Genesis of Satellite Navigation*

William H. Guier and George C. Weiffenbach

We remember very well our earliest days at APL in the Research Center. George had come from Catholic University in mid-1951. Bill had come from Northwestern University with a recent Ph.D. in theoretical physics that fall. We both remember that during those early days, Laboratory staff were working 6 days per week, and the atmosphere was very much a product of the Korean War and the mounting Cold War with the USSR. The professional atmosphere was totally set by Frank McClure. He was a giant to everyone, usually our superior in technical details, and always our superior in vision.

We were both members of the Research Center group whose assignment was to apply basic methods of math and physics to "task" problems of the Laboratory. Joe Massey was the Group Supervisor, although Bob Hart was clearly the leader of the group's major activity, mathematical analysis, and later would become the Group Supervisor. In those early days, our focus was understanding and then developing methods of signal processing to improve beam rider performance of the Terrier and Talos missiles for defense of the Fleet against air attacks, especially by enemy planes at very low altitude. This problem was referred to as the "low-angle problem" and was of particular concern then.

We also remember that even in the early 1950s, calculators were a tool with rapidly growing capability. Bill, during his schooling at Northwestern, was a summer intern at Los Alamos, New Mexico, the atom bomb laboratory. While there, he learned simulation methods for nuclear fission explosions, at that time integrating the equations of state with numerical methods developed by Richard Feynman on advanced mechanical calculators. With this background, Bill was asked by the Atomic Energy Commission to take a leave of absence from APL to contribute to one of the simulation efforts of the hydrogen bomb explosion, a radical extension of the methods he learned at Los Alamos and to be programmed on the brand new von Neumann–style electronic computers. His effort was located at the Bureau of Standards in Washington, D.C., using the just completed Standards Electronic Analysis Computer.

This effort, intentionally independent of the work at Los Alamos, was directed by John Wheeler of Princeton. Bill spent 7 nights per week "with" the computer and usually one-half day per week in Princeton. Bill returned to the Research Center in the spring of 1952 with the sobering knowledge that the H-bomb would work and the exciting vision of the future world of digital computers. This early experience with computers would allow for quick adaptation to processing satellite tracking data in years to come.

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The Monday after the launch of *Sputnik I*, we met in the cafeteria for lunch. Many were buzzing with the appearance of *Sputnik* and its implications for the Cold War and for the International Geophysical Year. We remember the widespread surprise that apparently no one had come to the Laboratory over the weekend and attempted to receive the signals. The more we discussed the issue, the more keen we became on listening in.

George was working on his Ph.D. dissertation in microwave spectroscopy, and he had the essentials for receiving the *Sputnik* signals. George had a good 20-MHz receiver and, fortunately, APL was just 12 mi from the Bureau of Standard's radio station, WWV, which broadcast the best available frequency and time standards. With WWV so close, a 2-ft wire hanging from the receiver was an adequate antenna. Therefore, a receiver tuned to 20 MHz using WWV yielded a superb reference for a microwave spectrometer. Furthermore, the Russians had set the *Sputnik* frequency about 1 kHz from an exact 20 MHz so that any receiver would produce an audio tone of 1 kHz plus or minus the Doppler shift generated by *Sputnik*'s motion. This offset of *Sputnik*'s frequency ensured that the received audio tone never went through zero, varying from about 1500 Hz to about 500 Hz, clearly audible throughout an entire pass. Anyone in the world who listened with a 20-MHz receiver would hear such a signal, providing a clear announcement to the world that the backward USSR had made good on their announced intention that they would launch an artificial Earth satellite as part of the International Geophysical Year.

Late that afternoon we heard the signals from *Sputnik* loud and clear and realized that we ought to record the signals and (perhaps for posterity) put an identifying time stamp on any recordings. During this time, people were spreading the word that George was "getting the signal," and many would drop by, further fueling our growing excitement about this marvelous achievement of the Russians.

We returned after dinner that evening. George included the WWV time signal on the received audio, "fussed" with gear to improve the signal-to-noise ratio, and made the output parallel to a standard audio amplifier for recording. Bill had promised to bring his newly acquired audio high-fidelity tape recorder to the Laboratory so that we could record anything we might want to keep, again with nothing yet specifically in mind.

That evening, we were receiving and recording complete passes of the satellite from horizon to horizon with no modulation on the 20-MHz frequency, what we would later call a "pure Doppler shift." It took awhile to realize that we could use the shifting frequency to advantage, assuming we were receiving the *Sputnik*. We estimated the total swing in frequency, substituted it into the simplest equation for the Doppler shift to yield an estimate of the speed of the source, and confirmed that it was about right for an orbiting body near the Earth. We could positively identify our source as a near-Earth satellite! Somewhat later that evening, we remembered that we could estimate the closest approach of *Sputnik* to George's antenna by determining the maximum slope of the Doppler shift—a method APL used in estimating the distance of closest approach of a guided missile to its target. From that time forward, we focused increasingly on quantifying the Doppler data and inferring the satellite's orbit from the data.

Within a few days, we were spending almost all of our time on "the problem." We did some homework and established the definitions for typical near-Earth satellite orbital elements using published literature from the U.S. effort to launch an artificial satellite during the International Geophysical Year, known by then as the Vanguard program. George had set up a way to digitize the recorded Doppler signals as the recorded WWV broadcast time at which the signal passed through a preset frequency of a high-quality tunable narrow bandpass filter. Bill was desperately trying to establish the values for the orbit parameters in terms of multiple sets of times and distances of closest approach corresponding to multiple passes of the satellite by our antenna at APL.

During this time we had lots of help. Some people helped with improving our antenna size and location to get signals closer to the horizon. Others volunteered to help reduce the data. Several friends checked Bill's algebra and solutions to the elliptic equations of motion. Harry Zink and Henry Elliot became frequent and then regular members of our effort. It was not organized; we all just did it.

Within a few weeks we were not playing with the orbit. Instead, we were inferring it by guess, by graphical methods, and by using other estimates we would read in the newspaper, e.g., the orbital inclination would be about the same as the latitude of the launch area in Russia. We were also beginning to predict rather well the time of appearance of the signals, thereby confirming our crude inferences (with hindsight) of the satellite's orbit.

We did not realize at the time that we were fortunate to have *only* Doppler data. Every organization in the United States, Europe, and the USSR that had a charter to track satellites had elected to use angle measurements based on radio interferometers. The Naval Research Laboratory, in its Vanguard program, had a sizable array of antennas to track its satellites. We were the only ones to analyze the application of Doppler data to this problem—these were the only data we had!

When *Sputnik* ceased transmitting, we (and others around the world) took a deep breath and reassessed what we had been doing and thought a bit about where we might go. Frank McClure had already encouraged us to report our progress to the Laboratory's Director, Dr. Gibson (he was always *Dr.* Gibson). He allocated some cherished funds to support a limited effort on the newly acquired Univac 1200F digital computer. The objective was to establish the ultimate accuracy for determining the orbit from Doppler data from first one and then several successive passes when computer power was not constrained. In addition, our success in orbit determination, although marginal, seemed to be better than other, more formal efforts. We reported our best orbit estimates to Vanguard headquarters, resulting in several inquiries about how we were doing this. John O'Keefe heard of our results through Vanguard headquarters and asked to come to APL to speak with us. He became a marvelous source of encouragement, as well as background knowledge on the near-Earth gravity effects on satellite orbits, which you don't find in astronomy books. O'Keefe had already predicted the effect of a north–south asymmetry of the Earth, the so called pear-shaped effect.

The culmination of this study with the archived *Sputnik I* data, and later with some of the *Sputnik II* dual-frequency data added, was a demonstration of the fact that a complete set of orbit parameters for a near-Earth satellite could be inferred to useful accuracy from a single set of Doppler shift data. The demonstration established that the whole Doppler curve was needed, nearly horizon to horizon, and that a first-order correction for ionospheric refraction was required, as well as an inferred correction for satellite oscillator frequency and frequency drift. Thus, the total number of unknown parameters is nine, six orbital parameters plus three system parameters, i.e., $6 + 3 = 9$ parameters. Included in this demonstration was a single-parameter model of the ionosphere electron density, which was also inferred along with the six orbital parameters. Implementation of this computer demonstration required the first of many innovations in special numerical methods for nearly singular and nonlinear least-mean-square inference in multidimensional space. During this period, several conjectures naturally arose, including the use of multiple harmonically related frequencies to reduce ionospheric errors.

From here on, we were in for the adventure of our lives. On Monday, 17 March 1958, Frank McClure called us to his office and asked us to close the door. He asked us if anything new suggested that we had exaggerated our claim that we could find an approximate orbit from a single pass of Doppler data. When we replied that nothing had really changed, "Mac" asked if we could invert the solution, i.e., determine the station position while assuming the orbit is known. Clearly, Mac knew that if the orbit was known instead of station position, the number of parameters was reduced to five parameters, two station position plus three system parameters, i.e., reduced from $6 + 3 = 9$ to $2 + 3 = 5$. Consequently, it was obviously possible and probably could be done with much higher accuracy. This, of course, was Mac's way of saying "go do an error analysis and let me know the answer ASAP." Over the next couple of days, we generated a preliminary feasibility study on the "inverse problem," later to become known as the "navigation problem." We did not fully realize the potential of what we were doing, but as usual, Mac's penetrating interest was sufficient for us to work diligently once again.

The study quickly evolved to the assumptions that the satellite is cooperative and radiates two frequencies that are very stable and sufficiently high to effectively eliminate ionospheric refraction errors, thereby reducing the dimensions of the problem to just $2 + 1 = 3$ parameters. The very first simulations indicated great accuracy—unbelievable accuracy! When we reported excitedly back to Mac, he, of course, was not surprised.

We learned later that many were concerned about navigating Polaris submarines such that a launch location at sea would be accurately known, ideally within a few hundred feet. In particular, Mac had been spending part of his time downtown in the Navy's Special Projects Office, which was responsible for development of the Polaris system and was aware of this serious problem in submarine navigation. He realized that the Doppler satellite tracking method, when "turned on its head," had the potential for a solution. Learning of our latest progress on a Friday, Mac had the idea to invert the process, called his close friend, Dick Kershner, and over that first weekend designed the essentials of the complete Transit Navigation System: multiple polar orbiting satellites radiating two ultrastable frequencies encoded with their orbit parameters, a satellite tracking system receiving these same two frequencies to solve the "direct problem," and an injection station to transmit the resulting orbit parameters to each satellite, which would continue to obit the Earth so that submarines with navigation receivers/computers could determine submarine position about once an hour anywhere on Earth.

The fact that we had been able to get our Doppler data with a simple nondirectional antenna now assumed major importance. The only other candidates for submarine navigation were to use active sonar imaging of the ocean bottom (a "no-no" for Polaris submarines, which were to be undetectable) and a Naval Observatory plan to use a 3-ft-dia. dish on a stable platform to make direction measurements—an easily detectable target for radar.

The rest of the story is well known. In a remarkably short time, a competitive proposal was generated for a Polaris Doppler navigation system. APL's proposal was accepted as the navigation satellite system, which, with a satellite weather observation system, became the first two operational satellite systems in the free world.

We have often pondered how and why it all happened so quickly and with so little of the aggressive competitive bickering so prevalent today. Obviously, part of the reason is that there was very little competition back then, given the fortunate fact of the initiating events. Equally obvious is the fact that APL was a superb environment for inquisitive young kids, and particularly so in the Research Center. It was an environment that encouraged people to think broadly and generally about task problems, and one in which inquisitive kids felt free to follow their curiosity. Equally important, it was an environment wherein kids, with an initial success, could turn to colleagues who were broadly expert in relevant fields, and particularly because of the genius of the Laboratory Directorship, colleagues who were also knowledgeable about hardware, weapons, and weapons needs. Finally, we agree that it probably would not have happened this way without Frank McClure and Dick Kershner. They were incredible; they were unique.

We are not immune from reminiscing about the "good old days," about Transit's accomplishments and legacies. Both of us have been enormously pleased at some of the past and present uses of satellite navigation, including the tracking of migrating birds and animals and effective search and rescue techniques that can pinpoint trouble in remote areas worldwide. We did predict many of the applications, such as oceanography. It soon became clear that knowledge of the Earth's gravity would require a major effort, but we did not expect it to become such a rich source of geophysical knowledge. In particular, we were as surprised as most by the size and complexity of the Earth's mass irregularities, and we take considerable pleasure in the consequent genesis of the science of continental drift, its application to geological and human evolution, and the present focus on the prediction of natural geological disasters. The use of range instead of range rate for aircraft navigation was evident at an early stage, but the technology was not yet available. The present Global Positioning System is the result of APL's pioneering work with Transit, progress in electronics, and the global economy. Of course, we underestimated progress in electronics. In particular, we did not predict the incredible extent to which size and cost would be reduced for everyday applications for the mass market, e.g., navigation systems for our automobiles and pleasure boats, and even handheld units for hikers. We will always look back with enormous gratitude and pride that we were part of it all.

THE AUTHORS

George Weiffenbach (left) and William Guier (right) at a recent symposium on the *Legacy of Transit*.

WILLIAM H. GUIER received his B.S. in physics in 1948, his M.S. in experimental physics in 1950, and his Ph.D. in theoretical physics in 1951, all from Northwestern University. He joined APL in the fall of 1951 as a Senior Staff Physicist in the Research Center, and immediately went on a year's leave to Princeton University as a special consultant to Project Matterhorn. He later was appointed Project Supervisor for Space Research and Analysis in the newly formed Space Department. He was named Group Supervisor of the Space Analysis and Computation Group in 1964. Dr. Guier joined the newly formed Biomedical Programs Collaboration with Hopkins Medical School in 1966, remaining a consultant in advance technology planning in the Space Department until he retired in 1992. He received the first Outstanding Young Scientist Award from the Maryland Academy of Sciences in 1959. Dr. Guier and Dr. Weiffenbach received the IEEE Pioneer Award in 1986 for contributions to satellite tracking and navigation, and the Magellan Prize for navigation from the American Philosophical Society in 1988.

GEORGE C. WEIFFENBACH received his A.B. in physics from Harvard University in 1949 and his Ph.D. in physics from the Catholic University of America in 1959. He joined APL in 1951 as a senior physicist in the Research Center. From 1969 to 1978, he was Associate Director of the Harvard–Smithsonian Center for Astrophysics. After spending a year at the MIT Lincoln Laboratory, Dr. Weiffenbach returned to APL, where he was the Director of the Space Department from 1980 to 1986. His research interests have included microwave spectroscopy, time and frequency standards, space systems engineering, geodesy, and geophysics. Dr. Weiffenbach and Dr. Guier received the IEEE Pioneer Award in 1986 for contributions to satellite tracking and navigation, and the Magellan Prize for navigation from the American Philosophical Society in 1988.