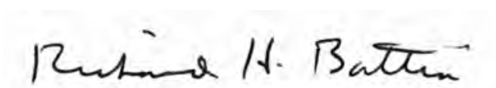

RICHARD H. BATTIN

1925–2014

Elected in 1974

"Contributions to the technology for control, navigation, and guidance for Apollo missions."

BY DONALD C. FRASER

Born in Atlantic City, New Jersey, RICHARD HORACE BATTIN (March 3, 1925–February 8, 2014) was educated at the Massachusetts Institute of Technology, where he received a BS in 1945 and a PhD in 1951. He became assistant director of the MIT Instrumentation Laboratory in 1951.

Dick was a brilliant mathematician with an uncanny ability both to solve practical problems in an intuitive way and to explain complex procedures in simple, elegant terms. The latter enabled him to provide a deep understanding of difficult subjects to generations of students who otherwise may have been lost in the mathematics, myself among them.

Battin's early 1960s paper that originated the concept of gravitational assist is perhaps the single most important insight that opened the door to exploration missions to every planet in the solar system. His work has also had a dramatic influence on the US aerospace guidance and control industry. We might very well not have landed a man on the moon if it were not for Dick Battin's pioneering effort.

An early example of Dick's intuition dates back to the 1950s, when he and J. Halcombe (Hal) Laning, a brilliant colleague of Dick's who among other things developed the world's first algebraic compiler, were collaborating on methods to guide missiles. Until then people were determining trajectories and guiding missiles back to them when they deviated. Dick and Hal realized that what was needed was a velocity vector that would take the missile from its current position to the target—the initially desired trajectory was not important. Out of some very complex analysis came a simple equation that became known as "Q guidance," named after the letter they chose to represent the key matrix in the underlying vector differential equation. But Dick's even greater contribution to this was a simple observation that had not been made before: calculating the difference between current velocity and the desired velocity yielded the "velocity to be gained." Aligning the thrust accordingly reduced the velocity to be gained to zero so that the missile went where it was supposed to go. This scheme was used in the Polaris guidance system and has been used ever since in virtually all missile and spacecraft guidance systems.

Charles Stark (Doc) Draper became a legend in the aerospace industry based on his World War II fire control work and his subsequent leadership in inertial guidance. As a result of this reputation, government agencies frequently came to his laboratory (the MIT Instrumentation Laboratory, now the Draper Laboratory) for solutions to "impossible" navigation, guidance, and control problems. They also allowed some brainstorming on what might be future needs. Shortly after the dawn of the space age Doc used this freedom to consider issues involved with sending a spacecraft to Mars to take photographs and bring the film home. Yes, film! Doc turned to Dick, Milton Trageser, and a few of their MIT Instrumentation Lab colleagues for the answer.

It was during this period that Dick developed his now well-known techniques for navigating and guiding a spacecraft outside Earth's gravity. These included the use of a telescope to do star and planetary/lunar limb sightings and the development of recursive algorithms to improve the quality of navigational estimates, including Q guidance refinement and entry guidance. He documented much of this and his later work on Apollo in his book *Astronautical Guidance* (McGraw-Hill, 1964). During this period he also discovered that one could design orbits that used the gravitation of both Earth and other planets to make more efficient trajectories in interplanetary space. The "Grand Tour" of the outer planets later used this technique.

In 1962 President Kennedy declared that the United States would land a man on the moon and return him safely to the Earth by the end of the decade. By this time, Dick had already done the work described above on space guidance and navigation and Draper's lab had developed and operated both inertial systems and early "computers" in the Polaris missile and in ship guidance systems. Based on this, NASA again turned to Doc Draper and asked him to develop the Apollo guidance and control system. His laboratory was awarded the first prime contract on the Apollo program, just 11 weeks after the Kennedy speech. Seven years later, history was made, but without Dick's early work on the Mars probe this may not have been possible.

Dick dedicated the next decade of his career to the development of the algorithms and software for the Apollo missions and those that came later. Under the leadership of Ralph Ragan (former AIAA VP of publications and second editor in chief of the AIAA *Journal of Spacecraft and Rockets*) and David Hoag, chief engineer, the program at the MIT Instrumentation Lab was divided into hardware design and development, run by John Miller (later founder of Intermetrics), and software, which Dick headed. All algorithms for guidance, navigation, and, after 1964, flight control, as well as the code to implement these algorithms, were developed under his leadership. An amusing anecdote from early in the period is that when NASA called MIT asking how big their computer for the mission would be, Dick replied, "Well, we've got to give them a number; just tell them it's a cubic foot." And that is what it became.

Following are a few of his accomplishments during this era.

As noted above, while working out how to get to Mars, Dick realized that he needed a means to improve navigational accuracy by using multiple measurements taken throughout the mission. This of course meant he also had to have a way of combining older measurements, taken elsewhere on the trajectory, with current ones. He devised what is today known as the "Kalman" filter before ever reading about Kalman's work. He did not do this in the abstract; what he did was in the context of a very real application—another example of his practical insight. By linearizing the dynamics relative to the nominal nonlinear trajectory, Dick was able to propagate covariance between measurement times using what is now widely known as the state transition matrix to obtain a remarkably compact algorithm that had to be compatible with a very constraining computer architecture. Compare Dick's 1962 paper on the recursive least squares celestial navigation problem to Kalman's original 1960 paper and you will see what I mean about his ability to make a complex problem seem simple.

The "filter" that Dick developed was dynamic in that the celestial equations of motion had to be processed in order to bring prior events forward to the time of the latest measurements. This piqued Dick's interest in the classical problems worked in earlier centuries by people like Kepler and Lambert. Dick spent several years working on his favorite hobby problem, known as the "Lambert problem," in which one seeks to find the orbit connecting two points in space with a specified time of flight. The problem is highly significant in mission analysis and orbit transfers generally. Dick's efficient "universal" solution of this problem holds for the entire energy range, covering elliptical, parabolic, and hyperbolic transfers, and he eliminated all classical singularities except those where the orbit plane is inherently not unique. He mentioned during the Richard H. Battin Astrodynamics Symposium that his solution of the Lambert problem was among his favorite accomplishments. Throughout the rest of his career he refined the solutions to these challenges with elegant, simple, and effective mathematics, many of which were published in the AIAA's *Journal of Guidance, Control and Dynamics*. He always laughed when I told him I expected his next paper on these subjects to be the impossible closed form solution!

Apollo was the first all digital fly by wire aerospace vehicle guidance, navigation, and control system. Given little or no history to work from, Dick and his team had to come up with methods for both the development and verification of the software—and on a program that was executed before the eyes of the entire world! He set the standard of excellence that was required by this high-profile manned space program and his mastery of making complex matters seem simple continuously came to bear on the problem. Methods developed under his leadership during this period are still in use today to develop and verify mission-critical software in myriad areas.

The Apollo guidance computer was extremely rudimentary by comparison to current models. It had less capacity than many of today's wristwatches, and enormously less than a smartphone. It was developed at Draper's lab under the leadership of Ramon Alonzo and Eldon Hall. The hardware had to withstand the space environment and simply could not fail—there was only one computer in each spacecraft, because of weight and space constraints. Widespread use of common hardware (for example, a single type of logic circuit) and exhaustive hardware testing succeeded—no Apollo guidance computer ever failed before, during, or after the Apollo missions.

These computers had a wire rope memory of 36,864 words and only 2,048 words of erasable memory to perform the entire mission, including all aspects of guidance, navigation, and control. The word length was only 16 bits, but one bit was used for sign and another for parity, leaving only the remaining 14 to do calculations—less than five full decimal numbers. There was no room for a higher-order language so all programming had to be done in machine language. The limited word length in particular was a continuous challenge to the software design, including the navigation filter.

The first attempts to use the filter in the Apollo guidance computer failed because of word length issues. Dick was very concerned about this and asked a young new employee, James Potter, to look at the issue. Jim was a brilliant cross-eyed mathematician who often seemed to be thinking about and looking at anything but the subject at hand (sort of like another MIT legend, Norbert Wiener). Jim disappeared for a few weeks, causing Dick to fret about both the practical problem at hand and his new employee. But Jim returned to Dick's office with the square root formulation of the "Kalman" filter, which resolved the issue—and is in regular use to this day.

This anecdote is testimony to the fact that Dick tended to gather brilliant people around him—they all enjoyed working with him and held him in the highest esteem. Most of us have been in environments where employees complained about the boss; I never heard such criticism of Dick—only the reverse.

Which leads me to some personal recollections about Dick, our time working together, and how he affected my career. He hired me from the Poseidon missile guidance group at the MIT Instrumentation Lab in 1964 and I worked for him until 1980 when I became the vice president of technical operations for the entire Draper Laboratory, at which time our roles reversed. My first assignment under him was to evaluate the feasibility of adding flight control to the Apollo guidance computers. The payoff if this could be done would be to eliminate significant weight from spacecraft by eliminating flight control–specific hardware.

With Dick's encouragement of a green engineer in his 20s (most of the team fit this description), our team thought it could be done. He agreed and NASA decided to proceed. Apollo became the world's first all-digital fly-by-wire control system. After the first lunar landing, some key members of the Apollo team left Draper's lab to form Intermetrics under the leadership of John Miller. This left some key positions open, including the head of flight control design and software for all the subsequent Apollo missions. Dick appointed me to that job (I was not yet 30), an act that greatly influenced my future and led to some very senior positions. But this is just one example of a story that repeated itself many times—many people for whom Dick was a mentor and/or teacher went on to have a significant impact on the aerospace and defense industry.

I began my association with AIAA publications as associate editor of the *Journal of Spacecraft and Rockets*. At the time, Dick was an associate editor of the *AIAA Journal*. It was very helpful to have such an experienced hand nearby to teach me the intricacies of the job. I later became editor in chief and eventually moved on to become the founder of the *Journal of Guidance and Control*. The first editorial team consisted of experienced associate editors with relevant backgrounds from the other AIAA journals plus a few new people like Stephen Osder, who proved to be the "Lou Gehrig" of associate editors. Having Dick as part of the founding team played a large part in the early success of this journal and made the task of getting it going a lot easier. It also occasioned some levity. As my boss he was just down the hall. Because he was also an associate editor for the American Astronomical Society (AAS), he sometimes received a paper that we had already rejected for our journal (rejecting papers almost always made him feel bad since he was a very feeling person). Needless to say, AAS did not publish those papers either.

Then there are the fun anecdotes. Arthur Bryson recalls that not long after Dick and Hal Laning published *Random Processes in Automatic Control* (McGraw-Hill, 1956), the local newspaper in Lexington, Massachusetts (where the Battins lived), reported that he had published a book on *Random Prophesies*. Given his ability to anticipate technical issues, perhaps this was more accurate than it seems.

The most famous of the Battin anecdotes was a software meeting in his office. A housefly was buzzing around annoying people. Dick, our world-famous guidance mentor, was fiddling with a pair of scissors. He suddenly lashed out with the scissors and cut the fly in two in midair—something no one was willing to attribute to luck!

There were other fun times, many involving travel. Perhaps tops among these for me was when he took me to an AAS conference at the Grand Teton Lodge in Wyoming, my first trip there. I think we gave a paper or a short course. But beyond the spectacular setting and the moose on the lodge's veranda one evening, my lasting memory from that trip was Dick introducing me to John Breakwell. (Between Dick and Doc Draper I had the good fortune of meeting most of our industry's early leadership.) But instead of discussing astrodynamics, John took us into the kitchen of the lodge, where a piano was stored, and entertained a growing group of people for at least an hour with his ability to play anything you wished. Another remarkable person and another technical giant!

Dick served on the MIT faculty for over 40 years. He introduced and taught the course on astrodynamics, and incorporated numerous practical examples based on his work on Apollo and other programs so his students were not learning in the abstract. Four of the people who walked on the moon and 38 astronauts have been students at MIT, and most took his course. He managed to simultaneously teach, write several books, and successfully manage a significant component of perhaps the nation's most challenging technical program. His classical textbook *Mathematics and Methods of Astrodynamics* (AIAA, 1999) is the most indispensable book in the field of astrodynamics, both for academic teaching and research and for advanced applications. It is a treasure trove of Battin's unique developments as well as numerous classical developments that he breathed new life into through his remarkable insights; these include his redevelopment of Gauss's hypergeometric functions and infinite fractions, and of Euler's "top-down method" for computing infinite fractions, and finally his use of these "special function" topics for important advances in astrodynamics computation.

When the MIT Department of Aeronautics and Astronautics established in 1981 an award in "recognition of outstanding teaching," Dick was the first recipient. Teaching was perhaps his fondest activity, and among his many lifelong honors, he was most proud of this one. From AIAA he received the Louis W. Hill Space Transportation Award (1972) (now the Goddard Astronautics Award), Mechanics and Control of Flight Award (1978), Pendray Aerospace Literature Award (1986), von Kármán Lectureship in Astronautics (1989), and recognition as an honorary fellow (1990); in 1996 he was selected for the AAS Dirk Brouwer Award; and in 2002 he received the Aerospace Guidance, Navigation, and Control Award.

Dr. Battin had been married for 65 years to the former Margery Milne who died in 2012. He leaves two sons, Tom and Jeff and their wives, Daryl and Linda, a daughter, Pamela and her husband Steve Sacks, five grandchildren (Matthew, Beth, Rachel Sacks, Kelly, and Christopher), and a great grandson, Logan, son of Matthew and his wife, Amber.