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Microwave Pioneers: Charles Elachi, "Dare Mighty Things"

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ABSTRACT This is the fifth article in our continuing series of biographical pieces with a technical lean (two in vol. 1, issue 1, and one each in vol. 1 issue 2 and issue 3). The subject of this paper is noted microwave radar remote sensing pioneer and National Aeronautics and Space Administration Jet Propulsion Laboratory (NASA/JPL) Director, Dr. Charles Elachi. Without a doubt, Dr. Elachi almost single-handedly pioneered the field of active microwave remote sensing from space. His early work on aircraft imaging radar and the deployment of microwave synthetic aperture techniques for ocean and land surveying led to a series of groundbreaking Space Shuttle missions and opened up whole new fields of research for oceanographers, geologists, planetary scientists, geophysicists, and even archeologists. Elachi's scientific and engineering accomplishments quickly led him up a long ladder within the NASA/JPL community, eventually landing him in the Director's chair. The title of the article reflects his mantra for success, both personally and for the institutions he played such a large role in.

INDEX TERMS Charles Elachi, Caltech, earth remote sensing, microwaves in space, microwave pioneers, NASA JPL, shuttle imaging radar.

I. INTRODUCTION

Dare Mighty Things[1] is a favorite phrase from a favorite historic figure admired by Charles C. Elachi, the subject of this Microwave Pioneer article.[2] It not only occupied a prominent place on his office wall but was also broadcast to the world – although playfully in binary code - on the underside of the parachute that glided the Perseverance rover safely down to the surface of Mars on February 18th, 2021 (Fig. 1). As you will read, it is also a very appropriate description and testament to an individual who, when the opportunity presented itself, did not hesitate to take up the challenge, no matter the risk of failure. In his case, it seems always to have resulted in resounding success!

Charles Elachi was one of four siblings growing up in a small town of around 1000 people in Rayak (also Riyaq or Rayaq), Lebanon, approximately 60 km east of Beirut. Rayak was known as a hub of rail traffic in the Middle East and Charles' father, Rokos, was a director of the rail station. There

[1]The phrase is from a portion of an 1899 speech by U.S. President Theodore Roosevelt which reads, "Far better it is to dare mighty things, to win glorious triumphs, even though checkered by failure, then to take rank with those poor spirits who neither enjoy much nor suffer much, because they live in the gray twilight that knows not victory nor defeat." The phrase was a favorite of Charles Elachi in his role as Director of NASA JPL and it was encoded in binary on the inside of the Perseverance Rover's parachute as it dropped down to the surface of Mars on Feb. 18, 2021

[2]This article was composed after an in-person interview on Sep. 22, 2021 with Dr. Elachi at one of his two offices at Caltech – the smaller one is in EE, the larger one in Geophysics – perhaps appropriate to the scale of his contributions as he sees them! Although we focused mostly on Dr. Elachi's pioneering work on microwave remote sensing, the subject of his very well-known college text – which has just been released in its 3rd Edition, we also had a chance to also talk about his role as JPL director and the many challenges and success stories he has had leading a major NASA center and responding to the demands of several different NASA administrations. This article explores only his microwave work, but this is by far the less dramatic of his many career successes!

FIGURE 1. View of parachute underside on the Perseverance rover with overlayed coded message text. Each of the three inner rings of white and red lines represents a 7-bit binary code spelling out "Dare Mighty Things" going clockwise with A = 000001, and with the outer ring spelling out the Lat. and Long. of JPL's Visitor Center. Image NASA/JPL, 2021: https://mars.nasa.gov/imgs/mars2020/spacecraft/markings/25646_PIA24431-parachute-decoder-ring-1200.jpg.

was also a large French military airbase near the town that supplied significant dreams about flying and perhaps having a career working in engineering and technology. Although neither of his parents completed high school, and his only links to the west were a magazine called "Life in America," distributed by the American embassy in Lebanon and a local movie theater that showed American films, the influence of the trains and planes was strong, and Charles gravitated towards math and science. At age 11, in a prescient happenstance, he recalls reading an article on the Jet Propulsion Laboratory which had just launched America's first satellite – Explorer 1, in January 1958.

What would become a very independent mindset, was enhanced by his attendance at a boarding school (Collège des Apôtres in Jounieh, near Beirut) starting from age 11 and extending through high school at École Orientale, in Zahlé (closer to home). Elachi graduated in 1964 with the prestigious score of number one in Lebanon on the Mathématiques Élémentaires – a national college entry exam. This distinction earned him a fellowship which could be applied to a university outside of Lebanon. Elachi was recommended to apply for a slot at the Joseph Fourier University in Grenoble, France, to which he was admitted. After a year he was able to transfer into an Ecole Nationale Supérieure program in what would become the National Polytechnical Institute (INPG), where he received a master's degree in electrical engineering in 1968 and where he studied radio electricity and gas discharge spectroscopy. One of his professors and mentors, and the President of INPG, was 1970 Nobel Laureate in Physics, Louis Néel, best known for his work on ferrimagnetism and superparamagnetism.

During a summer research program, Charles happened to meet a couple of US transplants studying French at Grenoble, who suggested he might like continuing his studies in the United States. One of his friend's father happened to be a Dean at University of Illinois and he sent Elachi a set of application forms for a bunch of top science schools in the US. In a typically haphazard manner, Charles applied to, and received acceptances from schools such as MIT, Stanford, Illinois and other US institutions, but he happened to notice that one of these, California Institute of Technology, a college he had never heard of, was very close to Hollywood (memories of American movies). In fairness, Caltech was also highly recommended by his professors at Grenoble. He accepted Caltech's full Ford Foundation Fellowship and arrived at the campus in Pasadena, California, in mid-August 1968.

In California, Elachi was housed with a family in which the husband worked at Hughes Aircraft, and in which the wife's family had Lebanese roots. JPL was occasionally a part of the dinner conversation, and Elachi came to understand that it was connected to the University – flash back to the article he had read as a child on the developers of Explorer I. Meanwhile, on the Caltech campus, Elachi hooked up with notable Radiophysics and Electrical Engineering Professor, Charles Papas, and started working on electromagnetic wave interactions in periodic media. He earned his Master's degree in 1969 and his Ph.D. in 1971 [1]–[4]. By 1970, he had also managed to land a part-time paying job at JPL, which he gladly substituted for his university fellowship.

After completing his doctorate in the summer of 1971, the JPL position became full time, but Elachi maintained a research fellowship at Caltech. He focused heavily on his specialty area – optical wave interactions in periodic media – publishing a considerable number of papers on the topic [5]–[8], many with nearby UCLA colleague and former Caltech student himself, Cavour Yeh [9]–[15]. He also received several patents on distributed feedback lasers and oscillators [16]–[19]. Elachi summarized much of his wave interaction research in a nice review article for PROCEEDINGS OF THE IEEE in 1976 [20].

At the same time, Elachi was working for JPL's Walter E. Brown – a pioneer in microwave radar for airborne applications [21]. He began, at Brown's request, to learn about and then help to put together a planetary imaging radar study – PIRS [22]. He was also taking advantage of his waveform expertise to look at electromagnetic waves interacting with both the atmosphere and the ground [23] – which would later lead to a strong and persistent interest in geophysics. Although the PIRS study never went forward as a NASA mission, it led to a proposal and fledging flight program to use synthetic aperture radar techniques to penetrate the Venusian atmosphere and to map the surface features, VOIR – Venus Orbital Imaging Radar [24]. VOIR was cancelled in 1982 due to budget overruns but was soon replaced with the Venus Radar Mapper in 1983. VRM was itself renamed Magellan in 1985 and launched in 1989 from the Space Shuttle Atlantis (STS-30) on a very successful four-year surface mapping mission at Venus – and remains a highlight of JPL's major planetary programs.

Tacking back to the mid 1970s and Elachi's early work on radar imaging, and before there were any satellite programs, there was an active aircraft campaign in Walter Brown's group. Brown was doing microwave backscatter

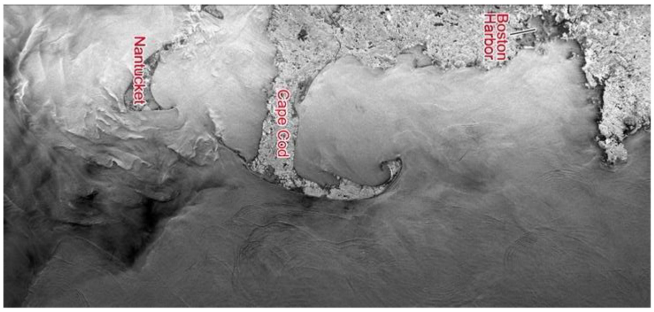

FIGURE 2. Seasat image of Boston harbor, Cape Cod and Nantucket Island where shallow shoals produce surfaces wave patterns contrasted by differences in the SAR scattering amplitude. Image credit NASA/JPL-Caltech /Alaska Satellite Facility, 2014: https://photojournal.jpl.nasa.gov/catalog/PIA18137.

measurements and synthetic aperture radar at L-band (25 cm; 1.2 GHz) and at 2 meters (150 MHz, VHF) and flying over ice fields (mostly Alaska and Greenland). The microwave signals could penetrate down to depths of 100 meters or more through snow and ice and retrieve layering information [25]. Elachi became the team leader, and on one flight in 1974, coming back from a flight over Alaska with their instrument aboard a NASA CV990, the team decided to turn on the radar as they crossed the open ocean to see if any surface features were visible. At the time, most SAR techniques depended on having a stationary target – and of course the ocean was covered with moving waves. What they observed was to open up a whole new field of geophysics – they were able to see, and thus track waves and features moving across the water surface [26], [27]. The resolution came from differences in the radar signature when reflected off the wave tops – which were very rough and scattered strongly, versus the wave troughs, which were much smoother in feature size at the scale of the microwave signal. Brown showed the results to John Apel [28] at the National Oceanic and Atmospheric Administration, Seattle, Washington who was extremely excited, and suggested that the L-band SAR instrument might be used to map wave patterns through cloud cover or bad weather, and might even be able to visualize the waves under a hurricane – something that was extremely interesting to oceanographers and geoscientists. Elachi was to experience such a flight himself – only once – when he later took the aircraft instrument through to the eye of Atlantic hurricane Gloria in September 1976, on a quest that went well beyond the call of duty in the interests of science [29]!

At this point there was still considerable skepticism about how well a SAR instrument might perform in space, versus a low flying aircraft. First, the resolution would be a major issue (an enormous antenna was required), but other problems also seemed significant – like being able to collect and process all the required SAR data, which at the time was captured on film using optical interferograms. Also, it was not clear that the same contrast in the wave crests and troughs that was observed on the aircraft instrument would still show up on a space view.

At the time NASA was getting ready to populate the Seasat platform, the first civilian satellite to focus on the oceans, and they already had an altimeter, a microwave scatterometer, and radiometers for height, wind speed and direction, and ocean temperature, respectively. Brown, with the help of Apel, Elachi, and the JPL radar team, were able to convince NASA to add an L-band SAR instrument to the payload under the conditions that it would be an engineering demonstration and that it could be built for a very limited cost.

Seasat, along with the new 1275 MHz SAR system which boasted a 10.7 × 2.16-meter deployable antenna – almost the size of the full solar panel array, was successfully launched from Vandenburg Air Force base in California on June 27, 1978 and operated for a little over 100 days in a circular orbit. The radar imaging instrument had a resolution of 25 meters and was able to see contrast both over land and water, validating the use of the SAR technique on a satellite platform [30] (Figure 2). It even generated some unanticipated controversy when a claim surfaced that the system could detect the wakes of submerged submarines, but this was never confirmed. What is certain, is that Seasat set the stage and the technology for an enormous number of subsequent radar-based satellite instruments, both for Earth remote sensing and planetary explorers, that continues to this day, and Elachi's JPL radar team was at the center of it all [31]–[35].

Even before Seasat launched, the JPL radar team was continually flying its instruments on aircraft platforms [36]–[44], honing its algorithms [45], and looking for additional opportunities. It so happened that in the late 1970s, the new NASA Space Shuttle program was getting ready for its first flights which were designated to be for engineering purposes only – no science instruments were to be deployed from the Shuttle bay for at least the first four launches. However, rather than flying the expensive new spacecraft empty, NASA released an announcement of opportunity for potential payloads that could fit entirely within the envelope of the cargo hold – nothing extending – and do something of purpose. Elachi's team was completing work on the Seasat instrument, and there were lots of spare parts and a complete working engineering model of the SAR system. He proposed that these be reworked and fitted into the Shuttle cargo bay and be deployed to observe the Earth as the shuttle passed over (top side looking down) with the bay doors fully open. The proposal was selected towards the end of 1977, and Elachi became the Principal Investigator of a major multimillion dollar space instrument at the tender age of 30. This prompted a quick trip back to school to get a Master's degree in Business at USC, which Elachi received in 1979.

SIR-A, for Shuttle Imaging Radar A, was launched on Columbia during STS-2, the second space shuttle mission [46]. It lifted off from Kennedy Space Center, Florida, on Nov. 12, 1981, and landed 54 hours later (having completed 37 orbits) at Edwards Air Force Base in California. SIR-A was by far the largest part of the five instrument payload aboard Columbia. The fixed 1275 MHz antenna was 9.4 × 2.16 m, weighed 181 kg, and stared at a 47-degree angle ahead of the

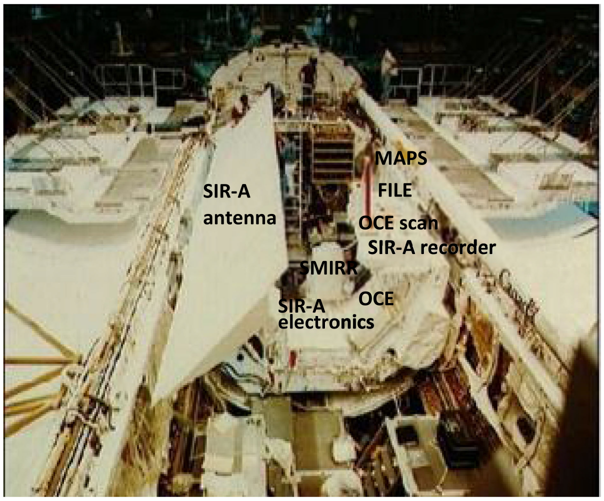

FIGURE 3. **View of STS-2 cargo bay with 5 instruments: SIR-A, OCE (Ocean Color experiment), SMIRR (Shuttle Multispectral Infrared Radiometer), FILE (Feature Identification Location Experiment) and MAPS (Measurement of Air Pollution from Satellites. Image Credit: NASA [46].**

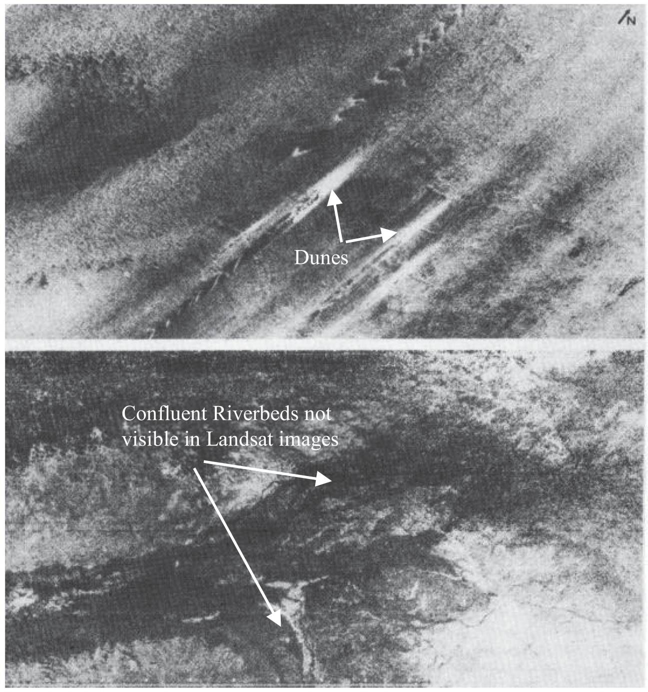

FIGURE 4. **Comparison of Landsat optical image (top) with SIR-A SAR image (bottom) of the region in the Arbain desert where Elachi *et al.* demonstrated that SIR-A was able to penetrate the overlaying sand dunes and down to hidden riverbeds. The center region in the SIR-A image shows two riverbeds coming together. The bright diagonal streaks in the Landsat photo are sand dunes that hide the underlying alluvium. Image reproduced from [59], Fig. 2. © IEEE, 1984, with permission (note image in [59] has (a) & (b) labelled incorrectly in the caption – top is Landsat, bottom SIR-A).**

orbital track (side-looking SAR). The ground track pixel size was 40 × 40 meters, and the radar pulse power was 1 kW. The backscatter radar interferograms were recorded onto an optical film through a cathode ray tube using an instrument left over from the Apollo 17 Lunar Sounder Experiment and was 14 years old when it was flown on SIR-A [46]. A photo of the payload on STS-2 with labels for the five instruments flown is shown in Figure 3. Approximately eight hours of observations were recorded, which demonstrated many of the SAR capabilities already realized from Seasat [47]–[52] and which led to a remarkable and unexpected geological discovery placing space-based radar observations at the heart of a revolution in geologic observations of the Earth as well as a significant new tool for archeologists!

When the images from SIR-A were processed, like the Seasat data, there were contrast features that were not immediately recognized as being due to expected backscatter patterns. Several such occurrences were spotted over imaging tracks that took SIR-A across very dry regions, especially in the sand covered desert areas of northern Africa. Geologists on the team noticed meandering patterns and coalescing tracks that appeared a lot like water pathways, but where overlaying NASA Landsat imagery showed nothing but sand dunes. Although the team was aware of the penetrating capabilities of microwaves in ice, they were not expecting significant soil penetration. However, the loss tangent of dry sand is in the range of 10^{-2} and the permittivity at 1 GHz is in the range of 3–4. The SIR-A pulses were penetrating an estimated 1.5–6 meters below the surface in places like the Sahara Desert [52]. What looked like riverbeds in the SIR-A images were very likely buried features with density differences sufficient to show backscatter contrast against the loose overlying sand (Figure 4).

In late September of 1982, a team from the US Geological Survey office in Flagstaff, Arizona put together a ground surveying expedition to a "buried river" feature highlighted in the SIR-A images in the Arbain desert – an extremely arid, dune covered area in southern Egypt and crossing over into northern Sudan. Elachi joined the expedition which included geologist and instrument scientist Ron Blom from JPL, long-time colleagues Gerald Schaber, J.F. McCauley and others from the USGS, a geo-archeologist, C.V. Haynes from University of Arizona, and a large local team from the Egyptian Geological Survey and Mining Authority. After flying to Cairo, they all met up in Kharga Oasis 200 km west of the Nile and at the boundary of the Arbain Desert. Another 10-hour drive across the sands brought them to the SIR-A track where, with a series of test pits, they were able to confirm the riverbed alluvium under the sand as well as uncovering artifacts from the human inhabitants of the region when it had been wet and habitable. Their findings, along with an overview article on SIR-A by Elachi [53], were published in the Dec. 3, 1982 issue of *Science* [54], which included a cover photo, and drew immediate global attention [55]–[57].

Coming back to the flight of SIR-A, literally within weeks of the STS-2 landing in Nov. 1981, Elachi had secured a second shuttle flight for what would be called SIR-B. SIR-B would field an improved instrument using most of the same hardware as flown on SIR-A, but with the ability to change the antenna angle and imaging track to allow for stereographic measurements and to reveal topological features. The JPL team began preparing for their next deployment, which was still a couple of years away.

Perhaps spurred on by this ever-increasing application of and attention to his research, and his association with geology and geologists, Elachi managed to set aside some time to go back to school and get a master's degree in geology at UCLA in 1983. Apropos, and during this period, JPL geologist, Ron Blom received an unsolicited phone call from documentary film maker Nicolas Clapp, who was putting together a story about an ancient and well rumored but lost city known as Ubar. It was thought to be somewhere in modern Oman and had served as a notable desert oasis and crossroads for the Frankincense trade more than 2000 years ago [58]. Clapp believed that NASA's penetrating radar imagery could help locate the lost city. Blom spoke to Elachi about the possibility of using SIR-B to look for Ubar and arranged a meeting with Clapp. Clapp is quoted [58] as stating that Elachi's response was: "Okay, let me get this straight: You want to use my spaceship to find your lost city?" It was too good an opportunity for Elachi – a newly degreed geologist with a strong Middle Eastern heritage – to pass up. It was agreed that so long as it did not interfere with the main mission goals, Ubar would be a target of opportunity for SIR-B. Meanwhile, more rigorous algorithms for pulling out the subsurface L-band SAR contrast in dry sands were being worked out [59].

SIR-B was slated for STS-41G which would launch on Oct. 5, 1984 and stay in orbit for a tad over a week. It would test the SAR instrument at three different altitudes (varying resolutions on the ground) and a number of different track angles (inclinations). This time, all the SAR data was digitized and saved on a high-density data rate recorder (HDDR) on board the shuttle and immediately relayed through TDRS (tracking and data relay satellites) to various ground stations. There was also a back-up optical system as on SIR-A. This was fortunate, as several technical problems, including a major fault in the positioning of the TDRS data transmit antenna, reduced the HDDR dataset to only around 7.5 hours, but the optical recorder on board brought in an additional 8 hours of imagery [60]. Despite the problems, the major engineering goals and a good portion of the science were all realized [61]–[64], including image tracks that would later be used to hunt for (and most likely uncover) the lost city (oasis at least) of Ubar[3] [65], [66], [67]! The benefits of performing microwave SAR measurements from space were now securely confirmed and the data was now being sought after by oceanographers, geologists, and archeologists [68]. Elachi also continued work on SAR data capabilities and analysis [69]–[71].

In 1984, Elachi took on the role of Manager of the entire Earth and Space Science Division at JPL, a major responsibility change from supervising a technical group. He was now overseeing hundreds of scientists and engineers, dozens of space flight instruments and missions, and many more proposals for potential JPL space science investigations.

By 1987, the radar group was ready for the next phase of the SIR series. This time the goal was multispectral imaging: using three microwave channels in L-, C-, and X-band (1.25, 5.3 and 9.6 GHz) to simultaneously acquire SAR data that could be used for more nuanced topological and geophysical signatures (for example, higher frequencies scattered off treetops, while longer wavelengths penetrated to the forest floors). It was also time for another major promotion. At JPL Director Lew Allen's urging, Elachi became the head of a new Directorate: Space and Earth Science Instruments, and at age 41, took a seat on the prestigious JPL Executive Council. As if he wasn't busy enough, he also turned his popular Caltech class notes from EE/GE 157, "Introduction to the Physics of Remote Sensing," which he had been teaching since 1982, into a textbook [72], providing a comprehensive resource for the next generation of space-geologists and geophysicists. Elachi was also rewarded by election to the National Academy of Engineering in 1989.

SIR-C was a much more complex instrument than anything the JPL radar team had built to date [73]. The three frequency bands required development of an extremely complex antenna and transmit/receive arrangement. The L and C band channels were implemented with dual-polarized microstrip patch antennas (18 in each band) and this time fed by multiple transmit receive (T/R) modules: 14 per antenna panel at L band, and 28 per antenna panel at C band. The arrangement created a phased array that could implement electronic beam steering from 38 to 123 degrees off the track direction. This was a major improvement over SIR-B, as the very large antenna structure (12 × 3.7 meters) and now weighing over 3300 kg, no longer had to be mechanically moved for data collection. The trade-off however, was that there were over 750 T/R modules needed to operate the two lower frequency channels. The L and C bands also had complete quadrature polarization sensing for the first time (HH, HV, VV, and VH) so that differences in backscatter signals due to target characteristics that had preferential polarization signatures could be used to enhance contrast.

The new X-band channel was contributed by DARA/DLR (the German Space Agency) and the ISA (Italian Space Agency) who were now, after seeing what JPL had done, heavily involved in developing their own SAR systems for space. The DARA/ISI X-band channel used a long slotted waveguide antenna with only one polarization and was mechanically tilted (it weighed only 49 kg) to align with the lower frequency L- and C-band channels during observations. A traveling wave tube amplifier provided the 3.35 kW pulsed

[3]Nicholas Clapp did indeed put together both a documentary film and a book highlighting his expeditions to Oman to search for the lost city of Ubar. Both Ron Blom, and for a short time, Charles Elachi, accompanied the expedition, which took place in 1993. As it turned out, the team did uncover an ancient oasis, and with the use of ground penetrating radar, a fort around it, using the SIR-B data to get to the general location where Ubar was expected to lie buried. Many subsequent archaeological investigations followed, and Ubar is now a major tourist attraction in Oman (https://omanpocketguide.com/tale-of-a-lost-city-ubar/).

source (up to 1700 pulses/sec) for the 9.6 GHz signal. The ground resolution for the L and C band channels was approximately 30 meters, and the X-band instrument had a 25-meter azimuth footprint. The corresponding range resolutions were 25, 25 and 20 m respectively for the three frequencies. The overall data rate was 90 Mbit/sec for the L and C channels, and 45 Mbit/sec for the X-band channel. All data was collected and stored on HDDR tape on board the shuttle for later processing – 32 terabits of it [73]!

SIR-C flew on two separate shuttle missions with near-identical overpass tracks but separated by six months: STS-59 from Apr. 9–20, 1994, and STS-68 from Sep. 30-Oct. 11 of the same year. This allowed the SAR instrument to collect and compare repeat passes over the same landscape and visualize both seasonal variations and potential movement within the scene – for example changes in snow or ice pack coverage, earthquake fault lines, etc. On both flights the SIR-C instrument performed beyond expectations, providing the first complete polarization/multispectral datasets for space-microwave SAR and imaging more than 400 key ground sites. The NASA portal describing the SIR-C instrument perhaps summarizes it best [73]: "The SIR-C/X-SAR science team, consisting of 52 investigator teams from more than a dozen countries, were using the SIR-C/X-SAR data in studies of ecology, hydrology, geology, and oceanography. Interferometric data were used for topographic mapping and surface change monitoring. In addition, observations of rainstorms demonstrated for the first time the capability of a multifrequency, multipolarization spaceborne radar system to quantify precipitation rates and to classify rain type … *Radar imaging of Earth has never been the same since SIR-C/X-SAR's demonstration of what's known as simultaneous multifrequency, fully polarized, repeat-pass interferometric SAR*." Quoting Charles Elachi directly, "SIR-C/X-SAR was the path opener for multiple U.S. and international missions that followed." A favorite Elachi image from SIR-C appears in Figure 5.

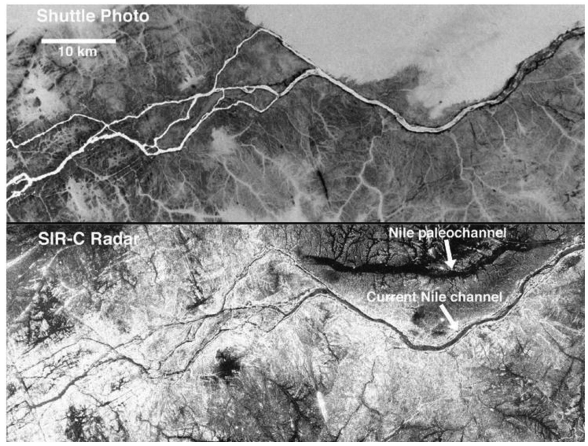

FIGURE 5. **SIR-C Image (bottom) compared to Landsat Image (top) of a region in Egypt where the Nile River has changed course in recent times. The SAR image (bottom) clearly shows the buried riverbed hidden under the sand – which appears in the Landsat (top) photo. Note the much higher contrast and detail of the SIR-C multispectral radar image compared to the SIR-A image shown in Fig. 2. Figure from Charles Elachi (NASA/JPL), 1994, with permission.**

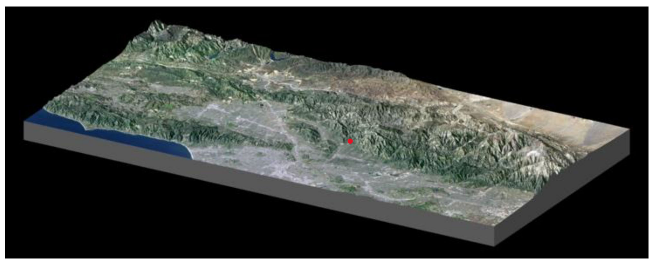

FIGURE 6. **SRTM Topological map of the Los Angeles Basin and surrounding mountains. Red dot = JPL. Image credit NASA/JPL/ NIMA, 2002: https://photojournal.jpl.nasa.gov/catalog/pia04967.**

Soon after the extremely successful SIR-C flights, Elachi became Director for Space and Earth Science programs at JPL, a precursor to his becoming the Director of the Laboratory in 2001. The SIR-C legacy was continued under the SRTM (Shuttle Radar Topography Misson) which flew on STS-99 in February 2000 and orbited for 11 days. SRTM carried C-band and X-band SAR imagers in the shuttle bay, similar to SIR-C, but with an externally deployed telescoping mast to hold additional phase-linked receive antennas in both bands at a distance of 60 meters from the primary transmit antennas. This gave the instrument instantaneous interferometric capability and allowed detailed topographical measurements (30 $\times$ 30 m horizontal track with 6 -10 m vertical resolution) to be made over 80 percent of the Earth's surface during the length of the mission [74], directly in digital format, thus replacing the traditional human labor-intensive stereographic approach (Figure 6).

Meanwhile, the planetary study that began Elachi's JPL career way back in 1971 [22], had finally become a mission. The Magellan spacecraft lifted off from Kennedy Space Center on May 4, 1989, with the major objective of topologically mapping the surface of Venus using microwave SAR. Magellan also carried radiometers for temperature and spectroscopic sounding of the upper atmosphere and an altimeter. The radar operated at 2.4 GHz using a 3.7-meter diameter antenna and had 150-meter range resolution. By the end of its roughly four- and half-year mission, Magellan had mapped 98% of the Venusian surface with an accuracy of around 100 meters [75]. Elachi was a science team member and was overseeing many aspects of the mission in his Directorate's role at JPL. He also worked with science team members on publishing some of the key initial SAR measurements, which came out in a special issue of *Science* in 1991 [76]–[79].

In the interim between major missions, Elachi continued to work, lecture, and publish [80]–[83]. Next up on the spacecraft queue was the major ESA/NASA/ISA (Italian Space Agency) Cassini - Huygens mission, which was going to Saturn with several planetary encounters along the way, and for our first detailed look at Saturn's moon, Titan. Elachi had been the team leader for the Cassini SAR instrument since 1990, so this was a particularly important mission for him. Cassini was the most ambitious planetary space system ever launched.

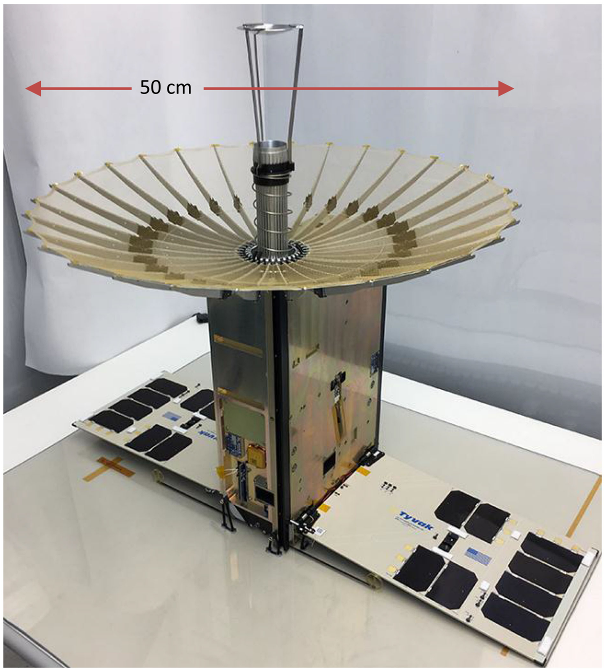

FIGURE 7. Photo of RainCube, a JPL/NASA CubeSat instrument deployed from the International Space Station in March 2018 and demonstrating a Ka band (35.75 GHz) radar for Earth precipitation mapping. The instrument was only 12 kg and used 35 W of power – compare to SRTM at 13,600 kg and 900 kWh! Image credit NASA/JPL ESTO 2018: https://www.jpl.nasa.gov/cubesat/missions/raincube.php.

Weighing in at over 5700 kg and carrying 12 instruments plus the Huygens probe that was to descend to Titan, it launched (appropriately) on a Titan IV rocket from Cape Canaveral on Oct. 15, 1997, on a 6-year trip to Saturn and a mission that lasted just a few weeks shy of 20 years! The original concept dated back to a European Science Foundation proposal from 1982 and became a competing US effort in 1983. Budget and teaming considerations turned the mission into a joint ESA/NASA collaboration in 1988 [84].

The Cassini imaging radar system operated at 13.78 GHz generating five separately switched and targeted beams through the satellite's main high gain antenna (3 m diameter). Weighing in at only 41.4 kg and consuming only 108 W it produced a beam with 0.35–1.7 km resolution and could penetrate through the atmosphere of Titan [85]. The ubiquitous science data from Cassini-Huygens classifies the program as one of the most productive and inspiring of any other planetary mission other than perhaps Voyager. Some of Elachi's most important papers from the SAR instrument are listed in [86]–[101], with the most exciting being the discovery of Titan's methane seas [90], [98]. Cassini appeared as the cover article in the May 13, 2005 issue of *Science* [89].

In 2001, Elachi became the 10th Director of JPL, taking the reins from Voyager Principal Investigator, Edward Stone. During his 16-year tenure as JPL Director, Elachi oversaw the launch of 24 space missions including the spectacularly successful landing of three rovers on Mars: Spirit, Opportunity, and Curiosity [102]. His many innovations in both science and mission proposals and instruments, as well as his dynamic and progressive management style earned him a prominant place within the historical leadership of NASA during what can only be termed a Golden Age for US space exploration. In 2006, David Gergen, writing for *US News and World Report* named him as one of 20 of "America's Best Leaders" on a most enviable list [103]. After retiring from the Directorship in 2016, the JPL Mission Control Center was renamed "The Charles Elachi Mission Control Center," a fitting honor.

Elachi continues to work at Caltech, to do research and to publish [104]. He just released the third edition of his Remote Sensing tome [105], with long-time friend and colleague at JPL and Caltech, Jacob van Zyl, who sadly passed away just a couple of weeks before the textbook was to be released. Perhaps the best moniker to describe Charles Elachi and his long and fruitful career was expressed by the title of an article written about him in in *Aerospace America* [106], Charles Elachi, "Space Explorer." In a fitting tribute to the technical progress this *Space Explorer* stimulated and spun off in the field of microwave radar from space is the image shown in Figure 7 of a recent JPL/NASA CubeSat instrument that was delivered to, and launched from, the International Space Station in 2018. Compare this to the SRTM! Last year Elachi received the National Air and Space Museum Lifetime Achievement Award.

We close this short biographical piece by looping back to our opening, and state that Charles Elachi has clearly lived up to his own mantra and *Dared Mighty Things*. We have all benefitted!

SUBJECT BIO

CHARLES ELACHI (Fellow, IEEE) received the B.Sc. degree in physics from the University of Grenoble, Grenoble, France, in 1968, the Dipl. Ing. degree in engineering from the Polytechnic Institute, Grenoble, France, in 1968, the M.Sc. and Ph.D. degrees in electrical sciences from the California Institute of Technology, Pasadena, CA, USA, in 1969 and 1971, respectively, the M.B.A. degree from the University of Southern California, Los Angeles, CA, USA, in 1979, and the M.Sc. degree in geology from the University of California, Los Angeles, Los Angeles, CA, USA, in 1983.

In 1970, he joined the Jet Propulsion Laboratory (JPL). From 2001 to 2016, he was the Director of JPL and the Vice President of the California Institute of Technology. He is currently a Professor (Emeritus) of electrical engineering and planetary science with the California Institute of Technology. During his 46-year career with JPL, he was a leader with developing the field of spaceborne imaging radar. He is currently a Principal Investigator on numerous research and development studies and flight projects sponsored by NASA, including the Shuttle Imaging Radar series (Science Team Leader), the Magellan Imaging Radar (Team Member), and the Cassini Titan Radar (Team Leader), a Co-Investigator of Rosetta Comet Nucleus Sounder Experiment, and a member of Science Team on NASA's mission to Europa. During his 15 years as the Director of NASA's JPL, he has completed 23 successful deep space missions, including landing three rovers on Mars (Spirit, Opportunity, and Curiosity) and two missions that returned extraterrestrial samples to Earth containing solar wind molecules and comet particles that are more than 4.5 billion years old. He is the author of more than 230 publications and the holder of several patents.

Dr. Elachi is a Fellow of the American Institute of Aeronautics and Astronautics and a member of the National Academy of Engineering and the International Academy of Astronautics. He was the recipient of the von Karman Award from the International Academy of Astronautics (IAA), the highest honor, in 2019. He was also the recipient of numerous other awards, including the ASP Autometric Award in 1980 and 1982, the NASA Exceptional Scientific Medal in 1982, the IEEE Geoscience and Remote Sensing Distinguished Achievement Award in 1987, the IEEE Medal of Engineering Excellence in 1992, the Wernher Von Braun Award in 2002, the NASA Distinguished Service Medal in 1999, the NASA Outstanding Leadership Medal in 1994, 2002, and 2004, the American Astronautical Society Space Flight Award in 2005, the NASA Exceptional Service Medal in 2005, the America's Best Leaders by *U.S. News & World Report* and the Center for Public Leadership at the Harvard University's Kennedy School of Government in 2006, the International von Kaŕmań Wings Award in 2007, the International von Kaŕmań Wings Award in 2007, the Sigma Xi William Procter Prize for Scientific Achievement in 2008, the National Academy of Engineering Arthur M. Bueche Award in 2011, the Space Foundation J. E. Hill Lifetime Space Achievement Award in 2011, the AIAA Carl Sagan Award in 2011, the 2016 National Space Trophy, the 2016 IAF Allen D. Emil Memorial Award, the Association of Space Explorers (ASE) Congress Crystal Helmet Award in 2012, the Aviation Week Lifetime Achievement Award in 2016, and the *Enigma Magazine* Award in 2019. He received two very special honors: the "Chevalier de la Legion d'Honneur" from France in 2011 and the "National Order of the Cedar" from Lebanon in 2006. He has also an asteroid named after him in recognition of his contributions to planetary exploration, and the NASA/JPL Mission Control Center was renamed the "The Charles Elachi Mission Control Center" in his honor in 2016.

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