What Do Saturn's Rings Mean to You?

Based on remarks made at the EE Department retreat of Monday April 16
in response to a question about the significance of Saturn for Electrical Engineering

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To wonder why some Electrical Engineers are sending instruments out to look at Saturn without even knowing what they will find is to forget how science works. This note is a limited reminder of the successes of that very method.

The opposite side of the coin would be to ask why laboratory researchers look for that which they plan to find or make that which they know how to make. Proposals often offer to do this. Is this methodology preferable in an Electrical Engineering Department? To ask this question is to ignore that successful practitioners of the first method are also good at the second activity.

As Gene Fubini (VP at IBM) said at a meeting of the School of Engineering Advisory Council, in the days when the proceedings were conducted openly for faculty to attend, "A physicist can become an engineer but an engineer cannot become a physicist. That must the telling us something."

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Since Saturn was mentioned deridingly let us remember that James Clerk Maxwell [1831-1879], the patron saint of Radio Science, wrote an Adams Prize paper on Saturn's rings. Those who know this will recognize that Saturn was a poor choice of object to poke fun at; others may like to devote some time to wondering about the connection between Saturn and Maxwell's equations, if the connection perplexes them.

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To say that Mission to Planet Earth makes sense but that the planets are remote is to forget that Earth is a planet. Radio studies of the atmospheres of Mars and Venus already factor into the study of the temperature profile and electrochemistry of Earth's atmosphere (greenhouse effect and ozone depletion) as well as into the huge computer simulation of nuclear winter with its global dust storm, of which the Martian atmosphere offers us a test sample. The contribution that Electrical Engineering makes to atmospheric studies consists of innovative instrumentation and measurement techniques that cannot be generated by meteorologists.

In passing, let us remember that Eshleman changed NASA's belief that instrumental parachutes could be dropped to the surface of Mars through 100 mb of N_2 when his radio occultation technique showed that the atmosphere was composed of CO_2. The radio technique, which requires instrumentation for measuring 0.001 m of path length in 2×10^{11} m, provides an example of making that which has not been made (in this case an electromagnetic tool) in order to look for something without knowing what would be found. The art of finding something significant in these circumstances is one to be admired. Eshleman also established that the atmospheric pressure on Mars is only 5 mb, so the parachutes would have crashed. Tyler and Simpson influenced the Viking I managers not to land on Mars on July 4, 1976 by introducing their radar data, an electromagnetic input not previously entertained, and thereby averted a dangerously rough landing in favor of the successful touchdown of July 20. These were good marks for EE at Stanford.

Without the active contribution from electromagnetic theory and practice which Electrical Engineering provides, these planetary applications would be severely handicapped. In fact, it would be fair to say that society depends on us for our electrical contribution to the purposes of society.

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Mention of Maxwell brings to mind Rayleigh [1842-1919], another great electrical hero, who followed Maxwell as director of the Cavendish Laboratory, established the international ampere, first worked out the plasma frequency $\omega_p^2 = Ne^2/m\epsilon_0$, and gave us the theory of waveguides. Not all Electrical Engineering students are taught, and I would like to emphasize, that Rayleigh honed his experimental and theoretical talents by attention to the atmosphere around us, being the first to discover that the air contains argon; in fact he discovered argon by looking at air without knowing what he would find (Nobel prize of 1904). How he planned this type of work, and made a success of it, is worth pondering. In another environmental application he explained the blue color of the sky by differential electromagnetic scattering from certain neutral atmospheric molecules at certain altitudes. Many other developments motivated by the environment include sound propagation through wind and fog and the propagation of seismic waves through the earth. Clearly much of the electromagnetic theory that we remember Rayleigh for was stimulated by problems of light waves, sound waves, ocean waves, and seismic waves in environmental media; in particular, the theory of electrical wave guides, which he left to us ready for industrial development in WWII, did not originate in electricity at all. We would like to attract people like the young John William Strutt to the Electrical Engineering department at Stanford. How does one recognize them?

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Mention of Maxwell and Rayleigh suggests looking at the other giants of our field. I have room only for Heaviside [1850-1925] , Kelvin [1824-1907] and Gauss [1777-1855].

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When you looked through Maxwell's two volumes in your student days you had trouble finding Maxwell's equations. That's because they are not there. Heaviside gave them to us in the form that we are familiar with. Heaviside also gave us the unit impulse function $\delta(t)$, known to us as Dirac's delta function. Heaviside invented operational calculus to solve electrical transient problems and gave us impedance, transmission line theory and distortionless telecommunication. Heaviside also became famous for the Heaviside layer when he deduced that the electrically insulating air must come to have a conductivity resembling that of copper as the altitude approaches 100 km, a result that still surprises people, and is another example of a contribution made by applying electrical background to the world outside the electrical laboratory.

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I am going to digress on the ionosphere before returning to Kelvin.

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It is perhaps the rearranging of the electric conduction currents induced in the Earth by the 100,000 amperes flowing above us in the ionosphere, about as far away as Berkeley, that caused the magnetic accompaniment to the earthquake of 1990 October 18 UT recorded by our colleague Fraser-Smith. Worldwide device sales to city managers in earthquake-prone regions will result if research on electromagnetic earthquake precursors is pursued at Stanford or elsewhere and substantiates Fraser-Smith's magnetic records. The measurements were not being conducted aimlessly but rather were commissioned for telecommunication purposes in the ULF bands; nevertheless, the serendipity that follows good basic researchers seems to have been at play when the equipment was installed at Corallitos, close to the epicenter.

In your dictionary you will find A.E. Kennelly [1861-1939] linked with Heaviside in this connection with the conductivity of air. Kennelly was famous for his charts of complex hyperbolic functions for solving telephone line problems numerically and I am the only person at Stanford who can still show you a Kennelly chart. Kennelly worked for Edison, deduced the electrically charged state of the upper atmosphere in 1902, and the same year was appointed Professor of Engineering at Harvard, where he settled.

Leonard P. Fuller, who received his Ph.D. in Electrical Engineering at Stanford, working at the Federal Telegraph Company in San Francisco with Lee De Forest, inventor of the triode, made the first height determination of the reflecting layer by 1914, reasoning from the behavior of commercial circuits.

Further probing of the upper atmosphere by swept-frequency cw radio led to discovery of the F-layer of the ionosphere by Appleton [1892-1965] , and confirmation by Breit and Tuve in 1925 by echo sounding. The two principal radar techniques thus originated in Radio Science from curiosity about the atmosphere that surrounds us (not in R&D aimed at developing an aircraft warning system, airport traffic control, automatic fire control for gunnery, or instrument landing systems, to mention some high-volume industrial activities that grew from the radar principle). Appleton received the 1947 Nobel prize for his part. Of course, modern radar had more than one root, in particular microwave radar, which grew from the cavity magnetron. The cavity magnetron did not arise from electromagnetic theory but from cut and try methods on the bench. Our colleague Buneman worked out the self-consistent field theory that first explained how the magnetron works. The F-region is now monitored continuously because of the navigational and other radio equipment depending on the minute-by-minute electron density variation of the atmosphere. This case history begins with electromagnetic exploration of a region of space formerly considered as a high vacuum (which it is) using new electronic tools, leads to one of the marvels of modern technology, and goes on to make the atmospheric medium amenable to yet more technological applications to daily use. Electrical technicians may think radar was invented in some company, possibly General Electric, and they may wonder why anyone would bother to use a good modern radar for such an obscure purpose as irradiating the ionosphere. We hope all Electrical Engineering students learn that it was curiosity about the ionosphere that called forth the feats of electrical ingenuity upon which radar is founded.

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Kelvin is well known for electrical measuring instruments and for his initiative in getting the submarine cable across the Atlantic. Like the best electricians, he applied his background in physics to the external environment being responsible for theories of the age of the earth and of the heat source in the sun. Earth currents induced by the ionospheric current plagued the cable until they were understood but were responsible for widespread destruction of power distribution equipment in Canada last year (> $100 million).

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Finally let us remember that Gauss, who is honored in the system of units, took his work on magnetism into the environment outside the laboratory and organized the first international scientific collaborative effort, for the purpose of measuring the Earth's magnetic field distribution. It was not known what would be measured. It would be fair to say that the Magnetic Union and its modern descendants, the International Union of Geodesy and Geophysics, the International Scientific Radio Union, and the American Geophysical Union have brought major contributions from the electrical laboratory to the purposes of society. Examples include prospecting for oil, weapon design, protection of astronauts on space walks, submarine detection, earthquake precursors, atmospheric science, etc.

Another thing about Gauss reminds us that our electrical contribution to other activities of society have not all been one way. It was Gauss who first applied the FFT technique to harmonic analysis of data sets; in his case the data set consisted of directional coordinates of minor planets. Here we see the tendency for scientists, working on problems that are hard by international standards, to hit upon tools that then feed back into various compartments of society. In our electrical compartment, we are very pleased to have the FFT, even if we forget that it was first used in astronomy. That reminds me that the Fast Hartley Transform, which has generated over 70 papers in five years in the IEEE, Electronics Letters, and one or two other journals lately, came out of efforts at spectral analysis here at Stanford also for astronomical purposes (indirect imaging). My interest in spectral analysis came from the need to design radio interferometers whose purpose was to look at the Sun and other celestial bodies that emit radio waves to see what could be found. This effort led to the first antenna system to exceed the resolution of the human eye ($50''$) and to the technology for microwave phase path measurement to 1 in 10^5, which is a prerequisite. The 11 years of daily microwave sun maps coming from that work were commended by NASA for contributing to the health of the lunar astronauts.

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In case anyone needs further reminder, the three laws of motion that govern all moving objects, including biological ones, came from the collection of astronomical observations, conducted without knowing what would be found. Interestingly, catapult design in the hands of Archimedes, who was no slouch but knew little about electricity, and gunnery development and ballistic studies in the days when the best minds worked on defense, did not give us the laws of motion. They came from the top problem of the day, namely the motion of the planets.

Perhaps the fruitfulness of astronomy as a source of productive results is worth thinking about.

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Turning now to more recent cases, a few years ago Villard, Manning, Eshleman and Peterson were building radiofrequency tools to study the trails of electrical ionization in the upper atmosphere produced by meteors impinging on the earth. A question that they and their counterparts in other leading countries were trying to answer was whether the meteors come from within or from outside the solar system. This question could conceivably have been answered without help from Radio Science; in any case it was dealt with by radio. What was found was an unexpected hail of particles at the rate of thousands per hour. Without this knowledge, the vital telecommunications links that today utilize the sporadic ionization trails of meteors would not be with us. The development of the special recording techniques was carried out in part by the efforts of the Electrical Engineering department, using the big dish on the hill.

This is an interesting case history to contemplate. How does one go about nurturing and transmitting this tradition of electromagnetic discovery followed by application, in this case to electrical telecommunication?

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Radio astronomy brought us big dishes, indirect imaging, the best images currently available with regard to both resolution and dynamic range, image handling programs for huge images, applications for masers, low-noise receiver technology, and much more. This all happened since WWII and represents prompt conversion into technology for the benefit of society. Radio astronomers made a big impact on the science of astronomy too, reaching 50 per cent of the whole some years back.

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In the HF band the strongest source of nonmanmade electrical interference, the design parameter that sets the level of transmitter power, was not discovered in the electrical industry but by radio astronomers Burke and Franklin at the Carnegie Institution, Washington. They were striving to build the first Mills Cross antenna before Mills did. They got theirs built first, and within a day or two discovered that the distant planet Jupiter was the source of the intense radio bursts, never before identified. Later we learned that the timing of these bursts is controlled by the satellite Io. It reminds us that Galileo did not know what he would find when he turned his new telescope on Jupiter. The four satellites that he saw led to a method of terrestrial longitude determination for navigation, only superseded when all mariners had access to chronometers by Harrison [1693-1776]; you can see the originals today at Greenwich observatory. The Jovian satellites also permitted the first determination of the finite velocity of light by Rømer [1644-1710]. As with the majority of discoveries mentioned here, this light-propagation discovery was not a result of trying to measure that which was discovered; rather, the goal was to establish what the timing of the eclipses was.

We see that fundamental discoveries relating to Jupiter have had various impacts on society, including items of importance to electrical technology such as HF communications and the velocity of electromagnetic waves. In a sense the very generation of radio waves by Hertz [1857-1894] traces back to the work of Maxwell and thus to the measurement of the velocity of light, which in turn traces back to Galileo taking a look at Jupiter.

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We may tend to forget the astronomical sources of modern knowledge but we need to cultivate the techniques by which discovery is made. Astronomical observation has a matchless record. Why is that?

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Recently we have read that the pulsar family, which has provided physics with a test of general relativity, and given the first evidence of gravitational radiation, now also has some members that are more stable than a rubidium clock. As three of these stable pulsars have now been found, without any knowledge that such things would even exist, it is now technically possible to supersede the laboratory clock as a time standard. The interesting thing about an external standard is that it could be independently available to different ground locations. Each time a fundamental standard is improved new things become feasible that were impossible before. Synchronization of clocks on different continents at the millisecond level is an example from a few years ago. To achieve this required not only good clocks but also the knowledge of the electromagnetic properties of the atmosphere out to satellite heights, the sort of thing that Radio Science at Stanford was actively engaged in at the time of Villard, who founded the Radio Propagation Laboratory at Stanford. Tony Hewish of the Cavendish Laboratory received the 1974 Nobel prize for the discovery of pulsars, the first year in which the prize was given for astronomy.

The Electrical Engineering Department at Stanford made a number of pulsar contributions. One piece of work conducted simultaneously at Stanford and Arecibo, Puerto Rico, showed that the pulsar amplitude modulation was due to the interstellar medium and not to the Earth's ionosphere. Another showed that the radio pulses recorded at Stanford were simultaneous with optical flashes seen at Lick Observatory. Tyler was a co-discoverer of the pulsar in the Crab nebula in 1976.

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Talking about fundamental standards, length measurement in geodesy used to be limited to 1 part in 100,000. In fact, that was the definition of geodesy. Now the GPS satellite system already offers us baseline measurement to millimeter accuracy commercially, over practical baseline lengths. Originally advertised as providing 10 m precision for civilians, the GPS satellite transmissions were ultimately to have been encrypted for military use, where a precision of 1 m was designed for. Encryption would deny precise radio navigation to incoming hostile missiles.

Exactly the same sort of position finding was already being practised by Very Long Baseline Interferometry, one of the spinoffs from radio astronomical interferometry. The practise of VLBI has filtered into the USGS, which had a tradition of precise astrometry, and the USGS can now measure continental drift at the cm per annum level! However, the main action in VLBI is still internal to astronomy, where one of the main current national instrumental thrusts is toward completion of the Very Long Baseline Array next year. People at MIT and JPL conversant with VLBI technique figured out how to treat the GPS satellite as a stochastic source, rather like a radio star, thus circumventing the need to know the code.

This is not a trivial exercise, involving as it does triangulation on a plurality of satellites, each at the end of a different airpath of unknown refraction. However, the ingenious technology deriving from radio astronomical practice has already demonstrated millimeter accuracy!

One application is monitoring the position of the face of a dam, day in and day out to guard against dangerous motion. Previously, one could hardly afford to send out a ground crew to do this once a month, and certainly not hour by hour. Automatic laser stadiometry equipment could also not be afforded.

There are endless other special applications resulting from this jump in metrology. However, an immense commercial impact comes from the fact that every city and county employs and spends a lot of money on ground surveyors. They are everywhere, with their tapes, tripods, transits, levels and laser rangefinders. In addition there are photogrammetrists flying over us every day taking stereophotographs of the crosses in the streets. A billion dollar electrical device industry (including $50 million sales out of Silicon Valley) is thus being born out of an interesting and quite brief history originating in Radio Science.

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After length and time there is mass. The international kilogram seems far removed from the ambit of Electrical Engineering but Radio Science has something to say there too. The best measure of G, the gravitation constant on which the weight of the kilogram depends, was once in the hands of Cavendish after whom the Cavendish Laboratory was named, where Maxwell, Rayleigh, J.J. Thompson (discoverer of the electron), Chadwick (discoverer of the neutron), Rutherford (splitter of the atom and one-time holder of the distance record for wireless communication) worked. (I worked there too.) Current measurements of G are interesting because if sufficient precision were reached one might be able to discern the parts in 15 billion change per annum to be expected if G depends on elapsed time since the birth of the universe. Dirac expected this. Well, the expected change failed to be detected. How? By planetary radar. By the most sophisticated pseudorandom code modulation in the business, combined with low-noise receiver technology and low-noise antenna design, the round trip time delay to Venus and back has been monitored through the year to just about the necessary precision. Further fallout from this experiment can be expected. For one thing, the Venusian atmosphere contributes to the time delay, and we are interested in that atmosphere because it has a bearing on the behavior of acid droplets in global circulation.

Spread spectrum technology, now pervading consumer markets such as urban vehicle navigation, may be better known to you than the early history of radar astronomy that led to the consumer products. But it pays to keep an eye on history lest we forget.

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Pioneering contributions to the coded pulse technique used on Venus were made in connection with Stanford's original doppler radar experiments on the moon. Doppler radar went on from radar astronomy to the RASS acoustic-radio technique which was developed by Peterson and is now capable of providing temperature and wind profiles up to 20 km without balloons. In another branch of this technologically sophisticated subject originated by Peterson, Vesecky is now showing that ocean surface currents of commercial interest to fisheries can be mapped as a function of time by a coastal installation that is an alternative to satellite-borne synthetic-aperture radar. Interestingly, floating buoys, which is what oceanographers have developed, are not reliable indicators of surface currents because of wind; electromagnetic methods, as we develop them, will prevail. Unexpectedly, the technique appears to be on the point of furnishing surface windspeed also. Some rather clever data processing is involved.

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Mention of synthetic apertures reminds us of another direct debt to radio astronomy, where aperture synthesis originated in an effort to measure the angular diameters of radio stars. Rotation synthesis originated in an effort to resolve detail on the face of the radio sun; together these two techniques merged to give us indirect imaging as practised today for constructing the highest quality images.

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Clear air scatters electromagnetic radiation because of statistical effects associated with temperature and the mean molecular mass of the constituents and with otherwise-difficult-to-discern density variations. This phenomenon was studied in the Electrical Engineering Department by Waterman who designed an ingenious phased-array scanning antenna system with which he tracked invisible air waves and studied temperature profiles. These internal phenomena of the air have become well known in connection with clear air turbulence. The group of radio scientists associated with the tropospheric commission of the International Scientific Radio Union has had a significant impact on meteorology. Existing instrumentation installed at Denver airport can produce vector wind profiles as high as airplanes fly using the phenomenon of clear air backscatter without the need to release balloons at 15 minute intervals. It may not be obvious to you how a single horizontal antenna array can extract the horizontal air velocity components as a function of altitude and it certainly would not have been obvious to meteorologists. It is another example of the dependence of society on the discovery of new knowledge about the environment we are imbedded in by Electrical Engineers. A big industry is about to develop as clear-air backscatter instruments are installed at airports around the world. This payoff traces back to people interested in microwave propagation through the atmosphere, in particular to the superrefraction that was noticed in the Persian Gulf in the early 1940s. It appears that exploring Earth's atmosphere has been a rich stimulus for desirable endproducts.

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STAR Lab is mostly nonastronomical but the technique of discovery as practised in other groups also furnishes examples of application to the purposes of society resulting from the same basic scientific method. The Omega system transmitters used by ships, planes and submarines for navigation cost 300 million dollars each but would cost less if the noise level at the receiver were less. Helliwell's group found out that the noise in the band utilized is set by Bremsstrahlung emitted by electron bunches dumped into the ionosphere from above by natural electromagnetic signals in the whistler mode. Knowledge of the whistler mode, leading to the generation of artificial whistler mode signals, goes back to our colleague Storey, who observed and explained whistlers while he was supposed to be doing something else (we were students together at the Cavendish Laboratory). He was the first to deduce the existence of significant electron densities in the region of the Van Allen radiation belts. The breadth of attention given to Storey's published work would be surpassed by few; two years ago I found that the latest comprehensive volume of the Science Citation Index mentioned 30 different current journals in which Storey's work was cited. How to learn to do work that achieves this degree of external visibility is an interesting question.

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It is not known what the VLF environment still has in store for us. Signals reported from the Soviet Union in the VLF band, and reputed to be earthquake precursors, were recently detected by our Electrical Engineering colleagues, who were able to make use of a satellite placed in orbit expressly for peeking at what VLF energy might be floating around in Earth's magnetospheric space. Like the instrumentation sent to Saturn, the VLF package satellite was launched without actual knowledge of what would be detected. The seismic correlation, if confirmed, will not be one that would have been discovered by the Geological Survey. The Survey is betting its discovery dollars on what it knows it can do, namely install more sensitive seismometers and strain gauges; but as should be obvious, the large earthquakes tend to be followed rather than preceded by smaller earthquakes. The history of discovery shows that the payoffs do not come from looking for what you know is there, but from designing advanced instruments to explore uncharted phase space. Of course it helps to be good at this; one factor is to be engaged in international competition with open publication.

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As a final anecdote consider the case of Jansky [1905-1950], instructed by Harald Friis at Bell Labs to build a directional antenna to scan the horizon and determine the direction of arrival of HF noise. Jansky was not looking for noise from the Galaxy, but that is what he found, and the exertions devoted to follow-up have had a profound impact on the whole of Electrical Engineering as well as on many other fields. A later Bell Labs noise survey, also motivated by the need to understand the power levels required by costly high-power transmitters, led to the discovery of the 3 K microwave radiation and Nobel prizes for Pennzias and Wilson. By 1967 we had shown at Stanford that the radiation was isotropic to ±5 millikelvins. By refined instrument design we then made the first determination of the absolute velocity of the Earth through the cosmic sea of photons. Seven years elapsed before Berkeley using a U-2 and Princeton using a balloon could confirm the Stanford EE result with modern equipment (see display case opposite Durand 301).

The discovery of the 3 K radiation (now 2.735 ± 0.06 K) has driven the technology for radiation measurement to orders of magnitude below the millikelvin level. The drive did not come from industry but from radio astronomy, as with so many other things. One lesson seems to be that we should keep our eye on the outside application and especially on the broad natural environment as one source for future thrusts.

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I do not have time to tell you about Vesecky's work on sea ice or on instrumentation for the oceanic surface layer (jointly with Khuri-Yakub), Clauer's work on satellite photography of the aurora, space shuttle experiments such as the electron-beam probe, electromagnetic phase measurement by square-law detector using Hartley interferometry, Buneman's 3D plasma instabilty project on the Cray, what da Rosa does, what Bell, Burr, Carpenter, Gilchrist, Hinson, Ison, Linscott, Marouf, Neubert, Samadani, Scott, Simpson, Tolat or Williamson are up to, or what Peterson is doing, or what Banks and Wiskerchen were doing. I myself am developing transform methodology by studying seismograms and by tackling hard problems of solar activity as recorded in geophysical and oceanographic time series; I expect that the IEEE will be a comfortable home for the results.

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I would certainly not discount Saturn's rings as a possible actor in another curious interaction with Electrical Engineering. On the contrary; if it takes electromagnetic tools to do the job, if it is hard, if there is international competition and publication, I would say that looking at planetary rings and atmospheres will prove to have been a good way to go. Perhaps Tyler's current $40 million proposal for the Cassini mission will bear me out.

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