Revealing the Molecular Universe: One Antenna Is Never Enough
ASP Conference Series, Vol. 356, 2006
D. C. Backer and J. L. Turner and J. M. Moran

Mapping HI and B at Hat Creek...and Beyond

Carl Heiles
Astronomy Department and Radio Astronomy Laboratory, University of California, Berkeley

Abstract. The Hat Creek 85-foot telescope produced the first complete surveys of HI in the Northern sky—superseded only recently—and initiated measurements of the interstellar magnetic field using Zeeman splitting of the HI line in emission. These endeavors required state-of-the-art electronics and spectrometers. Here I review the role of the Berkeley Radio Astronomy Laboratory and its 85-foot telescope in their initiative roles for these three areas of science and technology and trace their evolution to the present. The present emphasizes the great single dishes of our times, the Green Bank Telescope (GBT) for Zeeman splitting and Arecibo for HI mapping; Fourier-transform spectrometers using FPGA technology; and sustaining the future with the synergy of research and education.

1. Introduction

In the beginning[1] it was all single dish astronomy. Single dishes are good for studying diffusely distributed emission with low angular resolution. As radio astronomy progressed, so did the need for higher angular resolution. Jack played an important role in that development nationally, and at Hat Creek his role was crucial and transformational; by the 1980's, Hat Creek was mainly devoted to millimeter-wave interferometry. Nevertheless, despite Jack's single-minded devotion to interferometry, he played an important role with the 85-foot telescope by sharing his technical knowledge and expertise.

Single-dish astronomy at Hat Creek—as embodied by the 85-foot telescope—flourished at Hat Creek until the telescope's demise on 1993 January 23. It did pioneering and important work. The first major segment began with the discovery of OH masers (Weaver et al. 1965). It continued with other studies of OH, and also of other molecules having cm-wave transitions. However, I think it's fair to say that OH was a diversionary prelude to what we really wanted to do, which was to make high-quality maps of the HI sky.

We initiated two major HI research programs with the 85-foot. One, the sky surveys; and two, the measurement of magnetic fields using Zeeman splitting. These remain important research areas to this day. Below, I'll first describe how these developed in the beginning at Hat Creek, and then compare them with where we are now, and conclude with a summary of the current issues. And I'll do the same with spectrometers! Then again, it's not just research: the 85-foot

[1] of Hat Creek Radio Observatory, that is...

lives on by its contribution to our undergraduate educational program through continued use of its receiver electronics.

2. HI Sky Maps and Surveys

2.1. Then: Hat Creek

The HI sky surveys began in 1968 and resulted in three surveys: the high-velocity HI survey, which was done by Nan Dieter (1972: 115 pages in A&A Supplement Volume 5); the Galactic plane portion, which was done by Harold Weaver and David Williams (1973 and 1974: each a complete A&A Supplement volume!) and the normal-velocity sky outside the plane, which was done by me and Harm Habing (1974: again, a complete A&A Supplement). Note the hardcopy paper publication of these voluminous datasets. The presentation was all in position-velocity diagrams. Back then, just making such diagrams with a computer was a feat; Dieter, Weaver, and Williams used a Calcomp plotter, and I had some poor graduate student (usually Andy Fraknoi) paste together, side-by-side, four 18-inch-wide swaths of impact printer output to make huge "bedsheets," which were reduced in size by photography.

Today we would just write something short and distribute the data over the net. Some younger astronomers might think this paper publication wasteful and quaint, but in fact those complete maps on paper were very handy—for me, at least—and my personal copies of those A&A Supplements are dog-eared and one of the covers has fallen off. Paper copies are great for inspecting details and making annotations that last!

We also distributed digital copies. Back then we did this by mailing a big one-foot diameter reel containing 2400 feet of magnetic tape. There wasn't any `FITS` format and there was no easy way to transfer data between different brands of computer. So anybody who got these tapes had to figure out how to read them unless they had the same kind we did, a Control Data Corporation (CDC) 60-bit computer. It was worth the effort, though: these were *the* world standards for HI surveys, and remained that way for 25 years—until the Leiden/Dwingeloo survey appeared (Hartmann & Burton 1997).

As all California hikers know, it's hard to get a quick overview from a topo map because in mountainous terrain the contours are a mess. Your brain responds much better to images. Producing astronomical images from digital data was almost impossible at first. We managed, however, because I was chatting with Ed Jenkins at Princeton about this problem and his eyes lit up: "Let's try our 'Green machine'." They had adapted a machine used in magazine publishing; it read a digital tape and wrote the image out onto a giant 18×12 inch negative. We made black and white images and then did color, making three separation negatives to be combined by John Wilder, our Berkeley photographic expert, into color prints. These dramatic photos showed that the HI is often distributed in long, thin filaments (Heiles & Jenkins 1976).

At Berkeley the optical astronomers later obtained a scanning microdensitometer (the "PDS"), which could turn photographic images into digital data, and we paid extra for the capability of going the reverse direction, now writing the image on 35-mm glass negative plates. I did this for dozens of images—each one took 45 minutes. This was high technology: those 35-mm plates could be shown directly on the PowerPoint of the day, 35-mm projectors. I had to do all this on weekends, when I could keep everybody else out of the computer room. It was worth it: we were working with the Instituto Argentino de Radioastronomia in Argentina to get the southern HI data, and we (Colomb, Pöppel, & Heiles 1980) had images of the whole sky that show the most spectacular HI structure in the sky, the 120° diameter expanding shell associated with Radio Loop I (a.k.a. the North Polar Spur).

2.2. Now: Arecibo

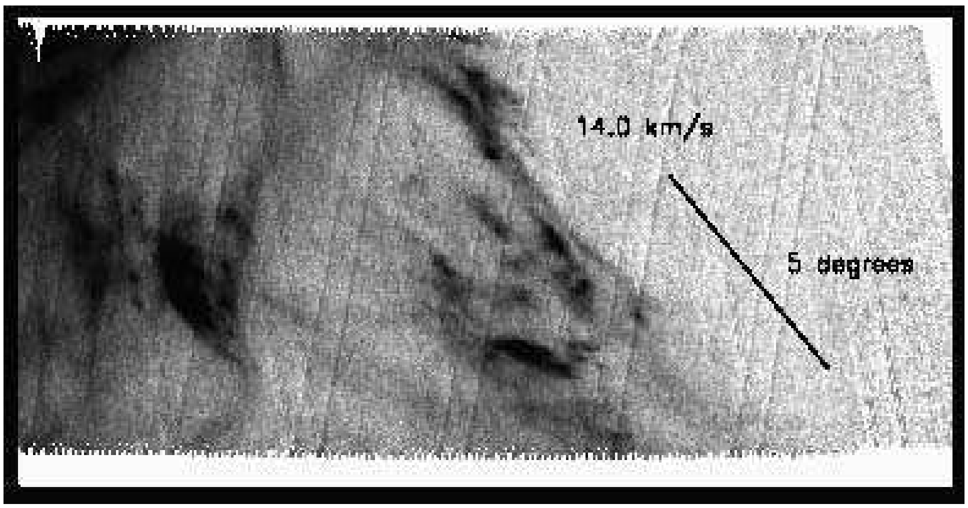

Figure 1. **Preliminary** $\sim 18^\circ \times 10^\circ$ image from the GALFA HI mapping program, courtesy of graduate student Josh Goldston. Note the dim, resolution-limited filaments running from 10 to 4 o'clock. Zigzag striations are instrumental and will be removed in the final product.

Up until now, all HI sky surveys had $\sim 36'$ angular resolution. But this isn't adequate: the spectacular IRAS maps of diffuse emission from dust revealed structures down to its resolution limit, $\sim 3'$—that's a difference of two orders of magnitude in beam area! The Canadians and Australians are doing interferometry to gain this resolution, but their sensitivity is poor; this prevents seeing weak structural features. Arecibo would have been ideal because a filled aperture provides the best sensitivity for diffuse emission and its angular resolution is $3\overset{'}{.}4$, but mapping HI with the Arecibo single-pixel feed is a long, slow process. Recently, however, Arecibo acquired a 7-element feed array called ALFA. We are using this to map particularly interesting areas. Figure 1 shows an example. Note the dim, resolution-limited filaments running from 10 to 4 o'clock (hard to see with this contrast stretch); this combination of sensitivity and resolution is unique to Arecibo.

With the seven feeds we cover almost 10 deg^2 per hour with excellent sensitivity. This is going to allow us to survey the entire Arecibo sky (declination -1° to 39°) with nearly 100 times more pixels than in the all-sky HI surveys with $36'$ resolution!

2.3. Future: Hat Creek Again—The Allen Telescope Array (ATA)

The ATA is projected to have 350 telescopes (one fewer than the number of baselines in the VLA...) packed quite densely, which will provide very good sensitivity for diffuse emission at $1'$ resolution. As Jack would remark, interferometry is always best! We are eager to begin working with this instrument.

3. Magnetic Fields (B) from Zeeman Splitting

3.1. Then: Hat Creek

What do you do after completing a sky survey? Doing more observations is often pointless—you have, after all, covered the whole sky. What you *should* do is spend the rest of your life looking at the data. And we certainly are doing that. But astronomers have this inner irrepressible drive to *observe*.

There are three major forces acting on the interstellar gas: gravity, gas pressure, and magnetic fields. Of these, magnetic fields are the hardest to observe—and also to understand, because the field's influence is highly anisotropic. The reigning attitude about the magnetic field was, and to some extent still is, "...the larger one's ignorance, the stronger the magnetic field" (Woltjer 1967).

At Hat Creek we had a telescope with almost unlimited amounts of time and a pressing need for observational information about the magnetic field. Verschuur (1965) had discovered Zeeman splitting for the HI line in absorption so we knew it was there; we wanted to measure it in emission so we could map it. This turned into Tom Troland's thesis. And what a difficult thesis it was!

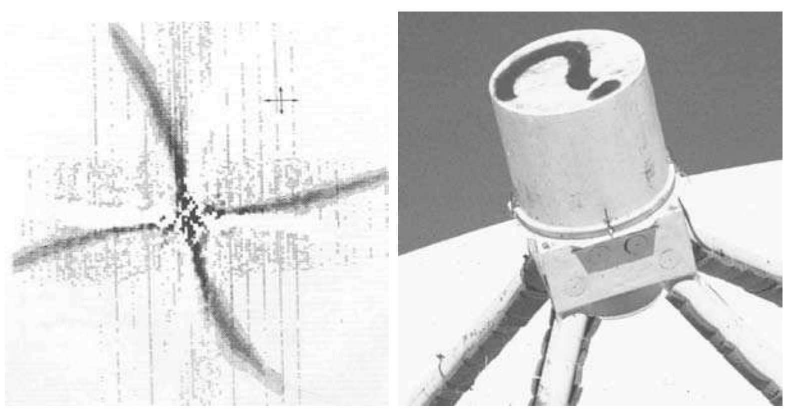

Figure 2. Left panel: Stokes V sidelobe pattern of the 85-foot telescope over an angular area $\sim 60^\circ$ diameter—it looks like a giant windmill (from Troland & Heiles 1982). Right panel: Hairy legs—anything to reduce far-out sidelobes!

Measuring Zeeman splitting means measuring the Stokes V spectrum, which is the difference between the two circular polarizations. So first, Tom and I had to make a dual-polarized feed that would provide the circulars. This was itself a major project which lasted the better part of a year; we had help from Jack and

Vic Rumsey (Jack's PhD thesis supervisor) at UC San Diego. Then Tom detected Zeeman splitting and things looked pretty good until we found out about "beam squint," in which the two circularly polarized beams point in slightly different directions. This is disastrous for measuring Zeeman splitting because the beam squint samples the first derivative on the sky, making a linearly-changing velocity with angle look like Zeeman splitting. And it isn't just beam squint, which affects just the main beam; all the sidelobes are highly polarized, too. Tom used the Sun to make a map of the Stokes V sidelobe response out to very large angular distance and found the strange windmill-type pattern shown in Figure 2, left panel. The peak amplitude in this pattern is small, but the pattern covers a huge area, and so it can produce erroneous results.

This huge polarized pattern, with its fourfold symmetry and, to some extent, smaller-scale polarized patterns, are clearly related to scattering from the feed legs. We tried to combat these sidelobes by reducing the scattering by wrapping them with a hairy, scratchy material called Ekkosorb (Figure 2, right panel). It helped at least a little, so we kept using it; the VLBI'ers didn't like the increased system temperature that it produced, so whenever there was a VLBI run the Ekkosorb had to come off—and then be reinstalled. Al Masters and his crew tied them on with rope and duct tape. We eventually convinced ourselves that our measured results were correct, and that we had (at least to some extent) conquered beam squint. So Tom got his thesis and a job (as a faculty member at University of Kentucky, where he's been ever since). We kept collaborating and produced several papers with maps of HI Zeeman splitting. Meanwhile, Gerrit Verschuur was using the Green Bank 140-foot telescope to make similar measurements. There were a few common positions and, until 1993, everybody's results were consistent (e.g., Verschuur 1989).

Despite the apparent agreement of the measurements, soon afterwards Verschuur (1993, 1995a, 1995b) dropped a bombshell. He asserted that "... claims of Zeeman effect detections in HI emission features ... based on observations made with presently available single-dish radio telescopes cannot be regarded as reliable." At the time of his paper, the 85-foot telescope had met its final destiny, but he meant his claim of "presently available telescopes" to apply to that telescope as well as other telescopes that were then available. And he was democratic: he meant his claim to apply to his own results as well! This is a strong statement and it has had a dampening effect on the field, making many astronomers highly suspicious of the published results.

Despite Verschuur, we are confident that our results are, in large measure, correct. Much of the evidence comes from my paper (Heiles 1996), which discussed the correction procedures for the HCRO data; I also tested these correction procedures on the North Celestial Pole, which is the one point on the sky where, for the 85-foot telescope, the main beam could rotate in a complete circle. More evidence comes from current graduate student Tim Robishaw's thesis (see below). We have discussed this situation in some detail in Heiles & Crutcher (2005), and, naturally enough, resolve the controversy in our own favor. In the late 1990's Verschuur toured Europe, spreading his gospel about our bad results, and only very recently have some European astronomers been convinced of our *true* gospel (thanks to Robishaw, who gave an excellent paper at the well-attended magnetic field conference in Paris in 2005 September). The Heiles and Crutcher paper goes on to discuss the major scientific results, where you should go if you want some real information about the interstellar magnetic field. Here, suffice it to say that there are good results for well over 100 positions in various locations. There are strong fields near the North Celestial Pole, and indeed in most regions that look like edge-on shells, and a large map of strong fields near Orion, which also includes a nice reversal in field direction across the Orion molecular cloud.

3.2. Now: Arecibo and the Green Bank Telescope

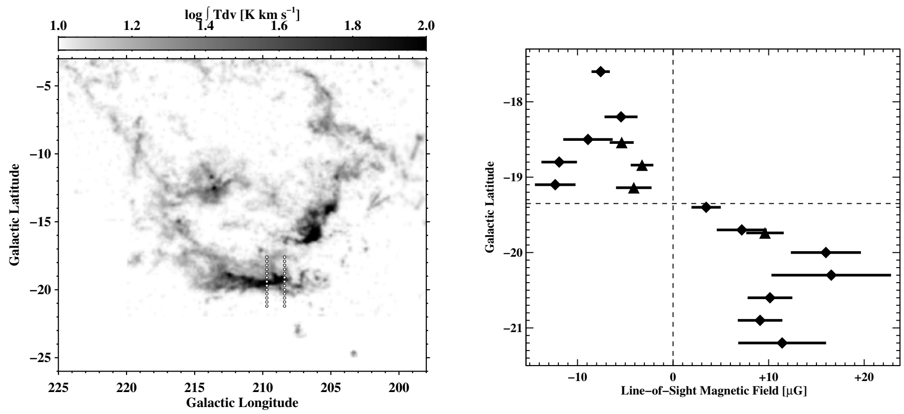

Figure 3. Left panel: The molecular clouds in Orion, with the constant-longitude strips observed for HI Zeeman splitting. Right panel: the derived magnetic field along the left-hand strip; note the reversal, which occurs at the cloud's axis. Images courtesy of Tim Robishaw.

Recent work has two directions. One is measuring field strengths in cold gas by using the λ 21cm line in absorption, represented by the Arecibo Millennium Survey (e.g., Heiles and Troland 2005). Because these are ON-OFF measurements, they are almost completely unaffected by most instrumental effects like beam squint. The other type is emission measurements with the GBT, which is possible because of the low sidelobe levels. This is Tim Robishaw's thesis project, and it is similar in spirit, and degree of difficulty, to Tom Troland's thesis. Currently, Tim's most spectacular result is the reversal of the field across the Orion Molecular Cloud (Fig. 3); when viewed together with the optical polarization data, it strongly suggests that the cloud contains a helical field, perhaps as theoretically described by Fiege & Pudritz (2000, and other papers in that series).

4. Spectrometers

4.1. Then: The Multichannel Filter Bank

As far as I know, in the mid-1960's there were just four multichannel spectrometers with at least 100 frequency channels in the world being used for astronomy: Sandy Weinreb's original 1-bit, 100-channel autocorrelator at Haystack, its twin at the National Radio Astronomy Observatory, the Jodrell Bank 256-channel autocorrelator and Hat Creek's 100-channel filterbank. The correlators were state-of-the-art digital devices; the filterbank was a state-of-the-art analog device based on the then classical way of doing spectroscopy, namely scanning a single filter across the line. The 100-channel spectrometers of this era would typically occupy at least two 6-foot racks—50 channels per rack. The Hat Creek spectrometer served very well for the HI surveys, but the digital revolution was upon us.

4.2. Later: The Digital Correlator

One-bit correlators evolved into three-level correlators, which was important because they could accurately measure power instead of just spectral shape. In the mid 1970's we (that's really RAL's Doug Thornton, Lynn Urry, and Jerry Hudson) began building a 1024-channel digital autocorrelation spectrometer—at that time, the largest in use on any single dish. Big progress: it occupied only a single six-foot rack! It worked wonderfully and was a crucial component in our subsequent Zeeman-splitting studies. It was our workhorse up until the 85-foot's demise, whereupon we sent it to Arecibo; they got a little bit of use out of it, but by then they were very well set up, correlatorwise, themselves, so it was a minor increment for them.

4.3. Now: Fourier Transform FPGAs

Correlators have remained the favored technique until very recently. The availability of inexpensive, hugely powerful Field Programmable Gate Arrays (FPGAs) has revolutionized the approach to spectroscopy. It's easy (at least for Jeff Mock, who did our GALFA spectrometer) to program these devices for Fourier transforms; for example, for the ALFA array at Arecibo we are using 14 of these spectrometers, two on each of the Arecibo ALFA beams; we obtain 8192 channels over our 7-MHz band and, simultaneously, 512 channels over our 100-MHz calibration band. Dan Werthimer and Aaron Parsons designed the board and layout, and quite easily stuffed all 14 spectrometers (really 28!) in a single 8-inch rack panel—about a million channels per six-foot rack! We've come a long way, and I can't help wondering where it will go from here.

5. The Dying Day and the New Beginning

5.1. Then: Death

We kept the 85-foot telescope very well instrumented, not only with state-of-the-art, low-noise receivers and the digital correlator, but also with safety features. One of these was a weather and wind monitor. If ice built up on the dish, or if the wind blew too fast, the dish stowed automatically. There was only one problem with our weather monitoring: while we could see what was happening, and we could move the telescope to a safe position in response, we couldn't actually *do* anything about the weather. Our inability in this area is what did the telescope in. I was driving up to Hat Creek that fateful night of 1993 Jan 23 to do some work on the system—and be there for a weekend visit of undergraduates taking Dave Cudaback's astronomy lab class. The following are excerpts from some notes I made that night in the dark, using my battery-powered laptop, which I sent to some special friends:

"It was a dark and stormy night. I head up lonely Route 505. Not many cars on it; I peg up to 85, pull out the radar detector, keep an eye out the rearview. Rain, rain, rain; Then...suddenly...stars, pinpoints of light and the absolute blackness of a moonless night. And WIND. Strong wind.

"Pull into Williams for a diet coke to stay awake. Later, pull into Corning, the 24-hour Safeway never fails. Let's see... cereal, fruit, rice, here's some nice fish, some frozen peas/onions. Should I get some Jack Daniels? Ahhhhhhhh... no. (I'll regret this decisison...)

"After Corning, the dark, narrow road is clear nearly all the way to Eskimo summit. Icy up there; and, over the summit, lots of ice. Also lots of little branches off of trees: the wind has been strong. I wonder how strong the wind was in the valley where the telescope... is.

"I drive slowly on the icy road. I am surprised to see a couple of cars come by the other direction. I notice more tree branches, lots of needles and pine cones on the road. As I go further there is more litter in the road. Larger branches—so large that, if you hit one, it would do damage. It's pitch black...I'd better be careful. As I go lower, the temperature rises and there is no more ice. But the new hazard, branches and parts of whole trees, keeps my speed down.

"Gad, that last stretch always seems the longest, I think. But, finally, here is the turnoff. The road to the observatory, Bidwell road—named after the local farmer—is FULL of little trees. Somebody has come along and cut them so that a car can get past; I'm glad for that. I begin to think seriously: these trees have been around for a long time. This must have been a mighty strong wind. I wonder... about the telescope...

"Here is the observatory entrance. The usual bright sodium light is out: the observatory has lost power. A big tree is down in the observatory road. Somebody has cut part of it away and driven around it. I follow the tracks, avoid getting stuck, and continue... when, what to my wondering eyes should appear... but... a pile of rubble. Shades of the 300 foot!

"I walk around it, check the lab building. It was miraculously untouched: the telescope blew down just to its side. How about the little [BIMA] array antennas? They look OK.

"OK, back to the dorm...I park, get my groceries and walk into the kitchen. Christ. Why didn't I get some JD?

"Plambeck must have heard me: he comes out of the sleeping area, asks if I've seen it. The wind came up all of a sudden, he says: 'While we were worried about a tree falling on the dorm, or our cars, Al rushed out to the meadow. Fifteen minutes later he came back...' This happened about 8 o'clock, just about the time I stopped in Williams to get my little diet coke. It was windy in Williams, too."

5.2. Now and Future: Life

Figure 4 (left panel) shows my response the next morning: salvage those parts! Take them back to Berkeley and set up an undergrad lab for radio astronomy! Dave Cudaback had developed an optical lab, which was hugely popular. This enthusiasm sparked an amazingly active and productive interest in undergrad-

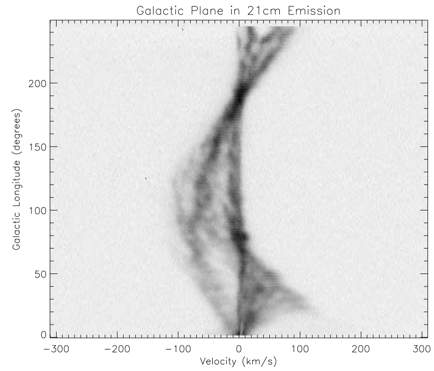

Figure 4. Left: CH salvaging all those goodies the morning after the collapse! Right: Longitude-velocity image from the new 14-foot dish at Leuschner (lifted from an undergraduate lab report by Kyle Englehorn).

uate education in the Berkeley Astronomy Department (BAD), which turned into GOOD for BAD undergraduates as a result, and it continues to this day by involving grad students, faculty, and even postdocs. The radio lab contributed a lot to this success.

We built a horn antenna on the roof of our building, Campbell Hall, for the λ 21cm line, and use Fourier-transform spectroscopy, which is implemented with a fast sampler and an ordinary desktop computer, to detect and map the emission. This year (2005) we didn't use the horn, but instead a larger 14-foot single dish from the Rapid Prototype Array of the ATA that is located nearby at our Department's Leuschner Observatory in Lafayette; with its beamwidth of 4° and the high-quality digital spectroscopy, we get terrific HI maps (Fig. 4, right panel).

We also built a 12-GHz interferometer on Campbell Hall's roof with which the students measure accurate positions using VLBI fringe fitting techniques as well as accurate diameters of the Sun and Moon using Fourier modeling. I find that the work with the interferometer is best summed up by the abstract from one of the first lab reports on the results from the interferometer (by then-undergraduate Robert Quimby):

"We used a small two-element interferometer with an East-West baseline to resolve the Sun and the Moon, and to observe the Crab Nebula, Orion Nebula, and Cas A point sources. The radius of the Moon on December 7 was 0.268 ± 0.005 *degrees, and on December 3, the radius of the sun was* 0.296 ± 0.006 *degrees at 12.2 GHz. The declinations of the point sources were measured as* 21.945 ± 0.001*,* -5.376 ± 0.003*, and* 58.751 ± 0.003 *degrees, respectively (assuming no error in the baseline measurement)."*

In the lab, the students are exposed to lots of numerical analysis and digital techniques. They do the real stuff, without black boxes and without canned software; instead, they write their own, using IDL. And I should add that Quimby's report, as all reports in this lab, is written in LaTex.

6. Postscript

We often think that our primary activity is research. However, getting students fired up about science, technology, and even astronomy is even more important—most of them are smarter than we are and they will do better research than we do. The 85-foot lives on by its role in training new students and getting them excited. What finer legacy could it have asked for?

Acknowledgments. Thinking back on the 85-foot, its successes come from the people who contributed. The principals include Hat Creek Directors Harold Weaver and Jack Welch; engineers Tap Lum, Doug Thornton, Lynn Urry, and David Williams; the site supervisors Warren Taylor and Al Masters. There are lots of others who are too numerous to mention here, and I'm grateful to them and apologize for not mentioning each and every name. A remarkable cooperative and energetic spirit pervades the people in the Radio Lab, which has made it so productive despite sometimes severe resource limitations. It is also a great pleasure to thank Josh Goldston and Tim Robishaw for their contributions to this paper. This research was supported in part by NSF grant AST 04-06987, and by the NAIC.

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