The Apollo Guidance Computer
A Users View

David Scott *Astronaut for the Gemini 8, Apollo 9, and Apollo 15 missions.*

In 1963 when NASA was conducting the selection of the third group of astronauts for the U.S. space program, I had just received a graduate degree at MIT and finished test pilots school. My interests and the program's need for a user to interact with the design of the guidance computer at the MIT Instrumentation Lab was a good fit. I was part of those discussions whether to use analog or digital controls that Eldon described.

The MIT Interface

When I was studying at MIT, the ability to rendezvous in space was an issue for debate. It wasn't clear whether it was possible to develop the mathematics and speed of computation necessary to bring two vehicles together at a precise point in space and time—a critical issue for the Apollo missions successful landing on the moon and return to Earth. Between 1963 and 1969, with the flight of Apollo 9 this was accomplished. I stayed in the spacecraft while Rusty Schweickart and Jim McDivitt got in the lunar module and went out about 60 miles away. The computer behaved flawlessly during our first successful rendezvous in space.

Another assignment for Apollo 9 was to take the first infra-red photographs of the Earth from space. To do this, a large rack of four cameras was mounted on the spacecraft. Since they were fixed to the spacecraft, the vehicle itself had to track a perfect orbit such that the cameras were precisely vertical with respect to the surface that they were photographing. During simulations it was determined that manual orbit procedures would be inaccurate. We were at a loss. About two weeks before the flight I called up MIT and asked if they could program the computer to give the vehicle a satisfactory orbit rate. They answered, "Of course, which way do you want to go and how fast?". In a matter of a couple of days we had a program and a simulator that automatically drove a spacecraft at perfect orbit rate. We got into flight with very little chance to practice or verify, but we put on the cameras and the results were perfect.

Potential Computer Failure

During the development process we ran many simulations of in-flight computer operations with particular concern for in-flight failure. But in the 10 years that I spent in the program there was never a real computer failure. Yet, people often wonder what a computer failure would have meant on a mis-

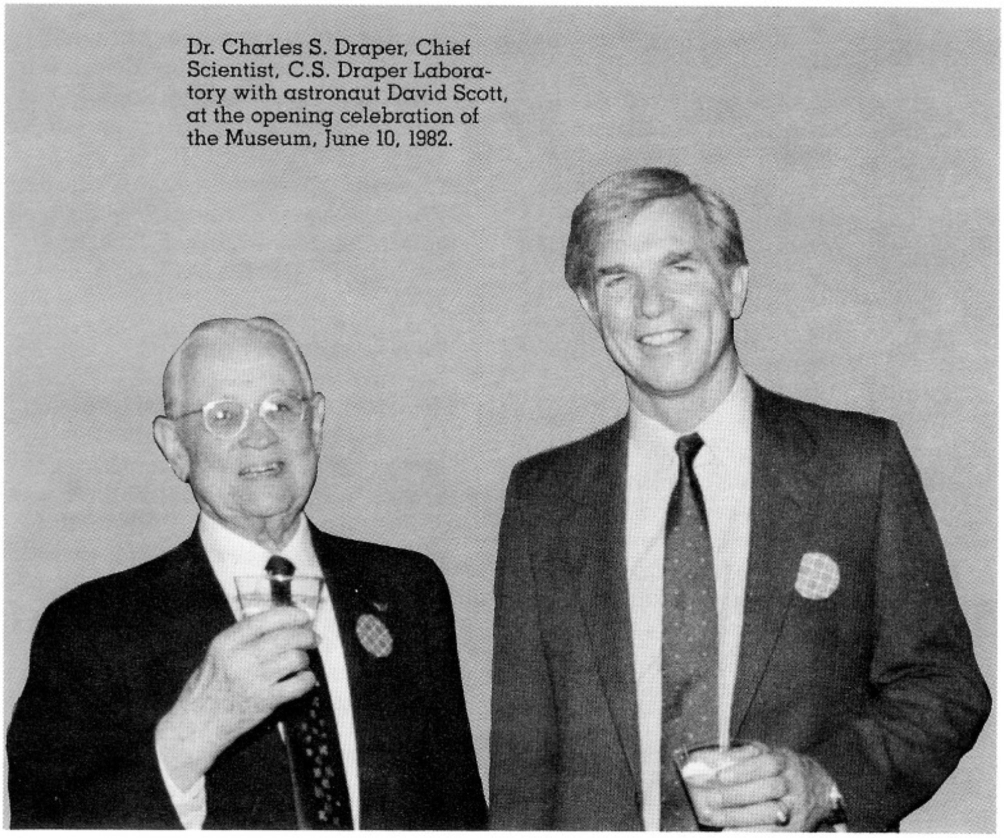
sion. It would have depended on the situation and the manner in which the computer failed. We probably would not have expired, but there were some parts of the mission in which a computer failure would have been especially compromising. Navigation was not necessarily time critical but the lunar landing was very time critical. You could have a situation during a lunar landing in which, if the computer failed, the engine would be driven into the ground. Unless the astronaut could react quickly enough to stop it, the Lunar Module could have been flung on its side. Chances are that the astronaut could prevent such an event by switching to manual control of the vehicle. It must be remembered that the computer had been designed to be as reliable as possible and the astronauts had a great amount of confidence in the machine.

And Problems of Success

We had a backup called the entry monitor system, which had a graphic display based on the accelerometers in the spacecraft. With this display the vehicle could be flown manually using pre-drawn curves to be followed for attitude, g-loading, and velocity. It was reassuring to know that we were still able to return to Earth even if the Apollo Guidance Computer failed. During reentry there was a scroll in the entry monitor system and we could see the computer tracking the predetermined curves all the way to the landing site. As our skills and the computer programs improved over the years of the Apollo program, we came down closer and closer to the carrier. Finally, by the last Apollo mission they didn't park the carrier on the landing point.

Excerpted by Ben Goldberg from remarks after Eldon Hall's Lecture, June 10, 1982.

The Apollo 9 Crew, (from left) Dave Scott, Command Module Pilot; Jim McDivitt, Commander; Rusty Schweickart, Lunar Module Pilot. Apollo 9 was launched on March 3, 1969. The first separation and rendezvous of the Lunar and Command Modules was carried out in Earth Orbit on this flight.



Dr. Charles S. Draper, Chief Scientist, C.S. Draper Laboratory with astronaut David Scott, at the opening celebration of the Museum, June 10, 1982.

"Before the missile and Apollo guidance programs, the problem of airplanes attacking ships at sea was a difficult one, so I began to do the ballistics analysis myself, plotting on a sheet with a pencil and a slide rule. This analysis worked well enough so that ships were able to defend themselves against air attacks. When the time came to develop the Polaris and Apollo programs, our attitude was much the same: we couldn't afford any failures, so we didn't have any."

Dr. Draper at the lecture on the design of the Apollo Guidance Computer.

Transcript of David Scott's remarks.

If you look today at what is available on the market and compare it with what we had to work with, you can see how times move fast and progress is absolutely fantastic. I thought I would relate to you, at Eldons suggestion, some of the things that we did as users, back in the old days, and some of the problems and challenges that we had, and some of the fun that we had.

I got my start in this business at MIT. I was a young pilot in the air force and always wanted to be e test pilot. They told me that the best way to do that was to get a graduate degree, so I looked around, and had heard about this school in Massachusetts, applied for it and was fortunate enough to be selected. I started my matriculation under the team guided by Doc Draper. I remember early on there was a lecture one night, given by a fellow from Germany named Werner Von Braun. A friend of mine and I went to listen to this and he was talking about rocket ships. I was an airplane driver and I remember when they announced the first Mercury astronauts and I thought, "monkeys". Anyway, we went to this lecture by Werner Von Braun and he had pictures of these big rocket ships and he said that we were going to send men to the moon on these things. Sooner or later I realized that Werner's philosophy was correct and he certainly was right.

One of the reasons that we were able to do all that we did during the Apollo program was that we had a terrific computer. After I left MIT , I went out to the test pilots school. I spent a couple of years there doing what I thought I really wanted to do until I realized that I got pretty interested while, I was here in school, in space as opposed to aeronautics. About 1963 NASA the selection of the third group of astronauts. I thought that since I enjoyed inertial guidance among the other things that I learned at MIT and I thought that I'd give it a crack. I was selected in October, 1963. I went to NASA as a captain, fresh out of test pilots school and fresh out of MIT. There were a total of 30 of us and they looked around to see who could represent the astronaut office in various disciplines with some background. Of course I was fortunate enough to have spent a couple of years working with people who ultimately built the Apollo Guidance system. Dick Batten was my thesis advisor. The first course I ever had that I knew what an inertial guidance system was, was taught by Walt Whitley and Doc Draper was head of the instrumentation lab where I did my thesis. When I was offered the opportunity to follow for the crew's guidance and navigation, I really jumped at that. I started coming back to MIT to monitor that for NASA in Houston, relative to the user. Being an astronaut, we helped in the design configuration from the users viewpoint. It was quite an educational process because one has to understand what goes on inside to be able to assist in the design outside. I spent many nights up on a roof in

Cambridge looking at the stars and working with a sexton, telescope, and computer. It all looks pretty simple and straightfoward now, but I reflect back on the crudeness in those early days and how little we knew about what we wanted to do. Many people knew, for instance the people who had invented the AGC, but to try to configure it and make it as useful as it eventually became was a remarkable achievement. In those days, 1964-65, there was a concept we called in-flight maintenance throughout the whole spacecraft. The idea was that if something failed it could be replaced in flight. They even established a course at MIT for 6 months to help teach people how to change components in flight. We never did that because it was tought enough to learn how to operate the first line systems much less change them. Late in the program we did have some things leftover in the early design in the spacecraft itself which reflected in-flight maintenance. This is because no one ever got around to changing that. This original design was quite different from what we ultimately ended up with. Another interesting discussion was on the type of clock to use. In those days everybody had analog clocks and watches. Nobody really heard of a digital clock. A computer naturally expresses its time digitally. It was quite a consideration on what kind of clocks to have. I think the influence of the digital computer ultimately showed the advantages, especially in the business of traveling in space, of a digital clock. The initial Apollo design design had three analog clocks on the panel and ultimately ended up with digital clocks. In fact, the whole control center in Houston ended up with digital clocks. We also had some challenges in the capability and capacity of the computer. This is in the days before anybody flew and the question was how may words you could get into it and what was the configuration. Core rope memory was something that precluded changes close to launch. At first everybody said "my goodness, we won't be able to change the day before the launch". In the end everybody said "thank goodness we change change anything the day before the launch". Everytime one little routine was changed, everything else had to be verified. Probably one of the best decisions that was made was to freeze it early and the programmers had to sit down and decide what they wanted to do. There were also some interesting limitations. We originally had 24,000 words and stretched it to 36,000 words, and that was a major effort. We also had this panel that was operated by the crew and great debates occured relating to what it should look like. How do you talk to a computer? When I went to school we had a language called MAC, which, I guess, was the predecessor to FORTRAN and many people did machine language. How do you take a pilot, put him a space ship, and have him talk to a computer? That is not easy in real time. Somebody came up with the verb-noun concept, but I'm surprised that it is not utilized in other computers today. It was very simple for us to operate with a series of two-digit numbers representing verbs and another series of two-digit numbers representing nouns. It was so simple and straightfoward that even pilots could learn how to use it. We had some interesting words. Our initialization program was 00. We abbreviated the identification the identification program with a P. If you ever had a problem you went back to 00, which we ultimately called P00. So, if you ever had a problem you went to P00, and reinitialized. We also developed the digital auto-pilot which was the DAP. Many of the guys had trouble touching all these keys. I liked it, I thought it was fun to get in there and see how fast you could go. Some guys could never really get a feel for the key punching and they wanted to reduce the number of keystrokes required to get information. At one point, we tried to design a semiautomatic program, or a minimum keystroke program. That became known as MINKEY. Some people liked MINKEY and some people didn't. It limited your capability but it was much easier to work. As we went through the development process and put the computer into operation, we had simulators in quite a few places. It was, with its computational capability, a joy to operate. It was just a tremendous machine. You could do alot with it and it was so reliable that we never had a backup. We never had a failure and I think that is a remarkable achievement. We had some gliches here and there, but, to my knowledge, in the 10 years that I spent with it there was never a real computer failure. We practiced alot of computer failures and simulated many failures, but we never really saw one. As I went through my career I spent a couple of years in the early design and development phases, and then I went off and flew Gemini 8 with Neil Armstrong. We had an interesting computational exercise ourselves. Another company had a computer in there and I remember that we had, for the first time, no reentry program. We had to read a tape in to program it. Neil and I had this little problem and had to come down early. In those days of Gemini there was a great competition to see who could land closest to the carrier with a computational capability on board. They were getting down to 12 miles, 9 miles, 6 miles, 3 miles, and it was really a great competition among the crews. Neil and I still hold the record for landing furthest from the carrier. We only missed it by 6,000 miles. Some people say it was the tape. Some people say it was the parameters that we loaded into it. Actually, it was some other problems. Another capability we had in the Apollo computer, moving past Gemini to my second flight, Apollo 9, was the digital auto pilot utlization capabilities. Apollo 9 was an Earth Orbital checkout for the entire Apollo configuration, all of the spacecraft, all the computers. It was a 10 day flight. The first 5 days were jam-packed with operational activities. We did such things as the lifeboat with the lunar module, which was subsequently used in Apollo 13. It was a demonstration of having the lunar module, which was the lander, and the command and service module, which was the orbital vehical, together and utilize the engine on the lander to actually get back from the moon, which Apollo 13 had to do. The program was written prior to Apollo 9 and we demonstrated it in flight. It was an interesting excerise. I was the command module pilot, and I was in the spacecraft that kept one person, while the other two guys would go down to the moon, although in Apollo 9 it didn't go to the moon. As my cohorts, Jim McDivett and Rusty Schweiker, performed the exercise in the lunar module of lighting the engines, I figured out a little program in the command modules, with the help of my MIT buddies, to monitor their burn in the reverse direction. I could then tell with my computer how their burn was going. Of course, I had the platform and accelerometers and everything, and it was just a matter of reversing a couple of signs and I could have given them, had they lost their LEM guidance computer, the cutoff instructions and everything else on board. That's not a big thing but for a user it's a big thing to be able to have the flexability to do something like that. Nobody had ever planned that and I found that when I was alone in the command module it was nice to have something to do. In this particular flight another thing we did was to burn the big engine on the service module which is a large rocket engine and combination. We had to actually light it and guide it through a manually controlled trajectory change. By that I mean that we actually programmed the computer to give us the parameters in a display format such that during a period of fixed time with the engine on, we would steer the vehical by hand. This was one of the fun things that I got to do. I actually got to hold the hand controller and, with the needles on the display panels being driven by the computer, fly the spaceship in space with the engine on for three or four minutes, which is a long time. That is a pretty exciting thing. All through a digital auto-pilot. One of the early fly-by-wire. Airplanes do it all the time now. That was an important demonstration of a new capability. I remember when we were having a meeting in Houston one time , and all the people from the instrumentation lab came and presented for the first time the idea of a digital auto-pilot. Everybody said, "You can't build a digital auto-pilot, why don't you guys quit wasting time. Go back to MIT and think". But it worked and now digital auto-pilot. Another thing we developed in those days was a rondezvous capability. When I was going to school, there was a question about our ability to rondezvous in space. Was it possible to develop the mathematics to bring two vehicles together at a precise point in space and time. Alot of people did alot of work. Slowly it evolved that we were able to do it, and now only that but we were able to put it in a computer in the space vehicle.

In Apollo 9, we did the first Apollo rondezvous. Rusty and Jim got in the lunar module and separated from myself in the command module. They went out about 60 miles and then came back in a rondezvous. Today, after all the Apollo work and everything, nobody thinks that is a big deal because we've done it so much, but at that time it was very interesting because they didn't have a heat shield. Had they not returned for the rondezvous, they would have had no way to get home. There actually was a way home but it wasn't a very good way. They could come down but even that little exercise was exciting. We didn't have everything that we wanted in the Apollo days. People used to think that we did, but we didn't. For instance, the command and service module, where I was, did not have a radar. There was no way you could actually measure range and range rate. We used to think that it was essential for a rondezvous. The lunar module had the radar. The command module did, however, have the computational capability to perform the rondezvous, but we believed that without direct range information the computation wouldn't converge. So Rusty and Jim went out, and part of the rondezvous was at night, and lo and behold, the light on the LEM, which I was supposed to watch through the sexton to monitor them, failed. They went into the dark side and that was the last that I saw of them for about 20 minutes. That gets to be rather exciting, especially when you are never really sure that the engine burned right and the attitude was right and it burned long enough, etc. I remember how exciting it was when they came into sunlight and I had them right dead center in the sexton. It was a combination of the two computers in which the computer in the lunar module calculated the burn and read out the residuals, and Rusty and Jim read out the residuals to me and I entered the burn parameters into my computer and I told my computer to point the sexton where they would be when they came into sunlight. All that got done absolutely perfectly. It was a pretty amazing operation. Another thing we had on that flight, which really wasn't associated with the computer was a little device we called the diastimeter, the diameter measuring optical device, through which we would look in specific increments of time. It would measure the size of the object and we could calculate range. The golfers used that to see how far the pin is. I carried that on Apollo 9, which alot of people used to call the disaster vehicle. I would have been able to put the range in and actually get some directly measured information. Alot of that ultimately evolved into an optical type rondezvous. Our worries in the early days about not having directly measured radar disappeared. As a matter of fact, I then got to fly Apollo 15, and we had done the rondezvous so many times that by my last flight, you could actually use a watch and a rate of angle change and piece of paper and do a rondezvous. It becomes very straight foward as long as you don't have too many uncertainties or a failure of some sort. It took me back to the days of the early sixties when people wondered if we could do one, and twelve years later we could do it in the back of an envelope. I thing that was made possible because we had a good computational capability in between. All the manual techniques really evolved from the computational capability of the computer. We followed the computer and by doing that we learned what the computer already knew in its trajectory analysis in a physical sense. Another thing that happened back in the Apollo 9 days was an event at MIT called Black Friday. Everybody conversed on the instrumentation lab and started taking programs out of the computer because there just wasn't enough memory. They took out some programs that were absolutely not supposed to be violated. But, as it turned out, the judgements were right and people would work around it and we'd figure out some other way to do it. At the time in the evolution of the ultimate capability of the computer, sometimes you just don't think that you're going to get there. I can remember times that we thought that the computer won't work, not enough memory, memory cycle time isn't fast enough, can't do this, can't do that, etc. It seems unbelievabe that we were able to do all that we did with that old stuff. After I got through with Apollo 9, I went on and spent some time as a backup crew member for Apollo 12. I then got into Apollo 15 which was the fourth lunar landing in 1971. By that time the capability had really matured, people understood it, and we were able to do alot more than even conceived of in the beginning. The lunar landing itself could have been done automatically and many times people ask me about that. Could it have been accomplished automatically through the LEM guidance computer? Nobody ever did it. We all felt that when you get that point and you are ging to land on the moon, you have to have your hands on the stick. I like computers and I believe in computers, but it aint going to land me on the moon. I'm going to do that. If something gets screwed up then it is going to me, it isn't going to be the computer. Actually, my thinking at the time was that if a problem did occur it was so time critical that you wouldn't have time to take corrective action, so you stay ahead of that problem by flying it manually. You are probably fooling yourself because you are still going through the computer. The stick that you move goes through the computer to fire the thrusters, which is not too different from the computer doing that itself. You feel different, though. The fact that the LEM guidance computer could land the LEM automatically indicated that a tremendous payload could be sent if the astronauts were removed. Anyway, we did our landing, and as this system evolved, we got more and more capability we had a switch that we put in. Instead of trying to descend to the lunar surface by some visual display and coordination of a throttle, we put a switch in the computer and everytime you flicked the switch you get a one foot per second change. This was a really nice way to land. Coming down at ten you go "click click,click" and you are coming down at 9,8,7, etc. and you would probably hear on earth the lunar module pilot calling out these descent rates, altitude, altitude and altitude rates. It sounded like the guy who was flying it was really precise with that throttle. Well, he was. He had a computer there doing it for him.

I remember one consideration that got alot attention at MIT and Houston. This was how to simplify the command for the computer to do the next step. We developed a button called the proceed button, PRO. Everybody takes that for granted now, but you should have seen the iterations we went through to get set this button, which is one button to push to have something happen. Alot if people were afraid of having no confirmation button. One just pushes proceed and things happen. We worked through that, although I remember that everybody in the lunar module during the landing had to think very carefully about which button they pushed. There ther threee buttons which you could push, and had to push in sequence. THere was a proceed button for the computer, an engine shutdown button which turned off the system, and an abort button which seperated the ascent stage from the descent stage and aborted you. All threee buttons were in the same proximity. One of them was a black background with a probe in it, another was blue, and the other one was red. But they were all the same size, and you really had to think about that coming down to the landing. When you got down you had to hit the proceed button to put the computer to sleep for a while. When the probes on the bottom of the landing gear touched the lunar surface you received a signal in the cockpit telling you that you were 10 feet from the ground. You had to shut the engine down because, on our flight in particular, we had an extended engine bell and if you settled on the lunar surface with the rocket engine running, you'd blow the bell out due to the compression. As soon as you received the signal you had to press the button to shut the engine down. You didn't want to push the abort button, however, because then you would never land. It was a very tricky situation. The human factor considerations came into play, but as I look back on it, I think we probably got away with one there because nobody ever hit the wrong buttons.

In summary, the Apollo guidance computer/lunar module guidance computer was a terrific system. It had alot of capability, alot of user input, and I don't know what the people who actually built the computers thought about us users, but we thought that it was pretty remarkable that all this could be done. One thing that I was terrific was when was on Apollo 9, about two weeks before flight, we had this big rack of four cameras that we wanted to point directly at the Earth and take the first real IR pictures that anybody took. There was different film in each of the four cameras. You had to point directly at the Earth, and as you were going over the Earth you had to track the vertical very precisely. In the simulators we found out that we could do fair, but not really as good as the principle investigators wanted. I remember that about two weeks before flight we called up the folks at MIT and asked if we could do a little orb-rate with the computer driving the spacecraft. They answered "Of course, which way do you want to go and how fast?". In a matter of a couple of days we had a program and a simulator that automatically drove a spacecraft at perfect orbit rate. We got into flight with very little chance to practice or verify, but we put on the cameras and it was perfect, you could not manually fly it that well. It did a very good job getting pictures.

Q. What sort of commands could you issue and what sort of functions?

A. The language that language that was developed for the user was a verb-noun language. Two digits would be a verb, for instance display the coordinates of, and two more digits would be a noun, for example velocity. So if you pushed VERB 26, NOUN 34, you would get a display of the three components of velocity. You could position the spacecraft at some orientation, attitude. You would load that in by doing a verb then a noun, load your coordinates of your position and you attitude, push PROCEED and it would automatically move the spacecraft to that orientation. With a combination of verbs and nouns we could display, manuever, we could turn the engine on and off, we could navigate and by the end of the program, we were using 50 or 60 words. For each flight people thought of more things to do.

Q. Are these programs basically built into the wire rope memory or were they programs using verbs and nouns.

A. Both. THe programs were actually written into the rope memory but addressing the programs and obtaining information and commanding the programs, the operational system, was really the VERB/NOUN system.

Q. What would a computer failure have meant on a mission?

A. It would depend on the situation and the manner in which the computer failed , and the point at which we were in the mission. Whether or not we would have expired had the computer failed, probably not. I say probably because some parts of the mission were very dynamic and some parts were static. There were benign situations where a computer failure wouldn't hurt you. Navigation was not necessarily time critical. The lunar landing was very time critical. You could have a situation in a lunar landing in which, if the compter failed, the engine was driven to the stops. There is a vertical rocket engine that gimbles and tilts, and if the computer were to drive it full to one direction, you're finished unless you can catch it. You probably could have caught it. Some were some breakouts in the hand controller that would have enabled you to catch it. Then again, the computer was designed to be reliable with high reliability parts, the whole concept was total reliability. You sure had alot of confidence in something like that after a while.

Q. What would have happened if the computer had failed during Apollo 13?

A. There was a backup system. The lunar module had what they call an abort guidance system which was a much smaller computer and much less capable. I think it would have depended on how well that less capable backup system would have worked. Theoretically, they probably could have done the job to manually linkage with the pilot flying it. I think it would have been very marginal. Apollo 13 was marginal all the way anyway. They were hanging on the very edge about every minute of the way. I would not like to have tried it anyway, but without an Apollo guidance computer I think it wouldn't have been a good think to try. That would have been what we call a double failure. The whole Apollo program was designed so that no single point failure could get you. Failures in series, depending on what they were, usually could be compensated for in one way or another by a backup system. Two major failures like that and total loss of the command and service module and lunar module computers probably would have been compromising.

The last time that I hit a proceed button was on August 7, 1971, just before reentry. I had been through an Apollo reentry before but not from the moon. When you come back from the moon you really have to hit the corridor. If you have a basketball and a baseball 14 feet apart, where the baseball represents the Moon and the basketball represents the Earth and you take a piece of paper edgeways, the thinness of the piece of paper would be the corridor that you would have to hit when you come back. That's only position. You have to hit it with the proper velocity, too. You have to have a good computer, and when you are approaching the reentry corridor you are thinking about that because you only have one chance. We had a bsckup system that we called the entry monitor system, which was a graphic display based on other accelerometers in the spacecraft. It was a nice display and you could fly it manually and there were some pre-drawn curves that you fly to relative to attitude, g-loading, and velocity. You always think about that one because it can get you down if the Apollo Guidance computer fails. In my guidance and navigation role in the early days I spent alot time on that one, too. I remember during the reentry saying "Well, here it goes". I pushed the proceed button and it was perfect all the way down. There was a scroll in the entry monitor system and it tracked the predetermined curves all the way in perfectly. As a result we came pretty close to the carrier. As a matter of fact, by the end of the Apollo days, they used to not park the carrier on the landing point.