities, although the contractors pushed very hard to do it.

Spicer: And you didn't want landing abilities for…

Kayton: I didn't want to get it bigger.

Spicer: …complexity reasons?

Kayton: Complexity and weight, yeah. The idea is Russian. That's a Russian-like idea. That one very simple…

Spicer: The most reliable parts are the ones you leave out.

Kayton: Yeah. For example; no interrupts. You know, I had for a long time wanted no interrupts on the Apollo. It was impossible. There were interrupts. An interrupt means you can't predict performance. The Apollo-- the abort guidance computer had absolutely no interrupts. So it was a purely synchronous, you call this-- you read the sensor, read a sensor, read a sensor, do a calculation, do another calculation, output to these sensors, then read again and then read. And just go through the cyclic routine. And it was absolutely reliable. Once it was tested, it was always going to work. You never knew on the Apollo once it was tested. Because the aborts; a guy could hit a hand controller at the wrong time and put in an abort and something would happen that nobody…

Spicer: Send too many interrupts?

Kayton: Yeah.

Spicer: Throw all the timing.

Kayton: You don't know what's going to happen. So this was a nice, simple guaranteed way to get home. And it was, I mentioned to you how Apollo 13 went home. That you used it.

Spicer: Just-- we're going to switch tapes in a second, but I wanted to ask you. Well, let's stop now and then we can tape then.

Kayton: Okay.

Spicer: Yeah. We'll switch tapes here.

END OF TAPE 1 / BEGINNING OF TAPE 2

Spicer: One of the interesting points that came up earlier was the divide between astronauts who come from a test pilot background and computers; the computers that they have to use during a mission. And of course, there's always a tendency with fighter pilots who are used to being very hands-on guys to want to interact or intercede in the flying of the vehicle. They don't want to really just sit back and let a computer do all the flying. And I'm wondering if you could tell us a bit about that. Some of the tradeoffs involved and the psychology of these guys.

Kayton: The Russian rendezvous were all automatic. The Russians would send progress spacecraft us, Salyut spacecrafts that their stations, the Salyut and then the Mir. And it was always automatic. Their crews just sat back and watched as near as we know. Or near as I know. And our guys would have the reverse. They wanted complete manual control. For example, we're going to get into a complicated story. The original rendezvous plan, the ideal rendezvous from a fuel standpoint is what's called the Homan transfer, where you fire the rocket at perigee, raise the apogee up and then meet the other spacecraft at apogee. And that is minimum fuel. And Homan, a German, calculated this back in the 1930s. Proposed that rendezvous technique and the original rendezvous plan for Apollo, in fact, for Gemini, was a Homan transfer. And when the crews got hold of it, they decided that was really not very good. In fact, even some of us engineers thought that. Because if you miss, and you go around the end, the spacecraft aren't together anymore.

Spicer: The error gets larger?

Kayton: Yeah. The orbit is slower. The intercepted orbit is slower, and so the target's way behind you, and now you've got to wait a long time before you can make it. You may be in orbit for hours or days before you could make it. So it was a very poor idea. I think the Russians still do that, by the way. Did for a while; did that. But our guys, motivated by the crew and by some engineers said you've got to go to a different way. And there was a big meeting at NASA run by the program manager to decide if the Homan transfer in a more manual way where you made a transfer maneuver and then two or three measurements as you climbed up. Each measurement bringing you closer to rendezvous. Called the concentric flight plan. Then you would eventually get there, guaranteed to get there in one transfer maneuver. And Buzz

Aldrin's thesis had something to do in an indirect way with this technique. And it's in the end what was adopted for Gemini. It was used on Apollo, and it's still used on shuttles. It's not-- there have been small variations. But there's a terminal phase initiation, two or three mid-course burns, and then a terminal phase final, which is the actual braking burn, which actually intercepts the target spacecraft. And the crews all had charts, particularly Tom Stafford who flew the first one on Gemini, had charts in which he would have manual calculations of what the angles ought to be at each point, so if he lost his radar, and if he lost ground contact, he could still do it manually by watching angles of line of sight and using a stopwatch and angle measurements. And that's typical of the way the crews insisted that things be done. And a lot of us engineers were with them. We did not have a lot of engineers that felt the Russian, MIT, the guy's mostly at MIT wanted to go Homan transfer and use the minimum fuel burn and thought there's no problems, we'll get there, you're not going to miss and all this sort of stuff. But the real world engineers, and especially the crew, said no.

Spicer: Now, these are navigational techniques that go back to almost sailing techniques?

Kayton: I would say.

Spicer: Using guide stars and kind of a <inaudible>.

Kayton: Yeah. That's right. In the sense, that's correct. You made intermediate measurements, and you continue to sail and you make another waypoint measurement, then continue to sail. And that's how this was going to be. And it guarantees a target. It really does. It guarantees you a target. And you have this manual option that the astronauts were so concerned about, particularly Stafford, that you have to have a way to do it in the event you lose the radar and in the event you lose communication with the earth. Because they're tracking you all the time. And they're always updating to you what they think the burn ought to be. I mean, it's your burn. You're the astronaut. You pick the number to burn; you don't have to burn what they tell you on the ground. You can burn what your onboard computer says. But normally, you're going to-- if the ground's tracking you, you're going to do what the ground says. You're going to do what they call external delta b; you're going to put the numbers in from the outside and burn their numbers. But you don't have to. And if you lose communication, then you have your own charts. And you can just get there by charts.

Spicer: So you have a fail-safe.

Kayton: Yeah. Double fail-safe. Ground measurements, onboard measurements and charts. So the whole thing worked. That was one of the issues I worked on. There were a whole lot of other issues. I can't take personal credit for everything, but the markings on the windows, I was instrumental. I'm not sure if I was the one who first proposed that, to have marks on the window. I think I was. So that you could see the number at which the target is going to be. There was a strip down the window with numbers.

Spicer: <inaudible>

Kayton: Well, the coax was a different one. That was heretical. This was an actual stripe painted down the window with numbers on it. The computer would tell you which number you could expect the target's going to be located. There were all kinds of little details about that. And then there were all the contractor issues; filters that didn't work and relays that weren't made on time and decisions at flight readiness reviews that gee, a part failed in the lab; how close is the part on this spacecraft to that lab thing? Do we need to take it off and change it, or can we go fly it anyway? Everything had pedigrees. I mean, these very expensive government parts for Apollo that are now called S-class. I don't think they were then called S-class. S meaning "Space". You knew who assembled it, when, what time of day, which shift did it. You knew where the materials came from. You knew-- you could trace it back to the mines as to where everything came from. And so if there was a problem, you could determine whether your part was similar to-- there was one, that's a big diversion. But there was one very clear case that I remember working on: a relay where a woman had altered the assembly procedure. She thought she came up with a better procedure than these engineers who never really did it. And so for a whole shift, she made a whole shift's worth of bad relays.

Spicer: And I guess one of these…

Kayton: And thought they were better. I mean, she thought she was doing-- she thought she came up with a clever idea. Didn't ask anybody, didn't say hey, here's a better way to do it, what do you think? But she just took it upon herself to do it. And so all the relays made on that shift, and I think it went several shifts, my recollection was before the problem was discovered, had to be taken out.

Spicer: So there are a couple of themes here that you're bringing up that I want to touch on. One is the establishing of a pedigree, as you call it, indicates to me that the semiconductor industry itself was being stressed in terms of delivering a quality reliable product by the objectives of the program.

Kayton: Yes.

Spicer: And also that the simplicity of the design of the Apollo guidance computer, for example, because it's so hard to qualify parts, and correct me if I'm wrong, but you wanted to keep the number of different part types to a very small number, so you wouldn't…

Kayton: Yes.

Spicer: Because qualifying any one part is so expensive. And I know I think in Eldon Hall's [book ["Jounrey to the Moon"], he talks about when people did these kind of ad hoc improvements. Or, you know, showed initiative-- what would be called initiative in some companies, but maybe wasn't appropriate in this context, where reliability is more important than performance, necessarily.

Kayton: Yes. And he's talking about parts in the computer. I'm talking about what's outside the computer in another box.

Spicer: Does he? I think maybe…

Kayton: No. It was in actually the-- I forget what the name of it was, but it was a box that was used as a substitute for astronauts during unmanned flight of LEM to turn on and off all the panel switches. There was no provision made for turning switches on and off without a crew doing it. So during the LEM One unmanned flight, a box was built that would short circuit all the…

Spicer: It's kind of an override or kill switch?

Kayton: Yeah. Well, more than that. It was a substitute switch operated by radio or by the computer. And the relays in there were the ones that I was talking about. But I don't know if Eldon [mentions it; the 7400 series chips, these four function and six function chips were developed both by Minuteman and Apollo. And I'm not sure how the two worked together, whether they both worked in parallel or more likely in those days they were competitive designs. The different companies, but they were the chips that everybody was using.

Spicer: And I think the Apollo guidance…

Kayton: <inaudible>

Spicer: Yeah. They were all NOR gates, right?

Kayton: I think that's right. I haven't read Eldon's book.

Spicer: Well, you've already talked about it already, reliability versus performance. Because obviously as the program went on, it took a decade, there must have been a temptation on the part of designers to maybe use denser parts or more elaborate parts. But because things get locked in and reliability, you know, is so important.

Kayton: Yeah. That's why aircraft even today are way behind. I mean, aircraft and spacecraft are always a generation behind the newest technologies. You don't want to fly, I mean, glass panels in airplanes, CRT airplanes, they didn't show up until pretty late. Shuttles had two or maybe three, but they were only for status indications. And that happens in 1970s, when there were plenty of CRTs around the industry. And, you know, autopilots are the same way. Everything happens very slowly. People-- gyroscopes, laser gyroscopes that were in use in airplanes for ten years before the spacecraft industry would even think about accepting a laser gyro in space, because nobody was sure what the reliability was going to be. That's true of a lot of technologies. Spacecraft, the airplane industry is late, and the spacecraft industry is even later in adopting these things. And that's I think right.

Spicer: Probably a good thing.

Kayton: Yeah. It's a good thing. Because once you're up there, it's hard. You have a failure three hours or three days out from the moon, you're in some degree of trouble.

Spicer: I wonder if you could talk a bit about the decisions that went into embedding basic physics and equations of motions and guidance and navigation into this improbably small computer with almost…

Kayton: 35K

Spicer: …almost no memory by today's standards.

Kayton: Yeah. Well, the key to that were the "Black Fridays." MIT was in charge of programming. And they would put in all kinds of clever programs. And NASA would have meetings up there about every two months or so on a Friday. They were called Black Fridays. And that's when you went through…

Spicer: Doesn't sound too good.

Kayton: No. You went through all the programs and decided which ones ought to fly and which ones were really interesting and we'll put them in for some later unspecified dates, and which ones you don't want to ever hear about again, you know? And people were very clever. They came up with all kinds of nice things. But it wouldn't fit. And you didn't want a foolproof computer. I mean, you wanted to have some spare space. You wanted to have not all the RAM; you didn't want all the RAM in use at one time. You had to have spare capacity. Because nobody-- with an interrupted system, you don't know what's going to happen. So one of the keys to that whole thing were these periodic reviews up there to try to trim down what's in the software; try to keep it under control. That continued under the shuttle, too, by the way. That problem was-- in fact, I think in the commercial industry, it's the same thing. And then the other thing on software reliability were simulators. The engineering department-- well, let me step back a minute. NASA, for our purposes, has four arms; NASA JSC. There's the engineering people, the flight operations people, the astronaut office, and the science office. And each has their own goals and their own interests. And all have to work together to get the spacecraft, though. The engineering people, you know, design the spacecrafts, go to the contractors for parts, buy it and test it. The flight control people take it over once it's done. It's no longer in engineering, and then they fly it. They create the trajectories and they write the timelines and write what the astronauts are supposed to do at every hour during the mission and so on. The astronaut office is concerned with training. They buy the true mission simulators and they train their crews to fly them. The science office always wants to get as many pounds of science equipment onto every spacecraft as they could. That was an interesting story on LEM One-- on the first LEM landing, LEM 11, Apollo 11. I remember sitting in meetings, arguing with them. There was a package called the ALSEP; the Apollo Lunar Surface Experiment Package, I think is what it stood for. They wanted to put the whole ALSEP on. And that would have reduced fuel. And I said I'd rather have the fuel on the first flight. And they were worried. Suppose there's never another lunar landing. We'll never get that data, you know? This is the first, and we want-- and so we compromised. They put one or two of the ALSEP experiments on and we got our fuel. Neil Armstrong needed that fuel, because he had to take over manually to land the spacecraft. So he needed that.

Spicer: Since you just brought this up, let's talk about that, the final 30 seconds or so, landing on the moon. Computer versus man, or computer and man, let's call it, and what happened?

Kayton: Yeah. The design was that the crew separates from the command service module on orbit, checks out the LEM, levels the LEM for a de-orbit burn and then coasts down. And at about 50,000 feet, I don't recall precisely, they turn on the descent engine. And then an automatic sequence begins. They could not-- we went through this manually in the engineering department. Those four, within engineering there were labs that ran simulations. They tried simulations of people trying to land from 50,000 feet to the ground. They invariably ran out of fuel. They didn't get to the right place. There was no way to get a guy out to the moon from 50,000 feet bringing-- throttling an engine by hand, getting the azimuth right, getting the downrange right and not only landing in a particular point, but even landing. There wasn't even a question of landing where you wanted to land. The simulations showed you just couldn't do it.

Spicer: You would crash?

Myron Kayton: Yeah. You'd crash or not make it or run out of fuel before you got down. Or if you landed, you'd land too fast or too hard and crash. So it was the-- it had to be automatic. So the descent engine starts to burn, and it burns through a very elaborate maneuver. We can go over more of that in a minute. Goes through a very elaborate maneuver, throttles the spacecraft down, slows it down, brings it to where it's going, and brings it to a point called-- remember you're thrusting along the axis of the spacecraft opposite the velocity vector, which is the most efficient way to thrust. So the crew is sitting back, actually they're rolled downward; they're looking straight down. They don't see anything out ahead of them. Down to a place called, well, I don't remember where they roll over, but where-- I do remember. At about 25,000 feet, you want to start getting landing radar updates from the ground. So the crew rolls the spacecraft over, landing radar is on the bottom. Now they're looking straight up at the sky. They still can't see anything. You're still thrusting automatically at the most efficient thrust, but you're getting radar inputs to update any drift of the inertial system. The inertial position is drifting, because the inertial calculations slowly drift with time. And maybe fast drift if there's something wrong. So the radar keeps updating. At a place called high gate, a couple, oh, I don't remember what altitude high gate was. I may even… It's in this book. We could find it. But since some of your guys might want to know it without looking up at the book. It's about at 8,000 feet above the moon. Spacecraft pitches up, so the crew can now see the ground. But now you're thrusting near vertical, and the velocity vector is this way. It's an inefficient thrust. But you're still doing it automatically, because of course the crew can't do this. Then you get down to a place called low gate, which is two, 300 feet above the ground. And at that point, the crew was supposed to take over. Actually, the guidance system was built to land from low gate. But it was understood that the crew would take over at low gate and land vertically. But the automatic system still had built in algorithms to be able to take it from low gate. Low gate is like a helicopter hover. You come down to low gate, you're standing still, hovering, and then you go down. And that was the crew's thing. Unfortunately, on Apollo I, there was some confusion in the computer. I don't want to try to remember. I think I remember what it was, but I don't want to try to remember in public because I'm not positive. I think it was a switch in the wrong position. And in fact, I'm pretty sure of that. So at about 1,500 feet, all kinds of data became saturated. I don't remember the difficulty, and Neil Armstrong had to take over at 1,500 feet and bring it down manually from 1,500 feet instead of from 200 feet. And he did it just about before he ran out of fuel. He was able to do it manually from 1,500 feet. Because I said, from 50,000 feet, you didn't have a prayer of bringing it down. But he was able to recover. And they were always looking at the possibility you'd have to abort during that 1,500 foot descent. If his fuel started to run out…

Spicer: Even that late, you could…

Kayton: Oh yeah. You push the abort button, the ascent stage would lift off and the abort guidance system would kick in and take you up and find the command module. You could abort any time. You could even abort from the lunar surface. You can even use the abort system from the lunar surface.

Spicer: Is it the same equations and computer…

Kayton: Same equations.

Spicer: …are the same ones you use to lift off?

Kayton: And the equations were complicated by-- I'll tell you an interesting story. MIT wrote the equations. The descent equations and ascent equations were written by MIT and programmed by them, in assembly code, by the way, for those who are listening to this. Because in the 35,000 word computer, you don't have room for the inefficiencies of higher level code and then compiling everything ten machine instructions for every compiled instruction. There's just no space for that. So it's all assembly coded. Everything was assembly coded. And I was going to tell you an interesting story about that and it just slipped my mind.

Spicer: The equations and MIT.

Kayton: Yeah. Yes. There was…

Spicer: Is this the guy who could read the listings?

Kayton: There was. That was John Norton [ph?].

Spicer: Recognize…

Myron Kayton: John Norton. I remember his name, which is astonishing. I remember what he looks like. John could look at those assembly code tables and find errors. Of course, he couldn't find them all. But he'd find errors. Every listing had to go through John to get John's approval before it went into the simulators. I sat on the change board where all the simulator tests came in. And I'm off what I wanted to say originally; I should write down what I want.

Spicer: Sorry.

Kayton: The DPS thrust restriction I'm going to write down. But the change board would get results in from engineering simulators and the astronaut's offices simulators. And there would always be things like, well, if this switch is on and that switch is off and this switch is in the standby position, then when you call program 42 now so and so, something bad happens, you know. And the change board was inundated with these things. What happened was you had two choices. You could say let's fix it for the next flight. Let's put it on a wait list for the flight after that. Or let's put it in program notes, which is what typically happened. There would be a set of program notes written that were cautions not to do things. And you'd hear the radio transmissions when an astronaut says he's going to do something, there's a long pause, and the ground will say; they didn't use the word approve because they didn't have to approve what the crew was doing, but they'd use something like yes, that's okay. Meaning they've looked up the program notes and there's no prohibition against what you're just about to do. So there was a lot of that in the Apollo, because of the fact that during the testing, you could not possibly-- but with an interrupted system, you could not possibly get everything out of it. Back to the MIT guidance equations. At one point early in the program, '66, '67 maybe, TRW discovered that the descent engine had an instability region between something like 65% and 90% thrust. 63 and 93; something like that.

Spicer: Pretty wide.

Kayton: Yeah. And there was an instability region. You couldn't throttle the engine. You had to go quickly through it. And remember this engine is throttling as it comes down. So one of the proposals was well, we'll redesign the engine. You know, my office was guidance and control. There's a parallel office developing the ascent engine and the descent engine. And that would have delayed the program and caused all kinds of problems. So I and some other people went to MIT and said can you live with it? And MIT played around with it. They came back with a guidance law and lived with it.

Spicer: Okay. I'm sorry, a guidance…

Kayton: A guidance law that would actually throttle through, not hold in that instability region, but throttle in the low region or the high region and switch back and forth.

Spicer: Okay. So they fixed the problem.

Kayton: They fixed the problem in the software.

Spicer: In the software rather than…

Kayton: And kept the unstable engine and saved untold millions of dollars. Plus schedule slips of, you know, who knows, maybe years. They had a whole new engine developed.

Spicer: Is that like a needle valve?

Kayton: Like a needle valve. They called it the _______. And the _______ had to be redesigned, and the shape was wrong or something like that. I never got into the details of it. But in any case, MIT got NASA out of it by saying we'll build a guidance law that can circumvent this throttling limitation.

Spicer: Good move.

Kayton: And it was in every flight. Every flight did it. I mean, as far as I know, to the end of the program, I know in Apollo 16 in this manual, they still talk about the exclusion region. Apollo 17 was the last one. So I assume TRW never bothered to fix that instability, because MIT avoided it.

Spicer: They solved the problem.

Kayton: You could go through it quickly, but you couldn't stay. You couldn't hold the thrust in that region.

Spicer: I want to ask you about, you brought it up, the verb and noun syntax of the computer. Do you have any thoughts on that? Why that was chosen?

Kayton: Well, I flew a couple of missions on a simulator, but I'm not really thoroughly up on it. There were programs which were mission phases. And in each mission phase, there were routines that you selected. And then in each routine, there were verbs which said do something, and there were nouns which were data that you loaded by hand. For example, if you wanted to see something on the display, or you wanted to enter a radar manually; enter a radar elevation angle and an azimuth angle, there would be a verb that would tell you to do that.

And then you'd enter the numbers on the nouns. Very cumbersome way to fly. there were, oh, probably 50-- there probably were ten or 20 programs, but there were probably 50 each of the routines, verbs and nouns, and the crews had to learn them. And they often depended on outside help to kind of get reminded. But that isn't the whole story. The abort guidance system had its own display, which was a direct memory access display, which was utterly different than the verb/noun system. There, you actually picked a memory cell and put a number into it. you had to know what each cell was for and put-- and store numbers in them

Spicer: How big was the memory?

Kayton: It was 2K of RAM and 2K of ROM.

Spicer: Okay.

Kayton: Tiny. Tiny.

Spicer: But each one had some kind of data value…

Kayton: Yeah.

Spicer: …that meant something like a parameter of the spacecraft or something.

Kayton: Right. Or part of an equation. I'll tell you another story about that in a moment if you have time. But one of my jobs when I got there was I was horrified and I said let's make the landing-- let's make the abort system at least have the same verb/noun system as the command module. It would have had to grow in size hugely to do it. And based on the sort of Russian like, which I didn't know at the time, but the Russian like view that I had, I wanted to keep it really simple and uninterruptible. And as soon as you made a complex verb/noun system, that would be out the window. So the poor astronauts had to learn two completely different ways of entering data into the-- and for the abort guidance, they relied a lot on the radios; radio communications to earth to help, for example, on Apollo 13. They ran the whole mission on the abort guidance system. They had to get help.

Spicer: Let me ask you about a typical mission, let's take Apollo 11, since that's the first one to land. How much of the mission is ground based and how much is spacecraft based? And what were the tradeoffs?

Kayton: Well, the ground is always tracking you, except when you're behind the moon. The ground is always tracking you. And the ground is always telling you what they think your state vector is. And as the astronaut, you're the captain of the ship. I mean, you have a state vector from your onboard inertial navigation system, the primary system. You probably don't have the abort system on. So you've got one from the primary system, and you've got one from the ground. And it's your choice as to which one to use, you know. The ground would like you to use theirs. And you might like to use yours. And I suspect that was a matter of personal preference on the part of the crew and it probably varied in different parts of the mission on how much confidence they had in the on board system.

Spicer: Yeah. Now, when they were actually planning all the mission itself computationally, you know, things need to be calculated during the mission. How did they figure out, you know, how much of that they could do on the ground and thus make the AGC smaller perhaps.

Kayton: Nothing. Nothing down. Everything was autonomous. The onboard system was fully autonomous.

Spicer: You have to be able to do everything.

Kayton: Everything. The assumption at every point is you're cut off from the ground. You have to-- you never hear from the ground again, you've got to get home. And NASA had, as you may know, this free return concept. Every trajectory, and that applies to command module, really not to the LEM, had to be such that if it continued, it would always come back to earth again. You could not build at trajectory like if it goes behind the moon, and you're supposed to de-orbit the moon and you don't, you've got to be able to emerge from behind the moon and continue back and hit the earth. So the command module was always protected that way by being able to hit the earth. The lunar module, of course, didn't matter, because it would burn up in the earth. It would never even come back to earth, but even if it did, it would burn up. It wouldn't make the descent.

Spicer: You were one of the main designers of the lunar module guidance?

Kayton: Of the guidance, yeah, I'd say. I was one of. As long as you say one of. There were a lot of people that I think did much more than I did. Particularly at MIT.

Spicer: Can you tell us about-- I mean, did you actually have-- I know you didn't have the thing in front of you, maybe towards the very end they gave you a tour or something of the actual LEM? Or were you…

Kayton: Well, I was at Grumman about every three weeks. But Grumman just took the guidance system from MIT and, you know, installed it. So my office had two functions. One is to work with Grumman on the development of the Grumman purchase guidance, which was the abort guidance system and the autopilot, the analog autopilot. And then the crew displays. And second, to work with the MIT office to get their equipment compatible with the vehicle. And I might say that the bureaucratic side, the way that was handled was there was there was a meeting called the GSOP, I think was its name. The guidance system-- no. That wasn't its name. I don't remember what it was called. But every month, all the contractors met in a conference room that I had, and I had a man, very competent fellow named Bob Lewis who was the secretary. And we would go around the room and look for all the changes. I mean, people had word order differences. People would have voltage differences. People would change grounds. People would-- all kinds of ridiculously simple things would happen. And you had to keep track of it so everybody made the change. You know, if somebody made a change in his equipment, everybody had to match it. And Bob would keep a very careful record of this. And write action items up and then contact everybody before the next meeting to make sure everything got really done. And the things all worked together.

Spicer: Where I was going with that other question was did you have a sense of maybe how fragile this lunar module was and what an amazing thing it was to be able to put this-- you know, earlier you mentioned it kind of had flimsy legs and was…

Kayton: Yeah. It was 4 psi interior. The only thing fragile about it, you'll be amused, when I flew it, I carried my boy scout axe with me in case there was a fire I could chop through the skin and get out. I literally did.

Spicer: That only works in a simulator, right?

Kayton: On the simulator. I carried my boy scout axe with me on the simulator.

Spicer: And this is a full physical simulator. Like a repair craft simulator. Not software.

Kayton: No. They're full. Full up. It looks just like a LEM. Astronauts had those. The engineers had the kind you were talking about; software simulations mocked up with maybe a visual display. But the astronauts bought full mission simulators for training. And they kept them in Houston and they had some at the Cape. And their people would be constantly flying missions and abort missions and contingency missions. I mean, you can't imagine how many missions these guys had to fly, because…

Spicer: Well, they're…

Kayton: Oh, and I might say going back to the issue of tracking, behind the moon, there was always this one source. Once you went behind the moon and fired DOI, the descent orbit injection, nobody had any data besides you. And when the command module went around the moon to come back to earth and had to accelerate itself, it's behind the moon, nobody is tracking them. And that's the time when the Walter Cronkites would always be biting their fingernails on the television to-- will the spacecraft re-appear and will it re-appear on the right trajectory. And so were the people at NASA were concerned the same way.

Spicer: I bet. Yeah.

Kayton: You know, you-- the ground is not watching. The ground's not tracking.

Spicer: Yeah. Nobody knows what's happening.

Kayton: Everything is being done based purely on onboard computations. The landing operations are all done in full view. One of the lectures I give these days is about landing on the back side to build a radio silent observatory. And that's going to require a lot of operations on the back side that can't be tracked. And the issues revolving around that and how to communicate the data back. A lecture I've been giving fairly regularly lately. But that's-- but NASA didn't face that. All of our operations were on the front side of the moon and in sunlight.

Spicer: So you brought up the issue of the secretary who was at these GSOC meetings, I forget his name.

Kayton: I don't think that was its name.

Spicer: Or whatever.

Kayton: Yeah.

Spicer: The monthly design meetings.

Kayton: The monthly meetings.

Spicer: Or engineering reviews. And the importance of version control.

Kayton: Yes.

Spicer: And, you know, at the same time that you're doing this, it's almost like building a boat as you're sailing. Because the whole field of computing and software engineering and/or you know, just software development itself is very new. And so I imagine a lot of the software engineering and techniques actually arose from the space program. Especially…

Kayton: Yes. I even wrote a memo on it and so did a lot of other people.

Spicer: Can you tell us a bit about that?

Kayton: Yeah. Well, you know…

Spicer: Reliable software.

Kayton: The issue of where-- who keeps the final deck of cards, you know, they used to be locked in somebody's desk at MIT. And I think the version flown was something like "Luminary 250" or 251 or something. And there were constant releases coming out. And the simulators are always behind, because they're running an older release. So all this-- just the thing you mentioned; it's like being on the boat while you're repairing it. You know, you can't wait. You can't stop everything and then say: "okay everybody's now going to test the same simulation." There wasn't enough time, which is why you had all these program notes. And I always likened that to the hardware, and I tried to draw parallels to hardware configuration controls in the memos that I wrote. But the-- and there were no rules for development, like go to instructions and these other things. Nobody had developed any hard and fast rules that said you shouldn't use certain loops or you shouldn't have loops inside loops. It was all machine coded and people did whatever they wanted. That wasn't where the problem was. The problem in my recollection was interrupted operator, crew interrupted programs that changed things.

Spicer: Yeah. The inability to predict computer…

Kayton: And that's where the abort guidance system wins, you see? Because it was synchronous.

Spicer: Yeah.

Kayton: Just completely synchronous.

Spicer: Right. And the old sort of navigation by starlight. It's immune to that as well, I guess.

Kayton: Well, the starlight wasn't exactly. The LEM had an optical tracker, but it was only for aligning the inertial system principally on the moon's surface. And the command module had a second scanning telescope also for aligning the inertial platform so that you knew what its orientation was when you went to make burns. But star-- those are the only star use were the scanning telescopes _______ on the command module; on the AOT, the Apollo Optical Telescope on the LEM.

Spicer: Can you give us a sense of the-- I imagine that the accuracy with which you could predict or you could put an object on the moon changed, say, from 1960 to 1970 due to

Kayton: I could give you an idea of the landing accuracy on earth when they came back, dropping from 200 miles to a mile. But I don't know what the landing accuracy on the moon was. I'm not sure it's easy to tell, because the moon surveying wasn't all that great.

END OF TAPE 2 / BEGINNING OF TAPE 3

Kayton: The Apollo 13 Movie did a superb job of capturing the feeling of the times and the urgency of the program, but they had one huge failing, that was no engineers. They had flight controllers and they had astronauts, and they omitted the engineers. They attributed the engineering to either the flight controllers or the astronauts, probably because they didn't want to introduce new characters. So, I thought that was...

Spicer: Didn't the engineers sort of -- weren't they the heroes, though, who figured out how to use duct tape?

Kayton: They were. They were. If you looked at the movie, those were the flight controllers and astronauts.

Spicer: Because I remember they were all trying to, with the scrubbers and trying to...

Kayton: Right.

Spicer: Anyway. Okay.

Kayton: Anyway. My recollection was there were no engineers in the movie, which...

Spicer: Of course pains you as an engineer.

Kayton: Pains me as an engineer. There were some other little -- there were some other minor -- when they take off, you see this moon and the spacecraft's heading right for the moon. Of course, if you did that, the moon would be 30 degrees ahead when you got there and you'd miss it by an immense amount. You should have shown the spacecraft going that way with the moon back here. It should have been about a 30 degree lead angle. But the movie...

Spicer: Hollywood.

Kayton: Hollywood. So anyway, that's a small aside.

Spicer: That's interesting.

Kayton: The fact that there were no engineers in the movie, sort of bugged me a little bit.

Spicer: Well, we're going to wrap up the talk about Apollo unless there was anything else you'd like to say.

Kayton: Fine. No.

Spicer: And move onto Shuttle or Skylab.

Kayton: Well, I didn't do much on Skylab, but I worked on the space lab in Europe. And that was a European-funded spacecraft. Originally was supposed to be a free flier. But the Europeans decided the environmental control systems would be out of their budget. So they decided then to pivot it out of the Space Shuttle -- well, actually, I worked on the Shuttle first. But let's talk about it. And then pivoted out of the Shuttle and put their experiments on the top so it would be far away from the vehicle. And then they decided even that was too expensive. So the space lab as built was the cylinder sitting inside the Space Shuttle with a tunnel going -- a rigid tunnel going into the Shuttle and using as much of the Shuttle facilities. And I was their chief engineer for a couple of years during the phase B, and I had just come off the Shuttle design at TRW, so I knew the Shuttle thoroughly. And I made every use of the Shuttle, the telemetry of the power and so on. The best decision I made was for the wrong reason. The question of computing, I had three computers. I had an experimental computer and I had a subsystem computer, and I had a switchable spare, which was nice because the experimenter guys could use the experimental computer. But I realized that -- and this is before PCs -- that experiment, some experimenters are going to want more computation than that. So, with each experiment station, I allowed a facility for a computer to connect to the experiment computer. I didn't know what it was going to be. And that was a smart idea without knowing that there were going to be PCs because the way the space lab really worked is all these experimenters brought their own PCs and plugged them in, and the experiment computer, instead of doing experiments, was just acting as a multiplexor to collect all the PC inputs and then turn it -- pass it on to the Space Shuttle, which would then telemeter it back to earth. So that was nice. And the subsystem computer worked okay. The subsystem computer handled the power and attitude control, and if one of the experimenters needed to control the attitude of the spacecraft and they allowed them to, well he could do it through the subsystem computer. So the subsystem computer, the idea of the subsystem computer, the experiment computer, and switchable spare worked great, and it allowed the addition later of PCs. Yeah. So that was space lab. And so it was used for, what, 20 years. It's retired now. It's retired as of '98 or something like that.

Spicer: Was it left in space?

Kayton: With the Shuttle. It stayed with the Shuttle.

Spicer: Oh, it got brought back down?

Kayton: Yeah, it'd go up with the Shuttle and it came down.

Spicer: Is it in the museum now?

Kayton: Don't know. I don't know where it is.

Spicer: Good to know.

Kayton: I have no idea where it is. I don't know if they built two of them or one of them. I don't remember.

Spicer: Tell us about...

Kayton: Shuttle movement, I was...

Spicer: Are you not involved with that?

Kayton: I was at TRW and TRW got a contract to do the electronics for the Shuttle. And I worked very closely with NASA, and it was one of my favorite projects. I really loved it. And I was the system engineer. It was somebody else who was chief engineer. And I did whatever I could to make that -- having just come from NASA's Apollo, I did everything I could to make Shuttle better. Now, one of the interesting stories -- actually, you're reminding me -- NASA says we should fly like the commercial aviators do. And they hired Pan American to work. There were two vehicle teams. There was a McDonnell team and the North American team. And they hired Pan American and TWA, one for each team, I forget, and the word we kept getting was, hey, we fly airplanes on Pan American or TWA. "We don't take any telemetry and we don't have any photography. You don't need all that stuff." And boy, I screamed and hollered, "You got to do it! What are you going to do if there's an accident? How will you decide whether you're going to fly again?" And we were called Shuttle. They called us Apollo fuddy-duddies or something like that. They had a name for us, the airplane, the Pan American and TWA, were, you know, you guys are stuck in Apollo and...

Spicer: Conservative?

Kayton: Yeah. You can't think out of the rule box of Apollo and you don't have any -- but boy, am I glad we did that and kept insisting on it. NASA went along, said you've got to have telemetry, and you've got to have photography. I mean, otherwise, you have an accident, what do you do?

Spicer: And when you say photography, can you explain that?

Kayton: All the launch photography.

Spicer: Oh, I see. Okay.

Kayton: All the launch...

Spicer: Video cameras?

Kayton: Cameras, yeah, photographing the liftoff. But, you know, we had I don't know how many points -- about 8,000 telemetry points on the Shuttle. There's about 8,000 different things being watched and downlinked, you know, as compared to, say, 200 on an airliner in their recorder. But in those days, they didn't even have that. In those days, the recorders were strips of smoke colored metal with 7 scratches on it, one for air speed and one for pitch. I forget what they used. They were scratched lines.

Spicer: On the metal band.

Kayton: Yeah, on the metal band. And people un-stripped the band, the metal band so it wouldn't burn in a fire. And then people would pour over it and trace all these lines across the band. And Shuttle had about 8,000 telemetry points, at least when I worked on it. It might be bigger now. And I thought that was utterly essential to do. And, yeah, I was an Apollo fuddy-duddy, you know, it had to be done, and I'm glad it was, because, you know, you have a Shuttle accident and you have those two tragic accidents, what do you do? How do prevent the next one? What happened?

Spicer: Yeah, and it's much more complex than an airliner by probably 100 times, maybe more.

Kayton: Well, they didn't appreciate it. I don't think the air -- and I don't know why NASA hired them in the first place. I don't know what the -- the point was to get the cost -- you know, there was a 100 dollar a pound -- people were talking about ridiculous numbers about how much it's going to cost to get things into space.

Spicer: Maybe there was a political desire. I know some people viewed the Shuttle as a making it as cheap to go up in space as a, you know, a really routine, daily kind of thing, which didn't turn out to be the case.

Kayton: Did not.

Spicer: Probably never really was if people were realistic about it. Space travel is so incredibly dangerous.

Kayton: It's dangerous, yes. And the crews knew that.

Spicer: Always will be.

Kayton: I mean, all the people, the crews that I worked with, and I worked with all the older astronauts. There were ones I've never met. But they now are retired. But they all understood that. It's a dangerous business. And they understood we're doing, they and we, the engineers and the flight people, were doing the best we could to make it as safe as possible and have all these redundant modes, alternate ways of doing things and making sure the parts were okay and they were going to have minimum chance of the failures of parts. Yeah.

Spicer: Tell us about the computers on the Shuttle.

Kayton: Shuttle had four, at one time five, IBM AP-101s. And my recollection was they were 64K computers when they started, and they're up to now about 256K, and they're redundant. They all load, they all collect the same data. And they compute output commands and then load [ph?]. And everything is fly-by-wire. You see, on mercury, the hand controllers had mechanical linkages to the valves. So, if you moved them a small amount, the valves would operate electrically. But if the electrical system failed, you moved it all the way to the edge, and then the mechanical linkage opened the valves and you could fly without any electricity. But starting in Gemini it was fly-by-wire. And you had to have some redundancy on board because if the electricity system failed, you're not going to be able to open those valves. So they would do connections and two sets of valves. And Shuttle had that, too. There were 16 attitude thrusters where you only needed 3 x 2. You only needed 3 axes x plus or minus. You only needed 6. And you had 16. So you had redundant paths and redundant electricity systems, and one system had to be turned off at the circuit breaker, at another system. And Shuttle took care of all this. It was the first fly-by-wire vehicle, the first vehicle to -- well, I don't know that I'd say that. Shuttle -- the Apollo lunar module was the first strapped down inertial system, but it wasn't redundant.

Spicer: Can you explain what strapped down means?

Kayton: Oh. Strap down, yeah, it means the gyros on the system are mounted directly on the body rather than on a gimbaled platform. The gimbals are very costly there. They require several motors and slip rings and wiring to them, and they increase -- you take a strap down package this big and put gimbals around it, and it gets that big and triples the weight probably. So, but there were advantages of going from Shuttle -- I'm probably getting a little tired, I'm sorry -- from the lunar module to the Shuttle. But the Shuttle had gimbaled platforms. They went back to gimbaled platforms because the crew, the lunar module was a slow rotating vehicle and could tolerate strap down systems. That's why it was the first to use them. But when you got to the Shuttle, the crew was able to roll and pitch the vehicle. If it was automatic, you might get away with strap down, but you had to go with a gimbaled system. I think they may now have -- they have now replaced them with strapped down laser gyros. I think those inertial systems have been replaced.

Spicer: Like ring laser gyros.

Kayton: With ring laser gyros. And it started with the tack [ph?] and landing system. It's now gone to GPS. There have been a number of at least navigation improvements, which I know most about, that have been made. And the cockpits are now all glass instead of having just three CRTs for status information, there's also CRTs for attitude and heading information.

Spicer: Right. Tell us about the -- I'm intrigued by the voting procedure on these computers, because I could see how there could be ties, for example, or if one of the computers is down, what happens? Could you explain this a bit?

Kayton: Yeah. There was a lot of discussion of that, most of which I don't remember how it came out. But when all four computers are running, you take the lower middle or the upper middle. That's the usual vote -- each actuator votes separately. And so...

Spicer: It sends a numeric value, you mean? Like a...

Kayton: Yeah. Say the Shuttle computers are telling an _________ to move up 10° and you get 10°, 10.1°, 10.2 and 10.3, you'll move 10.1 or 10.2 because you'll take either the upper middle or the lower middle of the values. And there are provisions that when the voting difference are too high to let the crew know, because the crew may then want to shut down a computer. If a computer is shut down, you then take the middle value. And if two computers are shut down, I think you're going to do a lot of manual flying. I don't remember. That's a two failure situation. But you still can fly. But then you've got to decide which of the two machines is right, and if a fault develops, you'll have to depend on ground tracking for your own sense of how the airplane's rotating. You'll switch from one to the other and see which one gives you better rolling or pitching performance. You may find you can tell by just changing, just switching back and forth which computer works. There were five at one time. The question of diverse programming came up when I was still on the Shuttle. That was about the end of my tour on the Shuttle was the question of diverse programming because all four computers are identically programmed and heavily interrupted into complex program, and everybody understood that if there was a software fault, it would be common to everybody, and you could wipe the whole Shuttle out on a software fault. Oh, yeah. So NASA agreed to put a 5th computer in, which was manually switched in place of the others. It wasn't part of the voting system. A program by a wholly different company. I think it was Logicon. And be able to fly with a different machine. It wasn't even an AP-101. It was a different machine, program. And that didn't last. I don't know, I wasn't on the program at that point to know what happened. But that, it may or may not have flown. And in any case, it disappeared, and the program is back to four now.

Spicer: So, this was a completely differently architected and built computer that met the same functional spec but by a different company, different parts maybe?

Kayton: Yes. Exactly that.

Spicer: Oh, how interesting.

Kayton: Just exactly as you say. And I don't even know if it was ever installed in any Shuttles.

Spicer: That's a pretty neat idea.

Kayton: Yeah. But that was at the end of my tour. That was the issue we were worrying about, and what about, what do you do with a common -- with all this voting and all this clever, you know, so switching back and forth -- suppose there's an embedded fault. And it's common, and it's never been discovered during the simulations, and you suddenly find it appears in flight. Now, in coasting flight, what you would do is just put everything into stand by. You would reload all the computers, and you'd start over again. But suppose it happens during powered descent and you're, this isn't _________. This is Shuttle, you're coasting down to the airport and trying to find the airport. All of a sudden four computers show some fault for some strange reason.

Spicer: That brings me to my next question, which is how much of a Shuttle flight, or what phases of a Shuttle flight can be flown without a computer, if any?

Kayton: Everything in orbit.

Spicer: Everything once it's in orbit?

Kayton: Yeah, once you're in orbit.

Spicer: Everything can be done?

Kayton: Yeah, everything can be done manually.

Spicer: Manually.

Kayton: You're back to concentric flight plan rendezvous, which you'd like to do computer burns based on the rendezvous radar but you have the options of using tabular angle measurements and firing along the line of sight, which isn't the efficient way, but you can get there. You can de-orbit based on time and _________ and you can come home. The things you can't do are boost into orbit and descend to your landing site. Those are the two things you can't do without the computer.

Spicer: Right. So, even with ground control or the actual launch phase is just too, controlling the engines is too complex to manually...

Kayton: Yes, manually. I don't know how much -- I know on Apollo, we found they could not descend and land. I don't know if anybody did any launch/abort studies doing it purely manually. But, remember, the computer's got to work. I mean, if you're hand controlling the thrust and the direction that's all going through the computer anyway.

Spicer: Oh, okay.

Kayton: There's no direct connection. It's like an A-320. There's no direct connection between -- and Shuttle, you know, Gemini, Apollo, Shuttle are the first fly-by-wire vehicles.

Spicer: So when we talk about a Shuttle computer failure, we're really talking about not the fly-by-wire system, obviously, which has to always function, but the guidance and navigation?

Kayton: Well, a computer failure could wipe everything out.

Spicer: Could wipe out everything?

Kayton: Yeah. Everything's intermixed. See, that's another thing. You keep raising interesting issues. Shuttle has four identical computers and they're all central. They have flight control, rendezvous, landing, ascent, check-out, everything's in there. Okay, so you make a change in anything, you've got to re-verify the whole business. And anything you put in there might screw up everything. Today's next generation is going to be separate navigation computer, a flight control computer, a telemetry computer interconnected, reason being two-fold: A. You could check them out separately. You don't have to verify everything when you make one change. And if you lose one, you don't lose everything. So if you have three navigation computers and four flight control computers and two telemetry computers, which is the kind of likely you'll do, then you're very much protected. In Apollo, we talked about that in the beginning, but the cost of computers in weight was so high. I'm sorry, I'm talking Shuttle. The Apollo was inconceivable. In Shuttle days, even, the cost was so high there was no way of having specialized computers for different purposes. It had to be a central computer, had to have all these interrupts, and therefore, anything could disable everything. And that's scary. In today's environment, that will not happen.

Spicer: Right. The telemetry is also handled by this computer?

Kayton: Oh, yeah, the Shuttle handles, it does everything. It operates the displays, it reads the keyboard. It telemeters, it reads the radars, it reads the tack ends for landing. It operates the gimbal systems on the engines. It operates the engine firings on and off. It operates the reaction control jets for orientation. It does everything. And this in a high order language on top of that.

Spicer: So, space flight is inconceivable without computers, basically.

Kayton: Oh, yeah, yeah. You couldn't. I mean, [Burt] Rutan is doing it, but it's not exactly space flight. He's just going up and hovering and coming down again.

Spicer: And he has no computers?

Kayton: No. Well, I don't know. I wouldn't say. He probably has computers. I don't know what extent he's got computers. But they're not complex arrays of computers if he's got one in there.

Spicer: Right. So, why don't you tell us a little bit about the future. Shuttle, did you kind of leave the field after Shuttle or what else did you...

Kayton: Yeah, I left the field after Shuttle and I got mostly involved in automobile electronics after that, which is much of my interest still right now.

Spicer: For professionally or as a hobby?

Kayton: Oh, professionally. Yeah. Automobile air bags, engine controllers, inter-computer links.

Spicer: Okay. Well, it's good to know someone from NASA's designing my brake systems. That's good.

Kayton: Yeah. Well, electronic, all electric brakes I haven't gotten involved in yet, and I sure would like to. And, you know, the future of cars is going to be drive by wire with a hand control or brake by wire where you touch the brake pedal and you don't compress pads but you actually, you send an electric signal out and throttle by wire. But all of those things are going to require heavy redundancy imitating the -- going back to an imitation of the Shuttle on an automobile.

Spicer: I don't know if the Airbuses do this, but it's certainly possible but probably not desirable that you can send all the computer information on a single fiber optic cable.

Kayton: I think they're redundant. They don't use fiber optics.

Spicer: That's not a good....

Kayton: They don't use fiber optics. They use copper.

Spicer: Wiring harnesses.

Kayton: But they send them a redundant -- Shuttle has redundant paths, four paths for everything. So everything is traveling on four paths through four computers. All the sensors are in quad -- I did a study I did personally with a fellow whose name I still remember, Bill Klein, who was the programmer from the reliability department, on the economic value of redundancy, that is, calculating the cost of the extra equipment and the probability reduction in the missions, and calculating what effect these have in a very elaborate model. This was when I was at TRW. And the numbers are about the same. The numbers on the actual vehicle are just about right. Three inertial systems, four computers, I forget, four flight control sensors, and so on. And the numbers came out quite accurate. And we didn't force it that way, we just ran the study and whatever came out we published it.

Spicer: I have an analogy, which with the IBM PC, which initially IBM had no parity bit on their memory, their random access memory, because one of their studies showed that the failure rate was actually increased by having that extra IC for parity.

Kayton: The extra bit.

Spicer: Chip. Is that the same kind of argument that you would have gone through in this case?

Kayton: Yeah.

Spicer: So the redundant computers, while they do give redundancy, are also adding another failure mode to the whole system?

Kayton: Yes. Yeah, and at the same token, as the reliability increases, as you have more parallel paths, you reduce the risk of vehicle loss, because we had a, I don't remember, like half a billion dollar charge when all the channels went out and you lost the vehicle or and at a charge for killing astronauts was in there as well. No charge for bad publicity. But it was a nice study. And I still have a copy of it some place, and it was a very nice study. And the interesting thing is it came out pretty well like the actual Shuttle, pretty well parallel. And as far as the future, as I mentioned, I think the distributed computing world is going to be the way, the next Shuttle. The next Shuttle, the next...

Spicer: Mission to the moon?

Kayton: Replacement Shuttle and mission to the moon, both are going to look like, they're going to both have redundant distributed redundant computers. And that's a challenge by itself to have all that stuff connected and have the switching right and have the right switching devices to, so if the switches themselves don't cause reliability problems.

Spicer: This is not necessarily computer related, but what are we going to do on the moon this time?

Kayton: My favorite subject is a backside observatory. To put up a multi-bandwidth backside observatory that is shielded from all the noise on earth so you can get a nice quiet environment and look out on everything from radio frequency on up to gamma ray frequencies. The big problems are operations back there and getting the data back, which I propose using a Lagrangian satellite for. And I propose some unmanned landings with the components, and have the crew come down and assemble everything. You know they might be there for a week to assemble everything. And have this thing grow. And then you add more sensors five years later and have another crew land.

Spicer: That's really interesting.

Kayton: Of course you need a communications station. You need a power station and then you need the observatory. The observatory doesn't stand alone. It needs the support of a communications station and then I even recommend the possibility if you don't like the Lagrangian satellites, and I can't tell which is better, you might want to run a cable around the moon through a relay station on the front side. That means a cable laying robot that would roll cable out, fiber optics, most surely, to roll the cable around to the front side of the moon.

Spicer: Sort of replaying what happened on earth with telegraph cables.

Kayton: Yeah, I guess.

Spicer: We lay the cables…

Kayton: …with the big rolls.

Spicer: And then came satellites and so on. Or maybe small relay stations every fifty miles or so, like microwave lengths.

Kayton: Yeah you might have microwave stations. That's a possibility too. I mention that in my lectures.

Spicer: Power problems.

Kayton: I published an article on this in the IEEE Aerospace and Electronic Journal I think in January of this year. I think it was January, it may have been February of this year and I've given a bunch of lectures on it.

Spicer: That's a neat idea.

Kayton: Yeah, microwave relays are one, but I think the Lagrangian satellite in the end is the one that's going to win out.

Spicer: And Lagrangian just refers to the orbit it has or the…?

Kayton: Lagrangian orbit is as far from the moon as it is from earth. It's a satellite that follows the moon around at the same distance from the earth. And any satellite that is put there is stationary. You have to station keep a little bit or you get pertubations, but it's a stationary point. And that will allow a view of the back... of about two-thirds of the backside. Not the whole backside.

Spicer: Is that useful for scientific, besides the radio observatory, just to map the moon for example.

Kayton: Well I suppose. I don't know. I haven't…

Spicer: The dark side is like a cartographic black hole…

Kayton: The backside.

Spicer: The backside.

Kayton: It's light half the time.

Spicer: Yes, I shouldn't call it the dark side <laughs>. But is there a good scientific argument for mapping the dark side?

Kayton: I don't know enough about that. I think the mapping is done from satellites these days. You put a polar satellite up and then you put an equatorial satellite up and you let them take lots of pictures and the photogrammetry types, the ones who look for Russian air bases and Iranian nuclear stuff. They know how to make maps from satellite pictures.

Spicer: Little pixels.

Kayton: There's a whole industry that understands that and I think JPL is the big player in the planetary mapping business. I doubt that you'd need a backside observatory or a Lagrangian satellite to map the back. Just the simple satellite would do that. But it would be of tremendous scientific benefit for getting longer range into the distance of the universe without the contamination of earth noise.

Spicer: Of all the noise humans make <laughs>.

Kayton: Yes. Radios and televisions and everything else.

Spicer: Is there anything else you want to say to conclude?

Kayton: No, but I was going to leave you that material.

Spicer: Well thanks so much for stopping by. I really appreciated it.

Kayton: My pleasure.

END OF INTERVIEW

