A BRIEF HISTORY OF THE INDIAN RIVER OBSERVATORY RADIO INTERFEROMETER

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A BRIEF HISTORY OF THE INDIAN RIVER OBSERVATORY RADIO INTERFEROMETER

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ABSTRACT

We describe the construction and evolution of a large amateur-built radiotelescope over the past 14 years. To illustrate the improvements in sensitivity achieved during the project, we include examples of observations made with the instrument.

RÉSUMÉ

Nous décrivons la construction et 1'évolution d'un grand radiotéIescope fabriqué par des amateurs pendant les 14 dernières années. Pour illustrer les améliorations de la sensibility réalisées pendant ce projet, nous incluons des exemples d'observations effectuées avec cet instrument.

Introduction. Technical progress is bringing the construction of highly sensitive radiotelescopes within the reach of private individuals. Amateur radioastronomers need no longer be limited to making observations of the Sun, Milky Way and the four strongest discrete radio sources. Components, which only a few years ago could be found only in large research facilities, can now be bought over-the-counter. However, building the large antennas and sensitive receivers, and the signal processing needed for some of the more ambitious projects, such as detecting quasars and other faint radio sources, may require the resources of a group. In this paper we summarize the planning and construction of the R. A. S. C. Ottawa Centre's "Indian River Observatory Radio Interferometer". We do not intend it to be a design description, but more an account of the way this project was carried out.

The IRO Radio Interferometer. The Indian River Observatory Radio Interferometer (IRORI) is the result of a number of factors which came together at the right time. The first was the need to move an observatory. For several years the Ottawa Centre had been operating its "North Mountain Observatory" (NMO), located near the town of South Mountain, to the south of Ottawa. The main instrument at the Observatory was a 40-cm Newtonian telescope. The southward spread of the city, together with the increasing number of neighbours, made it obvious that the observatory would have to be relocated. After a long search a suitable site was found, near Almonte, roughly 50 kilometres to the south-west of Ottawa. About two acres of land were generously offered to the Centre by the Mississippi Valley Conservation Authority. This was more than was needed for an observatory building, club house and car park; there was room for other projects, such as a radiotelescope.

The second ingredient was the appearance in, the Ottawa Centre of a new member (KT), who had been heavily involved in amateur radioastronomy in the United Kingdom, with members of the British Astronomical Association, and wanted to get involved in similar activities in Canada. The third ingredient was the mood in the Ottawa Centre. The successful completion of the observatory relocation was in sight, and there was a lot of enthusiasm for new challenges.

In early 1976, a meeting of seven interested Centre members was held at KT's apartment in Ottawa, and the possibilities were discussed in more detail. An important consideration was how the wide range of skills and expertise in the Centre could be harnessed effectively in such a large project. An extract from the original introduction to the project manual (to be) reads:

> "In a recent meeting, the Radio Telescope Group held preliminary discussions concerning the construction of a radio interferometer at the new location, now renamed the Indian River Observatory. At the meeting there was considerable interest in this project. It was decided that

> the construction of this instrument would be a joint effort, with the electronics being in the form of modules which could be built by members and incorporated into the final device."

Following this meeting KT gave several talks on radio astronomy at the monthly meetings of the Centre's Observers' Group (the active members of the Centre), describing the project and inviting members to participate. Since the "Great Observatory Move" of 1977 was reaching its climax, and was tying up all the Centre's resources, it was decided that major construction would be started in 1978. Work on the electronic modules for the telescope began in the fall and winter of 1977-78.

Since radio waves are much longer than light waves, very large antennas are required if reasonable angular solution is to be obtained. A radiotelescope, operating at a wavelength of 1 m, in order to achieve the same angular resolution as a 7.5 cm (3 inch) optical refracting telescope needs an antenna about 150 kilometres in diameter!

Our new observatory site was about 200 m wide. However, constructing a 200 m dish was out of the question. We could, however, build an interferometer (the operation of radio interferometers and other types of radiotelescope is discussed by Steinberg and Lequeux, 1963). In this way we could obtain some of the performance of a large radiotelescope, while actually building two much smaller antennas. Our initial design (13th July, 1977) consisted of broadside arrays[1], each 5 m square, separated by about 155 m in an East-West line. This would give us the angular resolution of an antenna 155 m across! However, the sensitivity would be dictated by the actual size of the antennas.

This relatively modest design did not last. In 1977 Larry Schweizer joined the group. This brought not only his practical expertise in engineering, but also a well-equipped workshop in Almonte, only a few minutes from the observatory. In addition, Larry donated $500 to the project. Our plans then became more ambitious.

The best general-purpose antenna design is the paraboloidal dish, which, like the paraboloidal mirror in an optical telescope, brings the received energy to a single focus. A single dipole[2] can then be used to collect the radio waves. However, building large dishes can be difficult and expensive, and so a compromise was made: a pair of 15 *X* 5 metre parabolic cylinders was decided upon. John Smith (a British friend of KT) had previously built an antenna of this kind, based upon the parabolic cylinders used in the interferometers at Cambridge University in the U.K. Robert Dick, together with other group members, made many significant improvements, and reinterpreted the design in terms of available materials. The final configuration gave a large surface collecting area while keeping the structure light and manageable, and not too high above the ground.

In the fall of 1977, group members surveyed the site, setting up the 155 m East-West interferometer baseline and marking the sites for the antenna support posts. Eight posts are used, four for each antenna. Mounting the posts (which are hydro poles cut in half), required eight holes to be dug, each about two metres deep. In late November 1977, Oliver Toop of Almonte dug the holes using a front-end loader, charging only a nominal fee. On several

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[1] **Broadside Array**: An array of dipoles mounted in front of a large, planar reflector, which increases the sensitivity of the array to waves arriving from the front.

[2] **Dipole**: A section of metal rod of length chosen to resonate with radio waves of a particular wavelength. It extracts energy from the waves and converts it into an electric current which can be transmitted through cables to amplifiers and other devices.

occasions large boulders were encountered, requiring the holes to be resited and the baseline to be resurveyed.

The rate of construction peaked in 1978. The antennas were prefabricated in Larry Schweizer's workshop. The eight parabolic sections were constructed from 1 X 1/4-inch mild steel strips. The sections were shaped and assembled using a plywood jig and then electrically welded. The preassembled and painted units were then transported to the observatory (in Larry's van) for final assembly. Figure 1 shows the assembly of one of the antennas on-site. The project required a lot of hard physical labour, such as digging (and then filling) holes, removing rust with wire brushes, and painting steel strip. This was done by Centre members, usually with Larry's tools.

FIG. 1 -One of the parabolic cylinders being assembled (summer, 1978). From to left to right, Jim Zillinsky, Frank Roy, Pierre Lemay, Priscilla Muir *(Photograph by Rob Dick).*

The antennas were designed to operate at a wavelength in the 1-2 m range. The structure was designed using Finite Element Analysis, and the cylinders were theoretically capable of supporting the mesh required for studies of cold, interstellar hydrogen, at a wavelength of 21 cm. We found this prospect very inviting, and decided that if possible the antennas should be modified so that when a suitable receiver could be built we could extend our observations to mapping neutral hydrogen in our Galaxy.

During the construction of the parabolic sections, tests were carried out (at Larry's) to check the stress model, and our workmanship. One of the segments was supported on a couple of wooden stakes and then loaded with four barrels, which were gradually filled with water. We needed to know at what point the structure would bend or if the welds would give beforehand. We added water until a failure occurred. When the barrels were within inches of being full the truss collapsed. It proved the welding was of high quality and the trusses could indeed support the mesh needed for operation at 21 cm wavelength. However, as we began to appreciate the scale of the project as originally conceived, proposals for hydrogen line observations were shelved, and finally dropped. We decided to stick with the original design, for antennas working in the 1-2 m wavelength range. One of the completed antennas is shown in figure 2.

FIG. 2--One of the completed 5 X 15-metre antennas (autumn, 1986). The operating frequency is 238 MHz. *(Photograph by Frank Roy).*

The IRORI was officially opened on 28th October 1978 by Arthur E. Covington, Canada's pioneer radioastronomer (figure 3). Accompanied by many muttered prayers and crossed fingers, with CBC-TV looking on, he switched on the instrument, and it worked!

FIG. 3-Canadian pioneer radioastronomer Arthur E. Covington makes the first observation, 28th October, 1978 *(Photograph by Jacqui Tapping).*

However the antenna sensitivity was only a small fraction of what we had hoped. We were not collecting all the energy it was intercepting. For practical considerations we had decided upon parabolic cylinder antennas. The disadvantage of this design compared with the paraboloidal dish is that, instead of bringing the received energy to a point focus, it brings it to a "focal line". To collect the signal a row of dipoles is needed, distributed along the focal line. We did not then appreciate how difficult it is to collect efficiently the signal from a cylindrical focus; it took almost two years to get a satisfactorily-shaped antenna beam!

Additional work was needed on the electronics in the receiver. The system was built when the group had been relatively inexperienced in construction techniques, and (obviously) had no knowledge of the problems of getting a radiotelescope operating *at that site*. Optical astronomers select sites for a dark sky. The radioastronomer's equivalent of a dark sky is the absence of interference from electrical equipment, and from radio and TV transmitters. It turned out that the site was quite poor (at 180 MHz, our observing frequency at that time), with strong TV interference and "spikes" and "buzz" from local hydro lines. It is not therefore surprising that initially the sensitivity was quite mediocre. Of course, being a very powerful radio source, the Sun was easily detected. In addition to the Sun, only four other discrete sources could be identified, the radio galaxies Cygnus A and Virgo A, and the supernova remnants Cassiopeia A and Taurus A. From these early fringes the estimated sensitivity was of the order of several hundred janskys (1 jansky = 10^{-26} W. m^{-2} .Hz^{-1}). The first dipole array was designed for 180 MHz, the idea being eventually to try Very Long Baseline Interferometry with John Smith in the United Kingdom, who was operating at that frequency. Unfortunately the interference was overwhelming, and the antenna performance was unacceptable. The antenna beam-profile had a pronounced resemblance to a two-humped camel, certainly nothing like the single, sharp beam we needed.

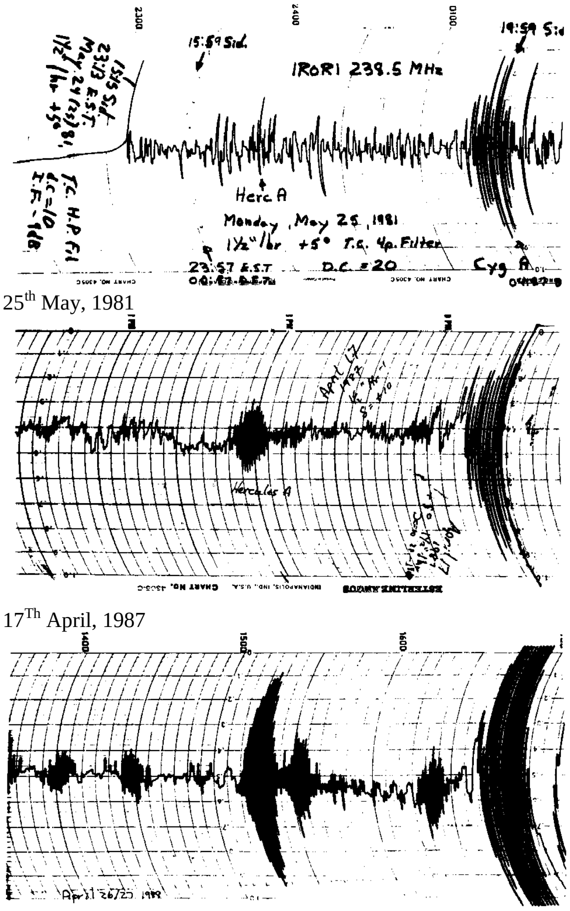
Having obtained some initial results, we began work to increase the sensitivity. By now the level of expertise in the group (which had diminished to about four) had reached a point where the initial versions of the electronics that were used to obtain the first observations could be replaced with improved designs. The receiver's local oscillator and intermediate frequency amplifier were rebuilt and laboratory-tested to fairly rigid specifications. There then began a steady evolution of the system, which produced improvements, sometimes slight and sometimes major. The dipole arrays used to collect the signal from the focal lines of the parabolic cylinder antennas had to be improved. Since they are responsible for collecting the signal intercepted by the antennas, increasing their efficiency became the highest priority as soon as the receiver was performing adequately.

In addition to participating in this project, Jim Zillinsky, one of the group, had built a small radiotelescope of his own, operating at a frequency of about 235 MHz. He discovered that the level of interference was low in that frequency range. So in 1980, two new 240 MHz dipole feed arrays were built; they consisted of eight dipoles for each antenna. Each dipole had a "bazooka" balun[3] for adapting the signal to the coaxial cable. A "Christmas tree" was built of RG 59 cable and commercially-available signal combiners[4] intended for use in cable TV. (These were bifilar transformers wound on ferrite beads. Types using resistors for matching are not usable for this application.) In each antenna, groups of four dipoles fed 4:1 combiners. The two outputs from these were then added in a 2:1 combiner, which then passed the signal to low-noise amplifiers attached to each antenna. At that time the noise temperature of the amplifiers was about 500 K.

These improvements significantly increased the sensitivity. The antenna beam was now better shaped and the interference problem was much reduced. In early 1981 we detected the radio source Hercules A, at 236 janskys the weakest source yet! Figure 4 shows the original record, along with later records obtained as the telescope was improved.

During the next five years the process of rebuilding and improvement continued. Recurrence of the interference problem led to extensive changes in the design of the receiver. In 1982 a new 30 MHz intermediate frequency amplifier was built, which includes 10 double-tuned stages, plus 6-pole and 4-pole passive filters. The whole device has a bandwidth of 900 kHz, with extremely steep skirts. An important part of overcoming the interference problem was to make the local oscillator stable and pure, and carefully to filter the signals coming in from the antennas so that spurious signals are not generated in the first stages of the receiver. Nevertheless, further small changes in operating frequency were

Observations of Hercules A



25th May, 1981

17Th April, 1987

26th April. 1988

FIG. 4-Records of the radio source Hercules A, showing the improvements made over the years *(Observations by Frank Roy)*. Top trace: installation of the second, 8 dipole array produced a better-shaped antenna beam and made it possible for the first time to detect Hercules A. Middle trace: The spacing of the reflector mesh was reduced to 3 inches, and low-noise (50 K) GaAsFET amplifiers were installed. These changes permitted the detection of the quasar 3C298, our faintest source up to that time. Bottom trace: New, broader-band dipoles were constructed, and the number of dipoles on each antenna increased to 12. The signals were collected using lower loss cables and new 12:1 coaxial combiners. Sensitivity increased fourfold, and 10-jansky sources could now be detected.

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[3] **Balun**: A concatenation of BALanced to UNbalanced transformers, an electrical device to transform balanced currents, such as those produced by dipoles, to an unbalanced current suitable for transmission through coaxial cable. The "bazooka" is a form of balun in which a coaxial sleeve 1/4 wavelength long is connected to the outside of the coaxial cable. It prevents currents from flowing in the outside of the cable.

[4] **Combiner**: A electrical device used to combine a number of input signals into a single output. For our application it must have as little insertion loss and phase distortion as possible.

required. It was found that the best compromise of good antenna performance and low interference occurred at an operating frequency of 238 MHz.

At that time an Esterline Angus strip-chart recorder was used as the main data-logging instrument. In 1984, in order to avoid unnecessary wastage of chart, and to facilitate unattended operation, a sidereal timer was installed. Over this period, myriads of new problems appeared: chart recorder ink froze, woodchucks ate the cable feeding power to the antennas, and lightning blew up amplifiers. On one occasion a wind storm blew both antennas partially off their mounting poles. Fortunately, they were still supported at both ends (15 metres apart), but were sagging more than one-and-a-half metres in the middle. The damage was minor. Metal straps were added to hold the antenna in place. On one occasion, one of us (FR) returned to the observatory after an absence of several days to find an enormous pile of chart paper on the floor. Instead of leaving the chart speed set to 1.5 inches per hour, it had been set to 1. 5 inches *per minute.*

In 1985 another programme of antenna improvements was started. This work continued into 1987. In order to obtain better performance at the new operating frequency, the number of wires making up the reflecting mesh surface of the parabolic cylinders was doubled, bringing the wire spacing to a twentieth of a wavelength. In April 1986 the 500 K noise temperature antenna amplifiers were replaced with GaAsFET amplifiers having noise temperature of about 50 K. Besides enhancing the sensitivity, the large, linear dynamic range of these amplifiers substantially improved the system's resistance to interference.

Early results with the improved antennas and lower-noise amplifiers were very promising; the sensitivity had increased dramatically. On 29th April 1986, FR used the telescope to detect the radio quasar 3C298, which is located in Virgo. As far as we know, this is the first amateur detection of a radio quasar. This source has a flux density of about 39 janskys at 238 MHz. The observation was reported in the August 1986 issue of the R. A. S. C. *National Newsletter.* The magazine *Sky and Telescope* mentioned this report in their section on international news in December 1986. The chart record of the quasar showed a signal-to-noise ratio of about 4: 1, indicating that it should be possible to detect sources as weak as 10 janskys. The detection record is shown in figure 6.

Quasar 3C298: 28th April, 1986

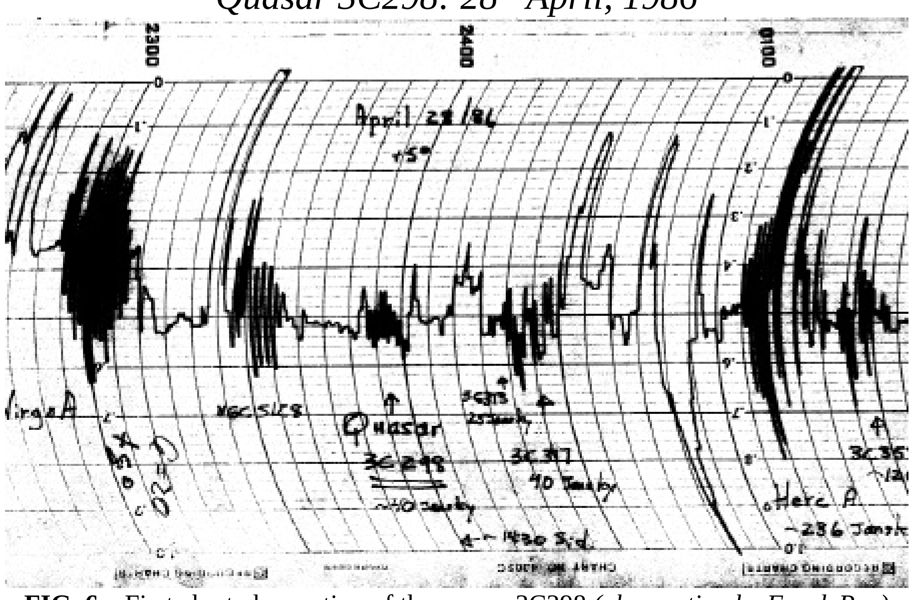

FIG. 6—First chart observation of the quasar 3C298 *(observation by Frank Roy)*

In 1987 a new set of dipoles were made using 5/8-inch outside diameter copper tubing, each again with a "bazooka" balun. The new dipoles had a broader bandwidth, making them more immune to mismatches in the cabling system. In order to improve the signal collecting efficiency, the number of dipoles was increased to twelve. The cable system for collecting the signals from the antennas was replaced. This time the dipoles were fitted with identical lengths of lower loss RG 8U cable. The signals from twelve dipoles were combined in a specially-made 12:1 quarter-wave coaxial combiner (figure 5). The bottom trace in figure 4 shows the results of these improvements.

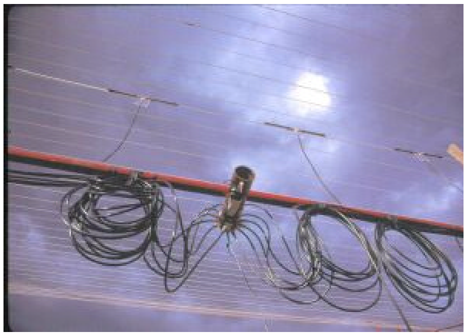

FIG. 5-"Medusa", one of the two 12-way signal combiners. These are quarter-wave sections of coaxial line which match 12 50-ohm lines in parallel (an impedance of 4 ohms) to the 50-ohm cable transferring the combined signals to the GaAsFET amplifiers. They are constructed from copper tube and have an effective bandwidth of at least 10 MHz *(Photograph by Frank Roy)*

Since the detection of 3C298, surveys of small parts of the sky have revealed many other sources, including a further six quasars. To date, some 100 sources have been identified; most are radio galaxies.

With the sensitivity now reaching the anticipated levels, attention was directed to the methods used to record the data. The strip chart recorder did not record data in a form amenable to easy analysis. For some years experimental use was made of an Apple II+ computer as part of a data acquisition system. An 8-bit analogue-to-digital converter[5] was used. Although somewhat limited by current standards, it amply demonstrated the usefulness of digital data logging as an analysis aid in amateur radio astronomy.

During the early days of the IRORI, three main goals were set: detection of a radio quasar, a map of the sky, showing discrete sources and the galactic continuum emission, and the detection of a radio pulsar. In late 1987 FR got together a group to undertake a detailed sky survey. They pooled their resources to purchase a more powerful, IBM PC-XT compatible computer for use with a 12-bit analogue-to-digital converter. The data are stored on a 30 megabyte hard disc drive. It is now installed on the telescope, and is being used to make unattended observations. The improvement obtained through digital data recording and signal processing compared with chart records is very visible in the recording of Hercules A shown in figure 7.

Each antenna has a fan beam 5 degrees in hour angle times 15 degrees in declination. At 238 MHz, the 155 m baseline gives a fringe spacing of about 0.5 degrees. At any one time, the antennas are observing all the sources in a patch of sky having an area of about 75 square degrees. As fainter sources are observed, the number per unit area of sky increases. At the current sensitivity of the IRORI, more than one source per 75 square degrees of sky is observed. This condition is termed as being "resolution limited". Further increases in sensitivity through using lower-noise amplifiers will not yield more sources. It would be more useful to make the antennas larger, which would make the antenna beam smaller.

[5] **Analogue to digital converter**: An integrated circuit that converts analogue signals to binary numbers suitable for processing by computers. Generally AID converters are specified by their resolution, which is set by the number of bits.

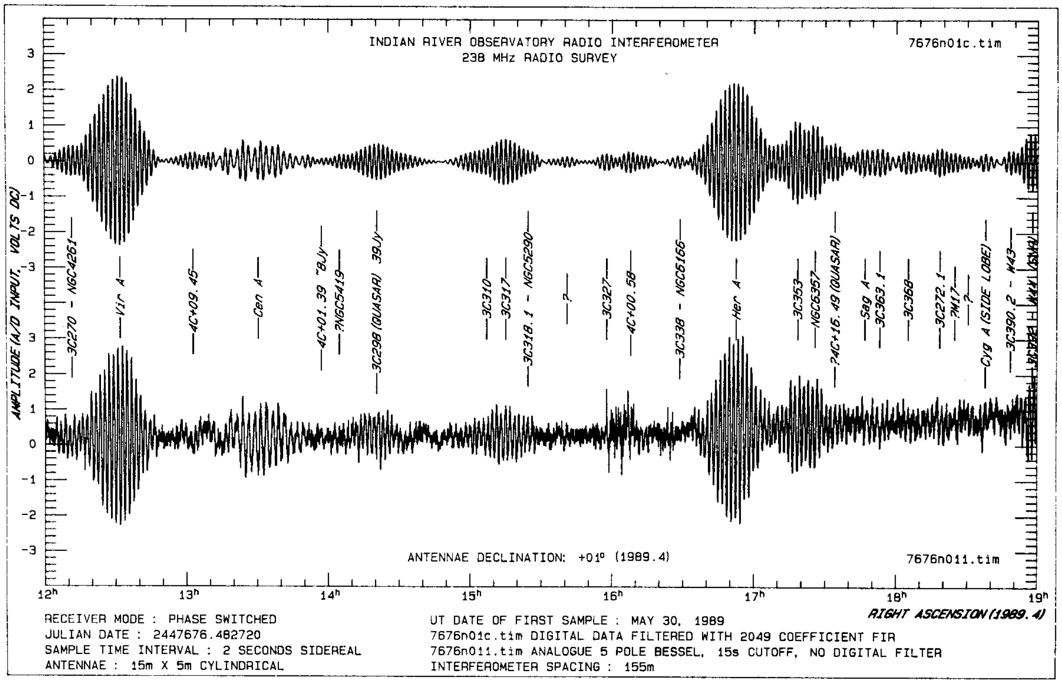

FIG. 7-A recording of Hercules-A and other fainter sources made using the digital data acquisition and signal processing system developed for the sky survey. The bottom trace is the original raw data with a bandwidth of 68 X 10^{-3} Hz. The top trace has been filtered with a Finite Impulse Response (FIR) digital filter with an equivalent bandwidth of 3 X 10^{-3} Hz with a centre frequency of 7.5 X 10^{-3} Hz. The sampling interval is 2 seconds. The sources were identified using *Sky Catalogue 2000.0* (1985) as the reference. This record well illustrates that the limiting factor with the radiotelescope is now confusion rather than sensitivity *(plot by Frank Roy).*

In order to use the radiotelescope simultaneously as a total power receiver, adding interferometer and as a phase-switched interferometer, further signal processing electronics were added to the receiver. It is now possible to map the galactic continuum, and using the data from the two interferometer configurations, estimate the sizes of some of the larger source structures.

This article may convey the impression that the work proceeded steadily from start to finish, punctuated with minor technical difficulties. This could not be farther from the truth. We encountered a wide range of difficulties, some of which took a long time to solve. Looking back we see that many of the problems were based upon trivial errors, although they didn't seem that way at the time. One important conclusion we draw from the experience is that success cannot be guaranteed; it has to be worked for.

As the rate of progress and type of work changed, the size of the group varied. In the early part of the project, when earth, steel and wood were being moved, the work parties often numbered a dozen people. As progress slowed, and the work became more technical, the group shrank down to one or two. This brings us to our second important conclusion: there must be a core person or two who have unlimited enthusiasm for the project, and keep it moving, despite the problems.

The IRORI project has taken more than ten years and has been a learning experience for all of us. One of us (FR) was a teenager at the beginning of the project, and knew little about radioastronomy and the technology that goes with it. Through experience gained while building and using the radiotelescope, he is now employed as an electronics technologist by a major electronics firm.

Another important conclusion is that the temptation to make a complex, sophisticated system must be resisted. Keep things simple but make them reliable. Under routine observing conditions it is not unusual to leave the instrument unattended for several days or weeks, recording data as part of a project. It is necessary that the data be consistent and uninterrupted by failures.

We did not find this an easy project. We soon learned that we had to make use of all the resources available, people and materials. Our ideas matured with the project, and considering the technology available today in the way of sensitive radio receivers and computer technology, the only fundamental limit is imagination.

Acknowledgments. Many people contributed to this project, too many to be individually listed here, but we must express our gratitude to Fred Lossing, who, as President of the Centre, was instrumental in getting this project started, and in helping out as the project progressed. It is hard to imagine how the project would have turned out without the participation of Larry and Ann Schweizer. The contribution they made to this project cannot be overestimated. Besides providing a well-equipped workshop within easy reach of the observatory, Larry gave enormous amounts of his own time, and in addition to a cash donation of $500, spent more of his money buying miscellaneous bits and pieces for the project. His expertise in seeing ways of handling some of the multitudinous construction problems was invaluable. Every week Ann provided enormous amounts of excellent food in what became a series of post-work barbecue parties. The postmortems on the day's work, and planning for next time, conducted under conditions of such hospitality are among the more memorable aspects of this project. The telescope would not have turned out so well, and the project would have not been as much fun, or as memorable.

We would like also to thank Arthur Covington for his encouragement, and for a donation of $200 for equipment improvements. Last, but not least, we would like to thank the Ottawa Centre for providing $1500 to fund the project, and for providing an excellent site.

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