Synthetic Aperture Radars

A PARADIGM FOR TECHNOLOGY EVOLUTION

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This is the 1984 Pioneer Award story—told in the author's own words—*Editor*.

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The famous science-fiction writer, Robert Heinlein, has a very good feel for engineering and technology. In one of his stories, he has one of his characters say, "When the time comes to railroad, everyone railroads".

These are wise words. They summarize in a nutshell how science and engineering work. I have used this saying for years as my slogan. At each point in time, concepts and technology appear which, in turn, make new developments possible.

Then, and only then, "Everyone railroads". If one hops to it immediately and starts building locomotives and track, he may be lucky and lead the pack. If he is a little slower, he will be on the heels of the leader. However, it takes the whole pack to railroad.

Each man, as he joins the race, brings new ideas and techniques with him. It is the sum of these ideas and techniques which turn the initial early work into a mature technology.

The history of synthetic aperture radar (SAR) is a beautiful illustration of this process. As I see it, Dr. C.W. Sherwin and colleagues conceived and proved the principle of focusing. It is the extraordinary resolution made possible by this technique which has made SAR radars so important.

Dr. Lou Cutrona, et al., invented the optical processor and developed it to maturity. For many years, the optical processor was the only practical method of converting "coherent video" SAR radar signals into images. The optical processor spawned a host of auxiliary SAR techniques. It also started a cycle of optical technology of first importance. It is called Fourier optics today.

I had the luck to conceive of the basic idea, which I called Doppler Beam Sharpening (DBS), rather than Synthetic Aperture Radar (SAR). Like all signal processing, there is a dual theory. One is a frequency-domain explanation. This is Doppler Beam Sharpening. If one prefers, one can analyze the system in the time domain instead. This is SAR. The equipment remains the same—just the explanation changes. Conception was reported in a Goodyear Aircraft report in 1951.

As the result of prior conception, I got to lead the pack, but I didn't lead it by any big margin. Let us take a look at what happened.

In 1949, I moved from Wright Field to Goodyear Aircraft, Akron. Goodyear had started to develop the radar guidance method which I invented at Wright Field. I called it "map matching". It became Goodyear's ATRAN guidance system. The technique is called correlation guidance these days.

At the end of the first year, Goodyear reopened its WWII plant in Litchfield, Arizona. Dr. Karl Arnstein, VP Eng., sent me to Arizona to form an advanced radar engineering group. This was about a year later.

This move gelled thoughts I had had since Wright Field days on how to get high radar resolution by observing the Doppler shifts of stationary targets. The time had come to railroad! The resulting SAR design was given in the June 1951 Goodyear report already mentioned.

There was a demand for higher resolution radar, not only for use in aircraft, but also in missiles. I was looking for a way to use very small antennas on missiles for ATRAN guidance.

Excellent coherent microwave power amplifier tubes were appearing. I used the Sperry SAL-39 power klystron designed as a ground beacon transponder at L-band. Storage tubes were available to store the Doppler records in such as the Raytheon "Radicon".

I had had very good luck developing "map matching" in an ultra-sonic simulator when at Wright Field. There I reworked the simulator used for bombardier training in WWII. In Arizona, I built a new simulator with a much more precise carriage drive. Fred Heisley was the mechanical engineer; Bill Welty was also a collaborator.

I didn't have a storage tube as yet, so I used an array of pentodes with floating plates corresponding to the storage tube storage surface. Signal was applied to the suppressor grids which mimicked the storage tube screen. Since storage capacity was low, we only used point targets in the simulator.

Early in 1952, we got this system working. It was the first operational SAR. The importance of this radar was immediately apparent to everyone. In the inset, I am reproducing the letter of congratulations went to me by Dr. Arnstein on 4 June 1952.

I admire Dr. Arnstein. He was an aeronautical engineer and stress analyst, yet he had the vision to back DOUSER right through flight test. Other executives reporting to him did not have such courage. They complained that I was violating the aperture relation.

In 1953, we built a second improved simulator and signal processor. The radar transmitter/receiver unit was built in Akron and shipped to Arizona. This processor had a pair of Raytheon storage tubes. This was DOUSER (Doppler Unbeamed Search Radar). The first images still in my possession are dated 15 April 1953. Dick Baum, Fred Heisley, and Ross Graves were collaborators.

From the published papers of Sherwin et al., I find that in 1952, the year we were operating the first SAR, Dr. Sherwin also recognized the SAR principle. Even more importantly, he saw how to produce focusing. This permits very high resolution by allowing the scene to be within the near-field of the synthetic aperture.

From about August to the end of the year, we flew DOUSER in a DC-3. We replaced a wingcap with a special cap containing a Yagi at 930 MHz. It was spaced off the true wing end by a quarter wave. There may have been a director as well. The beam was about 100° wide; it was beam-sharpened to about 1°.

The synthetic beam was scanned by use of an ultrasonic compensator. This was a cam-driven reflector in a trough which introduced a frequency shift at IF. This shift moved the various Doppler shifts in the real beam back to a fixed filter frequency.

After demodulation, the coherent video was stored in two storage tubes used in push-pull. These were Cornor-twin memories. Read-out from these tubes was filtered as mentioned above. The modulus for each range bin was found and the result displayed on a CRT.

This display looked like a standard PPI display. It scanned around the normal to the velocity vector over about 90°.

The correct PRF to eliminate distortion as plane speed changed was set by a primitive Doppler navigator servo loop within the radar.

This was the first fully operational SAR to take to the air and operate in real time.

Meanwhile, that same summer of 1953, Kovaly, Newell, Prothe, and Sherwin were recording coherent video on tape at Key West. The first good record was made on 8 July. The actual image was made at some later time on the ground. A laboratory frequency analyzer was used to separate the Doppler histories of the image pixels as they FM'ed through the radar beam. Frequency tracking means are not discussed.

On 13 August 1954, I filed the patent application for SAR radar. It was entitled, "Pulsed Doppler Radar Methods and Apparatus." No prior art and no interferences were cited by the patent examiner.

The filing delay of over a year resulted because GAC patent attorney, Al Oldham, had trouble understanding

GOODYEAR

Goodyear Aircraft Corporation

AKRON 15, OHIO

June 4, 1952

Mr. Carl Wiley
Department 29-A
Basic Physical Research
Goodyear Aircraft Corporation
Litchfield Park, Arizona

Dear Carl:

I was very happy to read your report GER-15-A and to find that you were able to prove that the system tested in the sonic simulator proved your prediction to be correct.

We all here appreciate the significance of this accomplishment and are very proud of your and your associates work.

Kindly accept our congratulations and our best wishes for continued success.

With kindest personal regards,

Sincerely yours,

Karl Arnstein

Karl Arnstein
Vice President

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NO CONTRACT VALID UNLESS IN WRITING AND SIGNED BY DULY AUTHORIZED OFFICERS

the device. Dr. Arnstein had to apply strong measures to get him to begin writing the patent. I had to tutor him.

The same year GAC built its second SAR at a shorter wavelength. It also used a filter-bank Doppler analyzer. Goodyear was on its way in the SAR radar business. It still is a major component of GAC radar business today, 30 years later.

In 1954, Lou Cutrona and associates joined the SAR pack. According to his papers, Cutrona et al. started the development of SAR optical processors. This was a very significant event. Optical SAR processors turned out to be the best SAR processor type up until digital processors became mature.

On 1 June 1955, I received a secrecy order on SARs from the Patent Office. It was not rescinded until 18 November 1964. This secrecy order barred me from writing papers on SARs for the technical journals for almost a decade.

In the meantime, I had formed my own company, Wiley Electronics. In 1957, Wiley Electronics completed and demonstrated ASTAR. This was the first real-time, point-focused, window-display processor. It was demonstrated in an ultra-sonic processor.

This occurred because we were teamed with Motorola. Before Motorola completed the radar RF head and got it mounted in an airplane, the contract was cancelled.

George Cooper was the project engineer. Emil Vecchio and Allan Love were also engaged in the design. Dr. Love did the analysis which showed that when the radar was focused at the center of the window, focus was within the Rayleigh limit over the total window area.

TABLE I
IMPORTANT SAR DEVELOPMENTS

ITEM	HOW IT WORKS	ORIGINATOR
Motion Compensation	Radar phase varied to correct for phase noise due to aircraft motion.	Cutrona for Valkerie
Autofocusing	High/low matched filter difference form error signal to correct focus.	John Kirk
SAR MTI	Optical processors can focus on moving targets & defocus the stationary scene.	Cutrona, et al
Inverse SAR	Target motion causes the target to make an image of itself by SAR means.	
Spotlight	A pencil beam tracks a scene area for a long time to produce very high resolution images.	
Multiple-look Averaging	Gets rid of image scintillation.	
Hard-limited, 1-Bit Processing	The data is in the zero crossings. Sure shrinks the computer!	
Topographic SAR	Uses interferometer to generate image contour lines.	Lee Graham/ GAC
Synthetic Coherence	Uses an internal reference phased by each magnetron pulse to get coherence. Sinco, flown at PAX River, used a rough quartz surface which acoustically scattered the transmit pulse at IF frequency. The result is a noisy, coherent signal which is a perfect reference.	Wiley
Antenna Beamed in Elevation for Orbital-SAR Use	Narrow elevation beam prevents range/Doppler ambiguity.	
Digital Processing	Compute the image!	GAC/Hughes?
Homing SAR	Keeps turning toward target down to zero range.	Wiley
Full-Window Optical Processor	Doesn't need that slit! So it sees fluctuating targets as they come through the window.	Horsch/ Autonetics
Long-Wave Foliage Penetration Radars	Operate in meter region	Folpen-Cutrona Loco-Wiley/ Horsch

The required Doppler shift was introduced by an ultrasonic Doppler compensator as in DOUSER. The required crow-foot speed needed to get focus in the center of the window was generated by a four-bar mechanical linkage.

Input to the four-bar linkage was from the ship navigation system. Long term navigation data came from a Doppler navigator. This navigator was part of the Wiley Electronics SAR unit. Fred Heisley designed the four-bar linkage and mechanical navigator unit.

The Doppler filters were barium titanate resonators. A device now called a "Hilbert transformer" was built into the filter assembly so as to recover all the data in the filtered video. The required phase shifts were generated by analogue filters synthesized by Emil Vecchio. A ringing, paired-echo filter was also synthesized for Emil for the purpose of weighting the synthetic apertures.

I note that Lou Cutrona reports the first successful flight of a film recorder for recording coherent video during this same year. The flight was made on 23 August 1957. The image was generated in the laboratory by an optical processor at some later time.

This takes me through the critical events in the very early history of SAR radar. I must admit that I do not have the chronology of later events as well in hand, yet as time went on, many significant ideas and techniques appeared. These developments changed SAR radar into the mature technology of today.

In many cases, I do not even know who the originator was; however Table I lists some of the most important items. If I think I know who the originator was, I put down his name. If not, I showed no name.

If I have done anyone a disservice, please send a letter to these ***Transactions***. Now is a good time to firm up this portion of the history of radar.

The story is not ended yet! All SARs up to now have generated image resolution normal to the synthetic aperture by ranging. Why not use a long linear array instead? The array beam now produces resolution normal to the synthetic aperture. Mount such a radar on the belly of a plane or satellite and pulse. The result is an excellent gap filler. It is high resolution, light and easy to stow.

Mount the array on an arm and spin it in a circle. Scan the array up and down. Pulse for each beam position at a medium PRF (MPRF). Beam sharpen each range/angle bin using the cylindrical Doppler history which results.

The result is a volumetric search radar which looks over 360° with a synthetic cylindrical array. This is a good ground-to-air search radar.

A little analysis will convince one that its power-aperture product is the same as the power-aperture product of a solid, real array with area equal to the area swept out by the synthetic array.

This is true even for regular SARs. I have a SEASAT SAR image in front of me made by McDonald-Dettweiler. One can see even boat dingies in Vancouver harbor from about 900 km away!

The SAR Radar is a bellweather in an even more important development already underway. It is the first of a new kind of antenna. I call them "electronic antennas".

Instead of producing a physical aperture for use in the image plane, one can use small probes in a frequency plane of the scene. The little probe measures the radiation structure in this frequency plane. A computer then generates the image by signal processing. The performance is the same or better than the competing real antenna. Computation replaces much of the bulky real antenna structure. Many radio telescopes use such techniques.

If one looks about, it becomes obvious that this new breed of antenna will sweep brute force antennas away in both radar and radiometric imaging. They will even invade the communication antenna area!

The storm is gathering! The whole field of antenna technology will be so different it will be hard to recognize by the time the storm has passed.