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Key Point:

- An overview is presented of the origins of space radio and plasma wave research at the University of Iowa

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The Origins of Space Radio and Plasma Wave Research at the University of Iowa

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Abstract This paper discusses my recollections concerning the origins of space radio and plasma wave research at the University of Iowa. My career in space research started when I was hired as a freshman engineering student by Prof. James A. Van Allen in April 1958, shortly after his discovery of Earth's radiation belts with Explorer 1, the first U.S. satellite. My early work mainly involved digital data system designs for the University of Iowa “Injun” series of satellites, the first satellites completely designed and constructed at a university. It was on Injun 3 that, at the suggestion of Prof. Brian J. O'Brien, I developed one of the very first radio and plasma wave instruments ever flown on a spacecraft. This instrument made the first pioneering studies of a wide variety of space radio and plasma wave phenomena, such as whistlers, chorus, and auroral hiss. These early studies were soon followed by somewhat similar NASA-funded Iowa radio and plasma wave instruments that were used to explore Earth's magnetosphere with the Injun-5, S3-A, Hawkeye, IMP, and ISEE satellites, the solar wind with the Helios 1 and 2 spacecraft, and the outer planets and interstellar space with the Voyager 1 and 2 spacecraft. My discussions of this very early era in space research, and the key people involved, are limited to the time period before roughly 1980.

1. Introduction

This paper is in response to a request for my recollections regarding the origins of space radio and plasma wave research at the University of Iowa, with an emphasis on the era before 1980. My involvement in space research at Iowa began in April 1958 when I was hired as a freshman electrical engineering student by Prof. James A. Van Allen. This was a period of very rapid growth in space research at Iowa. Only a few months earlier, Van Allen had discovered Earth's radiation belts with Explorer 1, the first U.S. spacecraft. Explorer 1 carried a Geiger tube designed by Van Allen to study cosmic rays but instead discovered the very intense energetic charged particles that make up Earth's radiation belts (Van Allen et al., 1958). I was probably hired because of my experience with electronics in high school, which primarily involved vacuum-tube technology. In engineering classes and in Van Allen's lab, I quickly became knowledgeable about transistors, which had only recently come into common use. I was also very interested in spacecraft telemetry. All the early U.S. spacecraft, such as Explorer 1, used analog telemetry. Analog telemetry consisted of a voltage-controlled oscillator that generated a transmitted signal that was proportional to some voltage. The voltage-controlled oscillator input was typically switched between various voltage sources. In the case of Explorer, 1 they were switched between the flip-flop stages of the binary counter used to measure the Geiger tube counting rate (Ludwig, 1960). Although simple to implement, this type of telemetry was very difficult to analyze on the ground. The transmitted frequencies had to be decoded by hand using a paper chart recorder, which was very time-consuming and inefficient. At that time, computers did not exist on the campus at Iowa, and the word “digital” had not come into common usage.

At the suggestion of a newly hired Assistant Professor, Brian J. O'Brien, I was urged to start thinking about a spacecraft-borne “encoder” that would transfer the “0s” and “1s” in the binary counter to a corresponding serial sequence of “0s” and “1s” that could be transmitted to the ground. I did this by finding a very simple method of converting the binary counter (often called an accumulator) into a shift register using a voltage control line that had only one resistor and one diode per stage in the counter. This system is now called a “shifting accumulator” and was later the subject of a patent application by the Office of Naval Research. By using one shifting accumulator for each particle detector, I devised an encoding system that could produce a binary data stream from an arbitrary number of detectors. Analog voltages, such as battery voltages, could also be encoded by the simple addition of an analog-to-digital converter. This encoding system was developed and first used on the University of Iowa Injun 1 spacecraft (see Figure 1), the first spacecraft

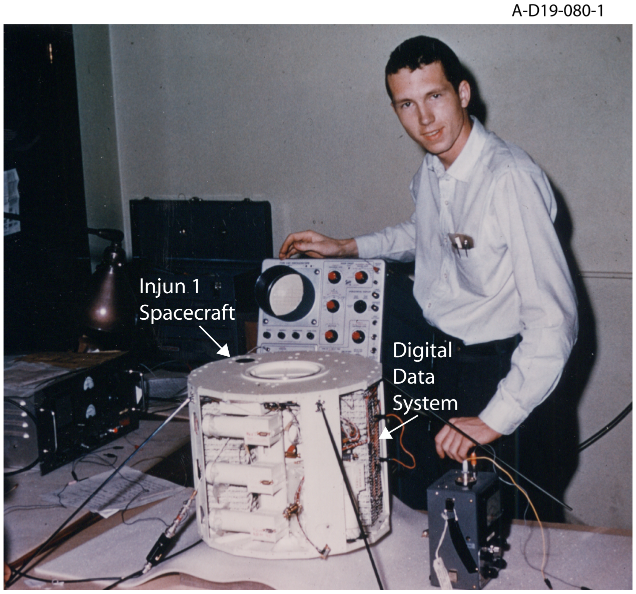

Figure 1. A picture of Don Gurnett, then an undergraduate engineering student, working on the Injun 1 spacecraft (ca. 1961). This was the first spacecraft designed and built entirely at a university and was one of the first spacecraft to use an entirely digital data system. The digital data system consists of the stack of electronics cards on the right-hand side of the spacecraft (photo courtesy of the University of Iowa).

designed and built entirely at a university. Using frequency-shift keying between two modulation frequencies, 3.072 and 4.096 kHz, which represented the "0s" and "1s," this encoder provided digital data at a bit rate of 256 bits/s from 13 particle detectors and an auroral photometer (O'Brien et al., 1962). Injun 1 was one of the first spacecraft to use an entirely digital data system and was the first in a series of five low-altitude polar-orbiting spacecraft built at Iowa, later known as the "Injun" series of satellites.

After the successful launch of Injun 1 on 29 June 1961, I took over as the project engineer in charge of the Injun 2 and 3 spacecraft. Unfortunately, Injun 2 suffered a launch failure on 24 January 1962, but Injun 3 was successfully launched on 12 December 1962. Note the very short development times between launches, less than a year. Because of noise in the telemetry link, it was soon discovered with Injun 1 that errors occasionally occurred in the binary data stream to the ground. If the error occurred in a high-order bit of a shifting accumulator, it could sometimes result in a very large fractional error in the counting rate for that detector. To counteract this annoying problem, starting with Injun 2, I incorporated a 16-bit error correction code at the end of each 256-bit data frame. The code was based on the sequential processing of the preceding 240 bits in the data frame using a feedback shift register scheme described in the pioneering book on error correction codes by Peterson (1961). This error correction system was used on all the subsequent Iowa satellites and virtually eliminated undetected errors. Such error-correcting codes have now become quite common and are widely used in spacecraft telemetry systems.

2. The First Iowa Plasma Wave Instrument

Next, let me explain how I became involved in space radio and plasma wave research. During the development of the Injun 3 spacecraft, Dr. Roger Gallet, a scientist from the National Bureau of Standards, came to Iowa and gave a seminar on some unusual very-low-frequency (VLF) radio sounds that had been detected with ground-based radio receivers. Three types were discussed: whistlers, dawn chorus, and VLF hiss. As part of his presentation, Gallet played audio recordings of each of these sounds, which I found to be quite fascinating. Whistlers consist of narrowband tones usually drifting downward in frequency on time scales of seconds. Whistlers were first reported by Barkhausen (1919) and were shown by Storey (1953) to be produced by the dispersive propagation of electromagnetic pulses from lightning through Earth's ionosphere and magnetosphere in a mode of propagation now known as the "whistler mode." Dawn chorus consists of many closely spaced audio frequency tones, often rising in frequency. In England, the term "dawn chorus" refers to the sounds made by birds when they wake up in the morning. Dawn chorus was also thought to be propagating in the whistler mode (Allcock, 1957) and is now usually referred to as simply "chorus" because it does not necessarily occur at dawn. VLF hiss consists of a broad band of radio noise thought to be associated with the aurora (Duncan & Ellis, 1959). Except for whistlers, which are produced by lightning, the origins of these unusual radio sounds were largely unknown, although it was guessed that they were somehow generated by streams or bunches of ionized particles moving along the magnetic field lines in Earth's radiation belts (Gallet, 1959). Since these VLF waves depended on the presence of an ionized gas (a plasma) to propagate, they are now generally called "plasma waves." For a discussion of the various wave modes that can exist in a plasma, including the whistler mode, see Gurnett and Bhattacharjee (2017).

After Gallet's seminar, O'Brien suggested to me that we should develop a VLF radio receiver for Injun 3. His initial suggestion was to include a frequency spectrum analyzer that could measure wave field intensities in a few select frequency channels, much as energetic charged particle instruments detect particles in different energy channels. After considering various options, we eventually contracted Raytheon Corporation to build a custom-designed spectrum analyzer for Injun 3. Raytheon was selected because they were already building audio frequency spectrum analyzers for laboratory use. However, their lab instrument, called a "Sonograph," was much too heavy to fly on a spacecraft, so we had them build a custom-designed

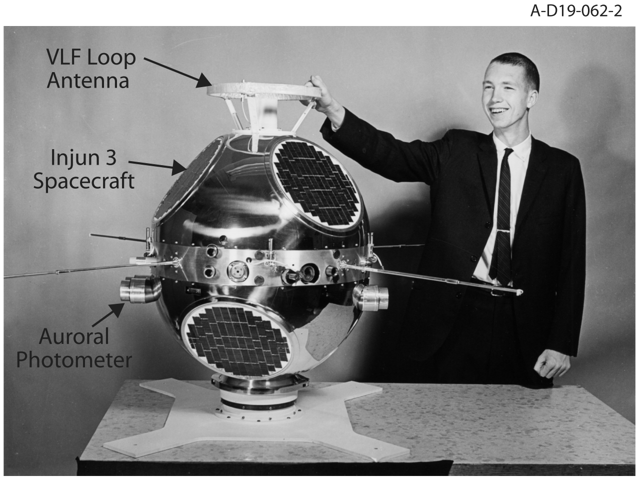

Figure 2. Don Gurnett pointing to the 50-turn loop antenna used by the VLF radio instrument on the Injun 3 spacecraft (ca. 1962). This was one of the first VLF radio instruments flown on a spacecraft, launched on 24 January 1962 (photo courtesy of the University of Iowa).

spectrum analyzer. Eventually, we settled on six channels covering the frequency range from 0.7 to 8.8 kHz (Gurnett & O'Brien, 1964). The limited number of frequency channels was dictated by spacecraft weight considerations. This type of spectrum analyzer is now usually called a multichannel analyzer or a sweep-frequency analyzer, depending on details of the design. Since ground-based VLF receivers at that time often used loop antennas for detecting the magnetic field of VLF electromagnetic waves, we decided to use a 50-turn loop antenna mounted on top of the spacecraft as shown in Figure 2. To limit interference from onboard electronics, such as the high voltage power supplies required for particle detectors, we required that all power supplies on the spacecraft operate at frequencies of 10 kHz or higher.

Although the multichannel analyzer was expected to give good spectrum measurements, with the limited spacecraft bit rate available and the large number of other instruments onboard, it soon became apparent that the wave intensities could be sampled at a rate of only about one sample every few seconds. Because of the limited frequency resolution and the very low sample rate, I realized that it would not be possible to resolve the complex fine structure of phenomena such as whistlers and dawn chorus. Being very impressed by the VLF sounds played by Gallet, I soon started to consider whether the signals from the loop antenna could be transmitted directly to the ground via the spacecraft 136 MHz transmitter. At this point we had already decided the digital telemetry would be transmitted at a bit rate of 1,024 bits/s (4 times that of Injun 1) using frequency-shift keying at 10.24 and 14.30 kHz. With this system, there was obviously an available frequency band somewhat below 10 kHz that could be used to directly transmit the VLF audio signals to the ground. However, we had to be very careful that these signals not be allowed to interfere with the digital frequency-shift-keyed signals, otherwise the digital data stream from the other instruments on the spacecraft could be seriously compromised. To keep the baseband VLF audio signal from interfering with the digital signal, we used a 0.5 to 7 kHz band-pass filter to restrict the VLF analog signals to a frequency range well below those used in the digital data channel.

There were also several other problems that needed to be considered. Because of the relatively wide bandwidth of the analog channel, ~7 kHz, and from our inflight experience with Injun 1, I anticipated that the signal-to-noise ratio available in the analog channel would be rather poor, probably only 6 to 8 dB. Since the signals from the loop antenna were expected to have a very large dynamic range, possibly as much as 80 to 100 dB, it was clear that an automatic gain control had to be used to adjust the amplitude of the transmitted VLF analog signal to the very narrow signal-to-noise ratio range available in the audio channel. Also, since the spacecraft transmitter was phase modulated, which had certain advantages, the amplitude of the combined signals from the analog channel and the digital channel had to be limited to a total phase deviation of not more than ±90°. Otherwise, the resulting nonlinear distortion near and beyond ±90° would cause strong cross-coupling between the two channels. To assure that this maximum phase deviation was never exceeded, diode limiters were placed on both the VLF analog signal and the frequency-shift-keyed signal such that the total phase deviation could never exceed ±90°. Both signals were given equal amplitudes. The combination of the 0.5 to 7 kHz band-pass filter, the automatic gain control amplifier, and the associated signal limiters was called a “wideband receiver” and is shown in the block diagram of the VLF instrument in Figure 3.

I also worried about another potential problem, which was that the phase modulated signal from the powerful, 1 W, spacecraft transmitter might get nonlinearly detected in the very sensitive loop antenna preamplifier. If such nonlinear detection was to occur and if the net gain around the signal path were greater than one, the system might become unstable. Such an instability could lead to uncontrolled oscillations in the analog VLF channel, like what sometimes occurs in a microphone/audio speaker system. To minimize this possibility, we carefully shielded the loop antenna with aluminum foil grounded to the metal shell of the spacecraft and installed various radio frequency filters throughout the wideband receiver system. Subsequent spacecraft testing of this hybrid analog/digital telemetry system showed that no oscillations occurred. This testing was complicated because to avoid interference from 60 Hz power lines, it had to be

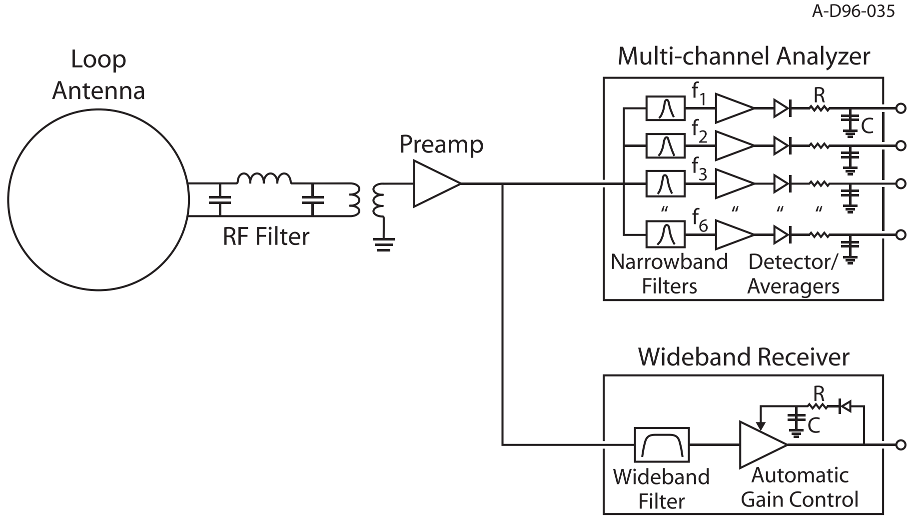

Figure 3. A block diagram of the Injun 3 VLF radio instrument. The instrument consisted of two main elements: (1) a multichannel frequency spectrum analyzer that provided wave intensity measurements at six discrete frequencies, $f_1 =$ 0.7 kHz through $f_6 = 8.8$ kHz; and (2) a wideband receiver that provided high-resolution analog waveform measurements over a broad frequency range, roughly 0.5 to 7.0 kHz (figure adapted from Gurnett & O'Brien, 1964, Figure 1).

performed in a low noise environment (my father's farm) well away from Iowa City. Despite this testing, Van Allen and O'Brien, who had the overall scientific responsibility for the spacecraft, insisted that a separate digital mode of operation, exactly like Injun 1 and controlled by ground command, be included in case the VLF analog telemetry system did not work properly.

When the spacecraft was launched, the VLF analog channel performed exactly as designed. I can still clearly remember when the transmitter was first turned on over Iowa City. We immediately heard an astonishing combination of whistlers, dawn chorus, and other strange VLF radio sounds. One of the ground telemetry station operators wrote in the station log book that the signals sounded like “the gun battle at O.K. Corral.” This was in late December 1962. A few weeks later, after Van Allen had heard some of the new space sounds, he called me to his office and told me that he wanted me to give a talk at the annual (January) meeting of the International Scientific Radio Union, which was held at the National Academy of Sciences in Washington, DC. As it was too late to submit an abstract for the meeting, he gave me a hand-written note asking Colin Hines, the chairman of International Scientific Radio Union-VLF session, to allow me to give a talk on our new results. I remember that the meeting was rather sparsely attended, as there were only a handful of people then doing ground-based VLF research. I do remember meeting Prof. Robert Helliwell, who would later become one of my mentors at Stanford University. This was my first scientific talk, a turning point in my career. It was at this point that I decided to switch from electrical engineering to physics. It is also ironic that this talk was in the same room where I would be inducted, over 35 years later, as a member of the National Academy of Sciences for my pioneering work on space plasma wave research.

Within the next year, after finishing my B.S. in electrical engineering in 1962 and starting on my Ph.D. program in physics, we began intensively studying the new VLF data from Injun 3. Without going into extensive detail, I will summarize some of the advances that were made. First, among the “new” plasma wave sounds that we heard was a rising tone at about 200 to 500 Hz that occurred immediately after an upgoing short-fractional-hop whistler. An example is shown in Figure 4. This rising tone turned out to be an entirely new type of whistler that propagates in a left-hand polarized electromagnetic mode now known as the ion cyclotron mode. The explanation of this new phenomena, now called an “ion cyclotron whistler,” eventually became my Ph.D. thesis (Gurnett et al., 1965). Also, see Shawhan and Gurnett (1966). The second major advance had to do with chorus. From observations on repeated high inclination passes over Iowa City, it became apparent that the intensity of chorus varied systematically with latitude. When the average wideband magnetic field intensity of chorus was plotted as a function of the McIlwain L-value, it was soon found that the most intense chorus occurred around $L \sim 5$, right in the middle of the outer Van Allen radiation belt (Gurnett & O'Brien, 1964; see Figure 5). Since the outer radiation belt is dominated by energetic 10 to 100 keV electrons, this new

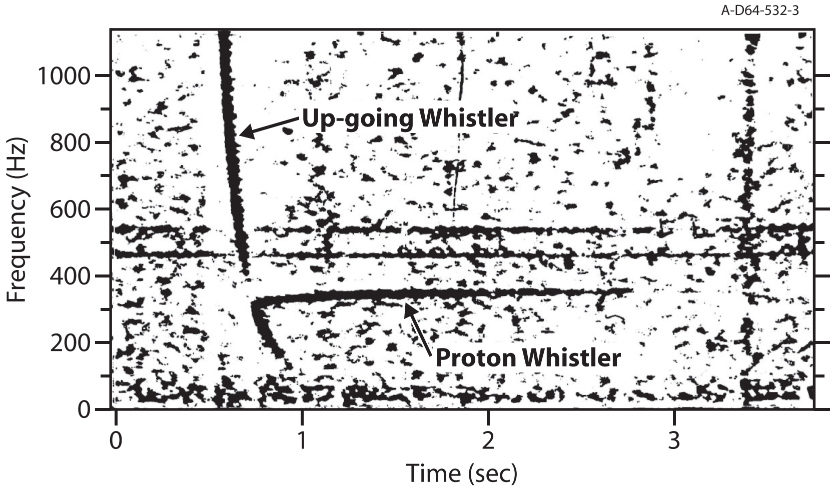

Figure 4. An example of a proton whistler detected by Injun 3. Proton whistlers consist of a narrowband tone rising in frequency immediately following an upward propagating short fractional-hop whistler. The frequency of the tone was found to be asymptotic to the local proton cyclotron frequency, which in this case is about 340 Hz. Later observations showed similar rising tones that were asymptotic to the cyclotron frequency of other positively charged ions in the ionosphere, such as He^+ and O^{++}. These ions associated whistlers are now called ion cyclotron whistlers (Gurnett et al., 1965) (figure originally appeared in Gurnett et al., 1965 Figure 1).

observation provided the first clear indication that chorus was produced by energetic electrons in the outer Van Allen radiation belt. This key observation provided the basis for the now famous theory by Kennel and Petschek (1966), who knew of our 1964 results, that whistler-mode radiation such as chorus is generated via a cyclotron resonant interaction with geomagnetically trapped energetic electrons in the outer radiation belt (I worked for a short time as a consultant for Kennel and Petschek at Avco-Evertt Corp. in the summer of 1965). Their theory also predicted that this resonant interaction would result in the precipitation of the resonant electrons. Later, using the Injun 3 data, we showed (Oliven & Gurnett, 1968) that chorus is closely associated with bursts of energetic, ~40 keV, electrons precipitating from the outer radiation belt, just as predicted. The third major advance was the observation on a series of high-latitude passes that the broadband whistler-mode noise known as VLF hiss, now commonly called auroral hiss, was directly related to the precipitation of the same low-energy ~10 keV electrons that produced the auroral light emissions (Gurnett, 1966; Gurnett & O'Brien, 1964). This association is illustrated in Figure 6, which shows simultaneous observations of (a) precipitating electrons detected by the onboard electron multiplier, (b) auroral light emission from the onboard photometer, and (c) auroral hiss intensities from the mult-channel spectrum analyzer. A key element that made these observations possible was the use of a bar magnet to align the spacecraft such that the fields of view of the electron multiplier and the auroral photometer were parallel to the local geomagnetic field (O'Brien et al., 1964).

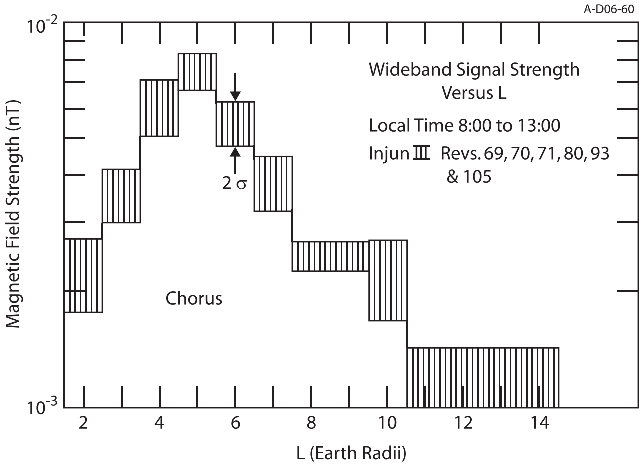

Figure 5. The average magnetic field intensity of chorus as a function of the McIlwain *L*-value in the morning local time sector, where chorus is often most intense. These early Injun 3 observations showed that chorus reached peak intensities in the outer Van Allen radiation belt at $L \sim 5$. These results provided the experimental basis for the theory, later developed by Kennel and Petschek (1966), that whistler-mode emissions such as chorus are generated by a cyclotron resonant interaction with energetic electrons in the outer radiation belt (figure originally appeared in Gurnett & O'Brien, 1964, Figure 9).

3. The Great Expansion in NASA Funding, 1965–1980

Nearly all the very early space research at Iowa was funded by the Office of Naval Research through contracts and grants to Van Allen. He had close connections to the Navy due to his wartime work on proximity fuses at the Johns Hopkins Applied Physics Laboratory and his later work on cosmic ray studies with captured V-2 rockets at White Sands, NM (Foerstner, 2007). At that time, the Office of Naval Research was a traditional source of support for scientific research in the United States. This source of support was largely ended by the Mansfield Amendment in

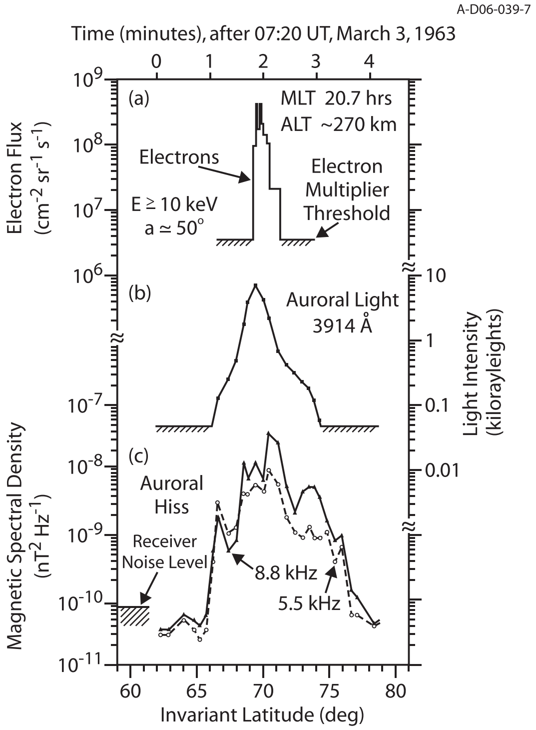

Figure 6. A high latitude Injun 3 pass over the northern auroral zone that shows (a) the simultaneous detection of precipitating ~10 keV electrons, (b) auroral light, and (c) auroral hiss. This and other comparable observations over the auroral zones provided the first convincing evidence that auroral hiss is produced by the same precipitating low-energy electrons that produce the auroral light emission (figure adapted from Gurnett, 1966, Figure 15).

1969. Although NASA was formed by an act of Congress in July 1958, it took several years before significant funding opportunities became available to propose instrumentation on NASA spacecraft. At the recommendation of Van Allen and the support of a NASA Traineeship at Iowa, in 1964–1965, I moved to Stanford University to work under the mentorship of Bob Helliwell, who wrote the now famous book on "Whistlers and Related Ionospheric Phenomena" (Helliwell, 1966). I also took plasma physics courses from Peter Sturrock and Oscar Buneman, which proved to be very valuable in my subsequent career. Upon finishing my Ph.D. thesis in the spring of 1965, I returned to Iowa, now as Assistant Professor, with the objective of continuing my research and teaching a new course on the rapidly developing subject of Plasma Physics. With a freshly minted Ph.D. in hand, I also began to seek funding for plasma wave instrumentation on NASA spacecraft. In this endeavor I was quite successful. A list of the various projects for which I received NASA funding from 1965 to 1980 is given in Table 1.

This period was a time of great expansion in all areas of space research, including space plasma waves. From the "orbits" column in Table 1, a clear progression can be seen from low-altitude polar orbiting spacecraft like Injun 5, which had an apogee altitude of 2,528 km, to increasing distances from Earth, like the Interplanetary Monitoring Platforms, IMP-6 and IMP-8, which had apogee radial distances of 33.3 and 46.3 R_E (Earth radii), respectively. Eventually, this trend went on to include non-Earth-orbiting projects, such as the Helios 1 and 2 missions close to the Sun, and interplanetary spacecraft, such as the Voyager 1 and 2 missions to the outer planets (Jupiter, Saturn, Uranus, and Neptune) and into interstellar space. One can also see in Table 1 the strong trend from single institution projects, such as Injun 5, which was built entirely at Iowa, to much larger international spacecraft projects, such as the International Sun Earth Explorers, ISEE-1, ISEE-2, and ISEE-3, which had instruments from 32 different institutions located in a dozen, or more, countries. This trend for participation of individuals from different institutions was also characteristic of plasma wave research. Although the University of Iowa played a key role in the construction of most of plasma wave instruments listed in Table 1, crucial ideas and complementary instrumentation were provided by individuals from other institutions. These included Bob Stone at Goddard Space Flight Center (GSFC; IMP-6 and Helios), Paul Kellogg at the University of Minnesota (IMP-6 and Helios), Fred Scarf at TRW Corporation (IMP-6, Voyagers 1 and 2, and ISEE-1, ISEE-2, and ISEE-3), Forrest Mozer at the University of California, Berkeley (ISEE-1, ISEE-2 and ISEE-3), and Jim Warwick at the University of Colorado (Voyagers 1 and 2).

Nowhere do these institutional collaborations play a bigger role than in the design and implementation of electric antennas. Since electrostatic waves in a plasma have no magnetic fields, for the comprehensive design of a plasma wave investigation, such instruments must have one or more electric field antennas. The design of electric antennas is difficult because they almost always have a big impact on the spacecraft structure and dynamics, as well as potentially interfering with the fields of view of other instruments. My first experience with an electric antenna was on the Injun 5 spacecraft (Gurnett et al., 1969). Motivated by the double-probe ideas of Fahleson (1967), I chose to provide a single-axis electric antenna by measuring the voltage difference between two 20.3 cm diameter conducting spheres mounted on the end of rigid folding booms as shown in Figure 7. The center-to-center separation distance between the spheres was 2.85 m. To distinguish electrostatic waves from electromagnetic waves, a 6-turn magnetic loop antenna was mounted on a separate long boom (see photograph in Figure 8), as far as possible from the spacecraft to reduce electrical interference from spacecraft. The alignment of the two antennas was chosen such that the axes of the electric ($+y$) antenna and the magnetic ($+z$) antenna were orthogonal. As with Injun 3, a bar magnet in the spacecraft was used to align the $+x$ axis of the spacecraft parallel to the geomagnetic field. With this system and using a dual-channel analog wideband receiver system to transmit the electric and magnetic field

Table 1
NASA-Funded Plasma Wave Instruments at Iowa, 1965–1980

Spacecraft	Launch date	DAG role	Orbit	Electric antenna	Magnetic antenna
Injun 5	1968 Aug. 8	Co-I[a]	Low-altitude polar, apogee altitude 2,528 km	Two single-axis spheres, 2.8 m separation	Single-axis 6-turn loop
IMP-6	1971 Mar. 13	PI	Eccentric-equatorial, apogee 33.3 R_E	Dual-axis, tubular dipoles, 92 and 53 m tip-to-tip	Triaxial single-turn loop
S3-A	1971 Nov. 16	PI	Eccentric-equatorial, apogee 5.2 R_E	Two single-axis spheres, 5.1 m separation	None
IMP-8	1973 Oct. 26	PI	Near circular-equatorial, apogee 46.3 R_E	Dual-axis, fine-wire dipole, each 122 m tip-to-tip	Triaxial search coil magnetometers
Hawkeye 1	1974 June 3	Co-I[a]	Eccentric polar, apogee 20.5 R_E	Single-axis, tubular dipole, 42 m tip-to-tip	Single-axis search coil magnetometer
Helios 1	1974 Dec. 10	PI	Heliocentric, 0.31 to 1.0 AU	Single-axis, tubular dipole, 32 m tip-to-tip	Tri-axial search coil magnetometers[b]
Helios 2	1976 Jan. 15	PI	Heliocentric, 0.29 to 1.0 AU	Single-axis, tubular dipole, 32 m tip-to-tip	Triaxial search coil magnetometers[b]
Voyager 2	1977 Aug. 20	Co-I later PI	Interplanetary, J, S, U, and N, then interstellar	Single-axis, v-shaped dipole, 2 tubular 10 m elements	None
Voyager 1	1977 Sept. 5	Co-I later PI	Interplanetary, J and S, then interstellar	Single-axis, v-shaped dipole, 2 tubular 10 m elements	None
ISEE-1	1977 Oct. 22	PI	Eccentric-equatorial, apogee 21.6 R_E	Dual-axis, fine-wire dipole, 215 and 72.5 m tip-to-tip	Triaxial search coil magnetometer
ISEE-2	1977 Oct. 22	PI	Eccentric-equatorial, apogee 21.6 R_E	Single-axis, fine wire dipole, 30 m tip-to-tip	Single-axis search coil magnetometer
ISEE-3	1978 Aug. 12	Co-I	Near equatorial halo orbit around L_1, then to G-Z	Dual-axis, fine-wire dipoles, each 90 m tip-to-tip	Single-axis search coil magnetometer

[a] Van Allen was PI of the spacecraft. [b] Provided by Braunschweig University.

waveforms to the ground, for the first time, we were able to determine the up and down directions of the Poynting flux of electromagnetic waves propagating along the geomagnetic field. A dramatic illustration of the effectiveness of this Poynting Flux system is illustrated in Figure 9, which shows the upward propagation of a whistler (red) from a lightning discharge immediately below the spacecraft, followed a few seconds later by the downward propagating whistler (green) returning from an ionospheric reflection in the opposite hemisphere. The subsequent reflection (red) of this downward propagating whistler due to the reflection from the ionosphere just below the spacecraft can also be seen. Another particularly interesting result of this Poynting flux measurement was the discovery that auroral hiss consisted of both upgoing and downgoing components, as shown in Figure 10. Later Gurnett and Frank (1972) showed that these upgoing and downgoing components of auroral hiss were directly related to beams of low-energy 100 eV to 10 keV electrons accelerated upward and downward along the auroral magnetic field lines by parallel electric fields. Quasi-static electric field measurements on Injun 5 also provided the first evidence of the U-shaped electrostatic potential structures now widely thought to be associated with parallel electric fields and Inverted-V electron acceleration events (Gurnett, 1972).

The S3-A satellite (see Table 1) also used a two-sphere electric antenna like Injun 5, but somewhat longer, with a 5.1 m sphere-to-sphere separation. The near-equatorial orbit of this spacecraft, with an apogee 5.2 R_E and a very specialized complement of instruments for detecting energetic electrons in Earth's outer radiation belt, made this spacecraft ideal for studying the origin of chorus (Anderson & Gurnett, 1973). However, due to weight limitations, a VLF magnetic antenna was not included in the instrumentation. This was unfortunate, because, had it been included with the magnetic antenna axis mounted orthogonal to the electric field antenna axis, as on Injun 5, we could have made wave Poynting flux measurements. Had this happened, we probably could have shown that chorus was generated within only a few degrees from the magnetic equator, a result that was eventually obtained nearly 20 years later by our three-axis electric and magnetic field measurements on the Polar plasma spacecraft (LeDocq et al., 1994).

As in most areas of science, there is strong pressure to increase the sensitivity of the measurements, and that is certainly true for spacecraft electric field measurements. Because the threshold noise level is set by the thermal noise of the electric field preamplifier (and sometimes spacecraft interference), the only practical

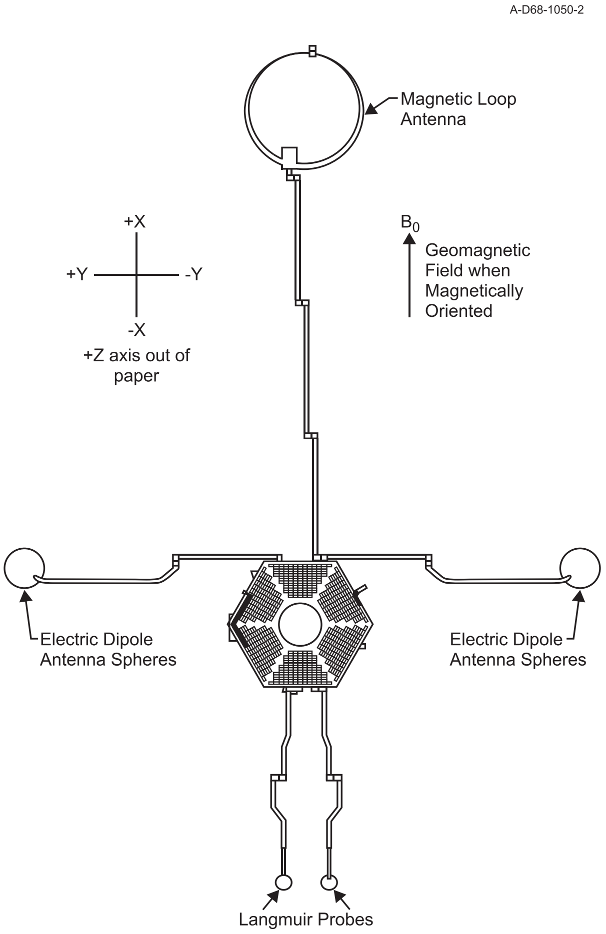

Figure 7. A drawing showing the orientations of the two-sphere electric field antenna and the magnetic loop antenna used on Injun 5. A bar magnet in the spacecraft was used to align the +*x* axis of the spacecraft parallel to the geomagnetic field (figure originally appeared in Gurnett et al., 1969, Figure 1).

method of increasing the electric field sensitivity is to increase the tip-to-tip length of the antenna. Several mechanical mechanisms have been developed over the years to make longer electric antennas. One such mechanism, developed by DeHavilland Corporation under the product name STEM (Storable Tubular Extendable Members), consists of a flat Beryllium-Copper tape, prestressed to roll up into a tube, that is initially stored on a cylindrical spool and then mechanically extruded to form a long tubular antenna element. A picture of a STEM-type deployment device is shown in Figure 11. Such antennas can be extended to considerable lengths. For example, the Alouette-1 spacecraft, launched on 29 September 1962, had two STEM electric dipole antennas with tip-to-tip lengths of 22.8 and 45.7 m. In the process of planning the wave experiment for the IMP-6 spacecraft, Bob Stone of GSFC suggested that we use such an extendable antenna for a combined radio astronomy/plasma wave instrument. He wanted the increased sensitivity of a long antenna in order to perform studies of low-frequency solar radio emissions, which were expected to be relatively weak. It was decided we would use two orthogonal dipole electric antennas with tip-to-tip lengths of 53 and 92 m. The different antenna lengths had certain impedance matching advantages for the radio astronomy measurements. The resulting instrumentation package, as eventually flown, came from four groups. The spacecraft group at GSFC procured the STEM antennas under contract from Fairchild Corporation and integrated the antennas into the spacecraft. Bob Stone's group at GSFC provided a 16-channel step-frequency (30 kHz to 10 MHz) radio astronomy receiver. My group at Iowa provided a wideband receiver, a 16-channel (20 Hz to 200 kHz) multichannel spectrum analyzer and a 1 m diameter triaxial loop antenna system. Paul Kellogg's group at the University of Minnesota provided a very high-resolution, 168-channel (12 Hz to 203 kHz) sweep-frequency receiver.

The IMP-6 spacecraft was successfully launched into a highly eccentric near-equatorial orbit (28° inclination) on 16 March 1971, with an apogee geocentric radial distance of 33.3 R_{E}. This was the first opportunity that my research group at Iowa had to make plasma wave measurements at large radial distances from Earth, well into the outer magnetosphere and solar wind. The first indication was that everything had worked properly, especially the electric antenna deployment mechanisms. However, it came as a surprise when Bob Stone called me shortly after launch and said that the radio astronomy instrument had a problem. It seemed that some type of interference was saturating the radio astronomy receiver over a broad frequency range from about 100 to 500 kHz. When I looked at our multichannel analyzer data, I could see the same type of broadband noise, also very intense but not saturating our instrument. Our multichannel spectrum analyzer purposefully had a very large dynamic range, ~100 dB, significantly greater than the step-frequency radio astronomy receiver. Upon further checking, it was found that the same type of noise was also present on the loop antennas. A quick check showed that the ratio of the electric (E) and magnetic field (B) intensities were consistent with $E = cB$, where c is the speed of light. This meant that the intense broadband noise was not some type of spacecraft interference but rather free space electromagnetic radiation, that is, a new type of radio emission. After collecting intensity measurements for more than a year to get good local time and radial distance coverage, we concluded that the radio emission originated from along the auroral magnetic field lines at altitudes well above the ionosphere, as illustrated in Figure 12. Furthermore, based on the intensity and solid angle of the emitted radiation, I showed that the total power emitted in the frequency range from about 100 to 500 kHz was extraordinarily large, ~10^9 W (Gurnett, 1974). This was the first conclusive evidence that Earth is a very powerful radio source, comparable in many respects to Jupiter, which two decades earlier had been discovered to be a powerful radio emitter (Burke & Franklin, 1955). Later, using direction-finding measurements from our instruments on the IMP-8 and Hawkeye-1 spacecraft, Kurth et al. (1975) showed that the radio

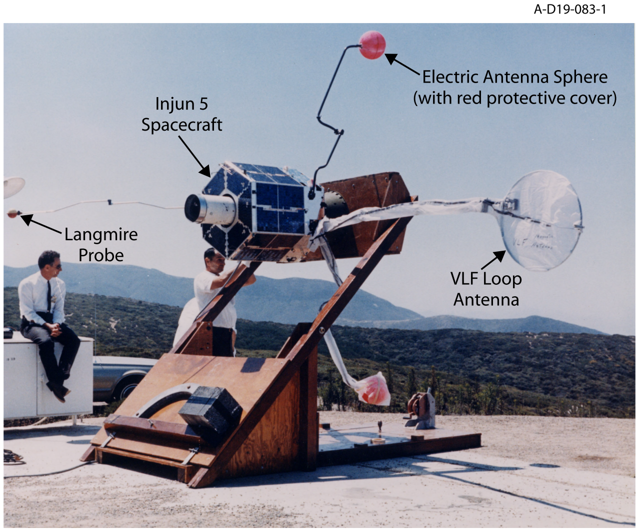

Figure 8. A picture of the Injun 5 spacecraft taken during a field test at the Pacific Missile Range to check the analog VLF analog data transmission system just before launch (ca. 1968) (courtesy of University of Iowa).

emission was primarily emitted from the nightside auroral magnetic field lines at altitudes of about 2 R_E. This intense radio emission is now called Auroral Kilometric Radiation and has many close similarities to the intense radio emission now know to be emitted from Jupiter, Saturn, Uranus, and Neptune.

Although the threshold sensitivity of the long IMP-6 antennas did not play a role in the discovery of the intense Auroral Kilometric Radiation, it soon became apparent that the high sensitivity of the long antennas played a very important role in the detection of several other types of very weak plasma wave emissions above and near harmonics of the electron cyclotron frequency and near the electron plasma frequency (Shaw & Gurnett, 1975). A plot of the electric field intensities for one such emission is shown in Figure 13. This emission occurs as a very narrow line at the upper-hybrid frequency, which is given by $f_{UH} = (f_c^2 + f_p^2)^{1/2}$, where f_c is the electron cyclotron frequency and f_p is the electron plasma frequency. The electron cyclotron frequency is given by $f_c = 28$ B Hz, where B is the magnetic field strength in nT, and the electron plasma frequency is given by $f_p = 8980\sqrt{n_e}$ Hz, where n_e is the electron density in cm^{-3} (Stix, 1962). The upper-hybrid resonance emission turns out to be very important as a plasma diagnostic tool. If the B field strength is known, which it usually is from the spacecraft magnetometer, a measurement of the upper-hybrid resonance frequency then gives the local electron density, which is often very difficult to measure in the outer magnetosphere. The event illustrated in Figure 13 is near the plasmapause and shows the very sharp decrease in the electron density characteristic of the plasmapause. Two types of upper-hybrid emissions occur. The first is due to an anisotropy-driven instability at the upper-hybrid resonance frequency (Rnnmark et al., 1978), and the second is due to thermally excited electrostatic oscillations at the upper-hybrid resonance (Meyer-Vernet, 1979). The thermally excited emissions are particularly important, because they are always present in the plasma. However, they are very weak and can only be detected by using relatively long electric antennas of the type flown on IMP-6 and IMP-8. Measurements of this thermal emission line are now widely regarded as the most accurate method of determining the electron density in the outer magnetospheres of Earth and the other magnetized planets.

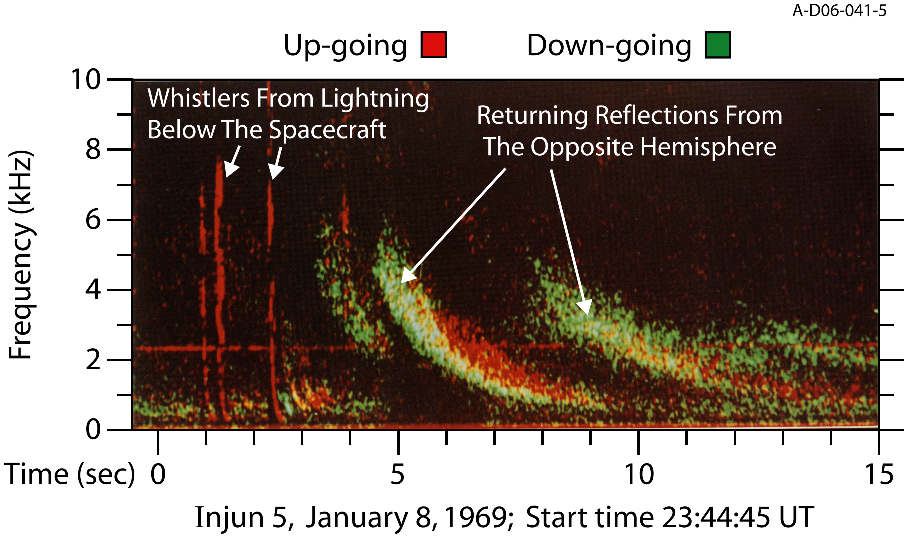

Figure 9. A color frequency-time spectrogram showing a series of whistlers detected over a thunderstorm by the VLF radio and plasma wave instrument on the Injun 5 spacecraft. The phase difference between the electric and magnetic fields allowed a determination of the upward (red) and downward (green) directions of propagation of the whistlers along the geomagnetic field (figure originally appeared in Gurnett et al., 1971, Figure 3).

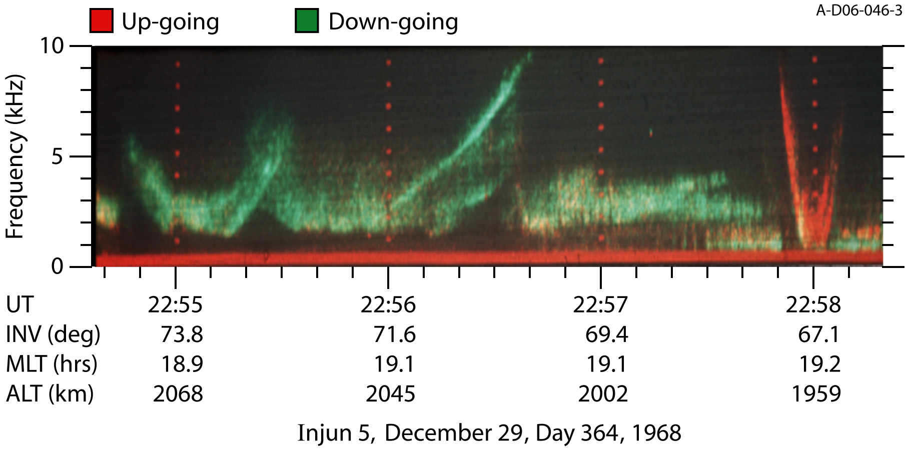

Figure 10. A color frequency-time spectrogram showing that auroral hiss consists of distinct upward and downward propagating V-shaped components. The V-shaped frequency-time structure is due to whistler-mode propagation near the resonance cone where the group velocity (Poynting flux direction) becomes very dependent on frequency (Mosier & Gurnett, 1969) (figure originally appeared in Gurnett & Frank, 1972, Plate 5).

Although the above discussion seems to favor the use of relatively long electric antennas, not everyone agreed that such long antennas are ideal for making space plasma wave electric field measurements. Several years earlier, on the OV3-3 and Pioneer 8 spacecraft, Fred Scarf of TRW measured electric fields in Earth's magnetosphere and the solar wind using very short electric antennas with effective lengths of only 0.3 to 1.0 m (Scarf, Crook, et al., 1968; Scarf, Fredricks, et al., 1968). An argument that he and others used in favor of such shorter antennas is that electrostatic waves (ion acoustic waves and electron plasma oscillations) can sometimes have very short wavelengths. The minimum wavelength of such waves is on the order of $2\pi\lambda_D$, where λ_D, the Debye length, is given by $\lambda_D = 6.9(T_e/n_e)^{1/2}$ cm, where T_e is the electron temperature in K and n_e is the electron density in cm^{-3} (Gurnett & Bhattacharjee, 2017). The Debye length can vary tremendously, from a few centimeters in the cold dense plasma of Earth's ionosphere, to many tens of meters in Earth's outer magnetosphere and in the solar wind. The problem is that if electrostatic waves exist with wavelengths shorter than the tip-to-tip length of the antenna, then the voltage measured at the base of the antenna due to these waves will be attenuated due to an "averaged effect" over the length of the antenna. A similar attenuation process also occurs for a double-probe antenna but not as severe. See Gurnett (1998) for a more detailed discussion of these short wavelength effects. So, the issue of what antenna length to use becomes a choice of not being able to detect short wavelength electrostatic waves if the antenna is too

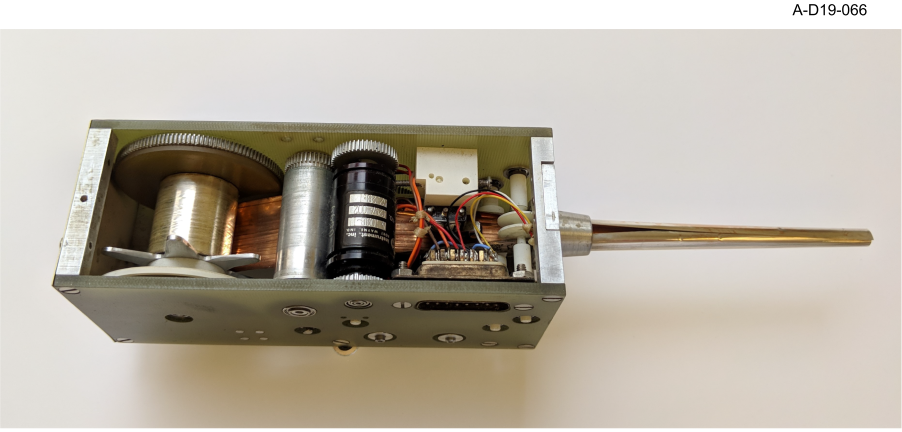

Figure 11. A STEM-type extendible electric antenna of the type used on IMP-6. The flat beryllium-copper strip wound up on the spool on the left is mechanically driven through the unit via a gear train and extruded to form the tubular antenna on the right (courtesy of University of Iowa).

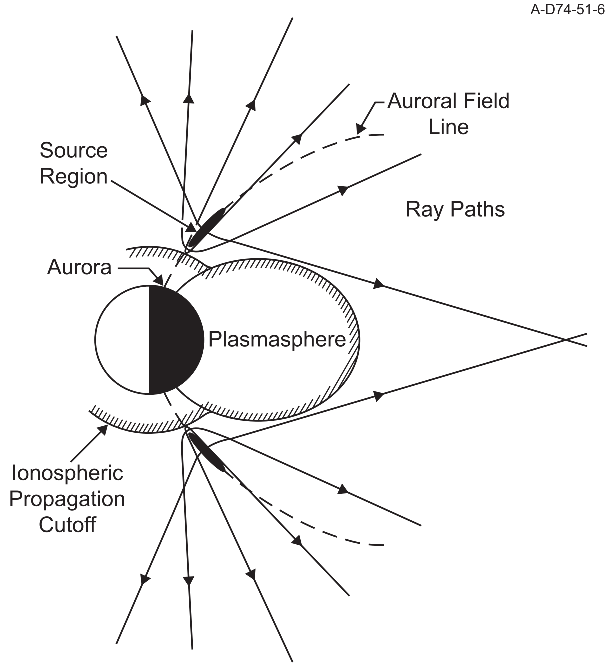

Figure 12. The source region of the intense auroral kilometric radiation, as detected by IMP-6, is located at high altitudes along the auroral magnetic field lines. This powerful radio source, which is driven by electrons associated with Earth's aurora, emits up to 10^9 Watts over a frequency range from 100 to 500 kHz. The resulting radiation is reflected by the ionosphere and plasmasphere and usually does not reach the ground (figure originally appeared in Gurnett, 1974, Figure 14).

long, versus not being able to detect very weak waves such as upper-hybrid emissions if the antenna is too short. The resolution of this issue really cannot be made until it is decided whether such short wavelength waves exist in the region of interest, and if they do, how important are they? To address this question, I added short electric antennas of the type favored by Fred Scarf, see Figure 14, to all the instruments for which I was responsible as the Principal Investigator (PI). These included IMP-6, S3-A, and ISEE-1, ISEE-2, and ISEE-3 (see Table 1). The net result after several years of comparison using data from these instruments is that, in my opinion, the advantages gained by being able to make accurate electron density measurements using the upper-hybrid emission line greatly outweigh the possibility that measurements of short wavelength effects may be compromised because the antennas are too long. However, short wavelength effects do exist and can be quite interesting (see Fuselier & Gurnett, 1984).

4. Voyagers 1 and 2

Although the above debate over the merits of short versus long electric antennas may seem academic, it has serious consequences when specific spacecraft are considered. When in 1971, a group of us (Al Franzen, JPL; Don Gurnett, Iowa; Bob Helliwell, Stanford; Bob Holzer, UCLA; Paul Kellogg, Minnesota; Fred Scarf, TRW; Ed Smith, JPL; and Eigel Ungstrup, Danish Space Research Institute) met to discuss a possible plasma wave proposal for the Mariner-Jupiter Saturn (MJS77) mission (later renamed Voyager), the issue immediately arose as to what kind of electric antenna to propose. From my favorable experience with IMP-6, I was naturally leaning toward the long STEM-type tubular antennas. On the other hand, Fred Scarf and some of his colleagues strongly preferred a relatively short antenna of the type shown in Figure 14. His idea was to mount the short electric antenna on the end of a long boom along with a single-axis search coil magnetometer for magnetic field measurements. The argument that he made was not really based on the physics merits but rather on the basis that this type of short antenna was much lighter and more easily accommodated on the spacecraft. The sensitivity advantage of the longer antenna issue was countered with the statement that Jupiter is already known to be an intense radio source, so "only the strongest waves will be important." I took the spacecraft accommodation issue quite seriously, because it was apparent that there was going to be considerable competition to get instruments on this spacecraft, with many potential conflicts. So after the intense discussions among the group, it was decided that we would submit a proposal with Fred Scarf as the PI that featured a short 0.6 m electric antenna and a search coil magnetometer, both mounted on the end of a long boom. An overview of the proposal was published by Scarf et al. (1971). A few months later, in mid-1972, we were informed that the proposal had been rejected by NASA. However, NASA did include a low-frequency radio astronomy receiver (1.2 kHz to 40.5 MHz) that used two 10 m STEM-type monopole antenna elements mounted in a V-shape configuration to measure polarization. The PI of the radio astronomy investigation was Jim Warwick of the University of Colorado. The MJS77 (Voyager) project officially started on 1 July 1972, with Ed Stone of Caltech as Project Scientist.

The failure to get a plasma wave instrument on the Voyager mission was a severe blow to the entire plasma wave team and any recovery from NASA's decision seemed hopeless. Nevertheless, over the next year or so, several of us continued to lobby NASA Headquarters and others about the need for a plasma wave instrument on the Voyager spacecraft. The main science message that we tried to push was that, given the highly successful Kennel and Petschek (1966) theory for the scattering and loss of trapped radiation belt particles due to plasma wave emissions, it would be folly to fly to Jupiter without measuring plasma wave intensities in Jupiter's radiation belts. Finally, in February 1973, with time running out to build a plasma wave instrument in time for launch, I sent a very detailed proposal to Mike Mitz at NASA Headquarters. With the concurrence of Fred Scarf and Jim Warwick, I proposed that we at Iowa build an almost exact copy of our S3-A

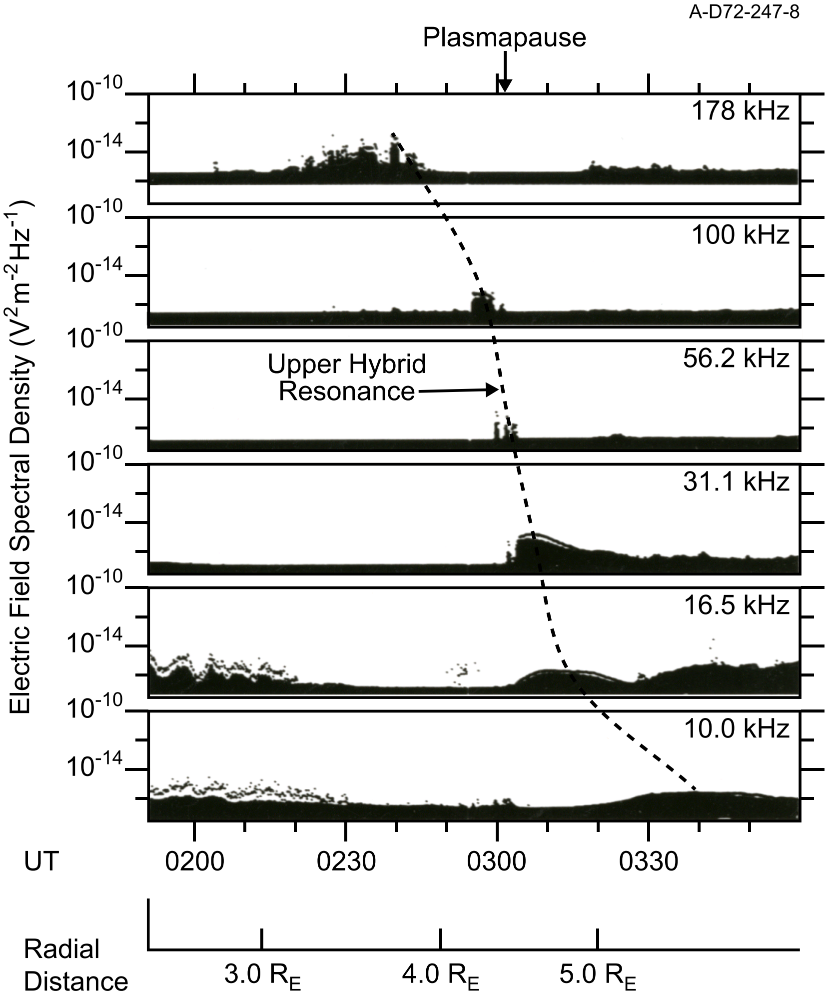

Figure 13. Measurements of upper-hybrid resonance emissions as detected by the IMP-6 multichannel spectrum analyzer. This narrowband emission is frequently used to compute the local electron density (figure was adapted from Shaw & Gurnett, 1975, Figure 1).

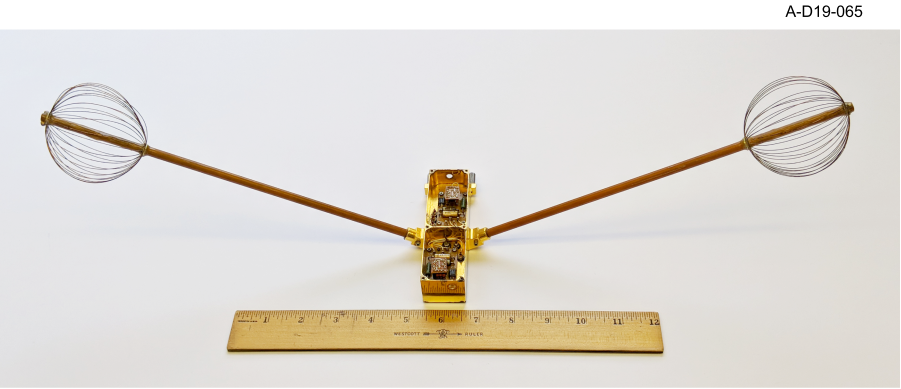

Figure 14. A picture of the short electric antenna that we provided for Fred Scarf on IMP-6, S3-A, and ISEE-1, ISEE-2, and ISEE-3. Instead of using conductive spheres at the end of the two short rods, spherically shaped fine wires are used to create capacitive coupling to the plasma (courtesy of University of Iowa).

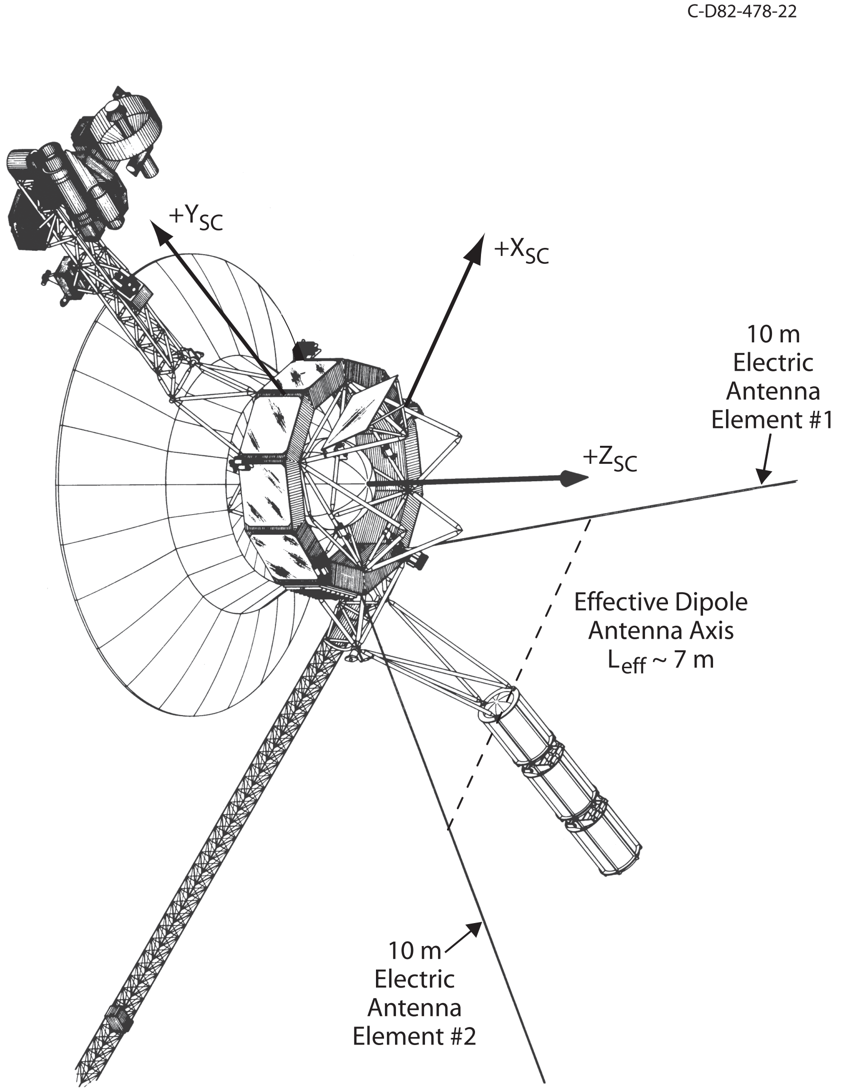

Figure 15. A perspective drawing of the Voyager spacecraft showing the two 10-m STEM-type tubular antennas used by both the plasma wave and radio astronomy instruments. The antennas are mounted in a 90° Vee configuration. The plasma wave instrument uses the two antennas as a dipole with an effective length of $L_{\mathrm{eff}} \sim 7$ m, and the radio astronomy instrument uses them as two independent monopoles to measure the polarization of radio emissions (courtesy of NASA and the University of Iowa).

plasma wave instrument and connect it in a dipole configuration to the two 10 m electric antenna elements that Jim Warwick was providing for the radio astronomy instrument (see Figure 15). This proposal had several desirable features. First, it was a very simple instrument, consisting of a 50 Hz to 10 kHz wideband receiver and a 16-channel (10 Hz to 56 kHz) step-frequency multichannel analyzer, very similar in concept to the Injun 3 plasma wave instrument. Second, it weighed only 1.4 kg and required only 1.1 to 1.6 W of power, depending on whether the wideband receiver was off or on. Third, and possibly most important, I made a strong case that we at Iowa could complete the instrument construction within the proposed cost, weight, and power in time for the launch in 1977. In late July 1974, we received notice that our proposal had been accepted, with Fred Scarf as PI, and myself as the Co-I responsible for constructing the instrument. As part of the arrangement, Fred Scarf and I agreed to share equally in the scientific results from the mission, with participation of my students as needed. The first Voyager Science Steering Group meeting that I attended occurred on 13 August 1974, and at that meeting, I learned that our plasma wave instrument was to replace Blamont's Ultraviolet Spectrometer (UV) instrument, which had been remove from the spacecraft. In my notes for that meeting, I recorded a statement from Bud

Schurmeier, the Project Manager, who recalled that there was a "savings in both weight and power by switching from the UV to the PW." In a more recent 2019 discussion with Ed Stone, the Voyager Project Scientist, he stated that the ability of the plasma wave instrument to determine key parameters, such as the plasma density, was a key scientific factor in the decision. Also, data from the December 1973 Pioneer 10 flyby of Jupiter probably played an important role. The Pioneer 10 flyby showed that the Jovian radiation belt proved to be much more complex than expected, and it was clear that measurements of plasma waves were needed to evaluate the pitch angle diffusion and loss of energetic particles from the Jovian radiation belt.

A complete description of the plasma wave instrument, as flown, is given by Scarf and Gurnett (1977). The Voyager 1 and 2 spacecraft were successfully launched on 5 September and 20 August 1977, and the plasma wave instrument made the first plasma wave measurements at Jupiter (Scarf et al., 1979), Saturn (Gurnett et al., 1981), Uranus (Gurnett et al., 1986), Neptune (Gurnett et al., 1989), and in interstellar space (Gurnett et al., 2013; Gurnett & Kurth, 2019).

5. A Modern Perspective

From a modern 21st century point of view, the plasma wave instrumentation described above may seem almost crude. With few exceptions, all the plasma wave receivers and associated electronics were of analog design. Compact high-speed analog-to-digital converter chips that could convert electric and magnetic field waveforms to a digital data stream simply did not exist at that time. On Voyagers 1 and 2, the analog output of the wideband receiver was converted to a digital data stream that went to the spacecraft digital tape recorder with 4-bit resolution at a sample rate of 28,800 samples per second. However, even then, the analog-to-digital converter was constructed from discrete parts, that is, transistors, resistors, and capacitors packaged in printed circuit modules. You will notice in Table 1 that there are numerous cases where multiaxis electric and magnetic field sensors are listed for various spacecraft, for example, IMP-6 and IMP-8 and ISEE-1, ISEE-2, and ISEE-3. With good intentions and with somewhat different details in each case, we tried to transmit the electric and magnetic field waveforms to the ground via analog telemetry so the wave normal and the Poynting flux of electromagnetic waves could be analyzed. However, these attempts to transmit the electric and magnetic field waveforms via analog telemetry did not perform well. Usually, there was either too much noise in the analog data transmission channel or the phase calibrations were not adequate to give reliable wave normal and Poynting flux results. The one exception was ISEE-1, where a "wave normal and Poynting flux analyzer" was included in the onboard instrumentation (Gurnett et al., 1978). This instrument resolved the antenna waveforms into sine and cosine components within a very narrow frequency range. The sine and cosine components were then digitally sampled simultaneously with 8-bit resolution to capture the relevant waveforms. An automatic gain control kept the resulting waveforms in the proper amplitude range. Data from this instrument were later processed in considerable detail to analyze the propagation of plasmaspheric hiss in Earth's magnetosphere (Storey et al., 1991).

In sharp contrast to the present era, there is almost no need for analog electronics in spacecraft plasma wave instruments. Using chips with thousands, if not millions, of transistors in a chip, the electric and magnetic field waveforms can be sampled directly at the antennas and processed in almost any way imaginable. Instead of analog receivers we can now design completely digital receivers with selectable bandwidths of almost any desired mathematical shape based on Fourier transform theory. Instead of wideband receivers, waveforms can now be sampled in selected bandwidths and stored in memories of almost endless capacities. Phase shifts between different waveform channels can now be controlled with mathematical precision. I only hope that those who deal with such modern technology can appreciate how it was during the early days of space plasma wave research with analog electronics.

Acknowledgments
I wish to thank Larry Kepko of GSFC for the invitation to write these recollections about the origins of space plasma wave research. I am also eternally grateful to Profs. James A. Van Allen, Brian J. O'Brien, and Robert A. Helliwell for giving me advice and support during the early stages of my career. I also want to thank the many people who contributed to the success of the numerous radio and plasma wave instruments that we have flown over the past 60 years and to my wife for putting up with the many inconveniences that resulted from this line of work. I also thank the University of Iowa for their support of my career, including this document.

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