A personal history of the DRAO's 10-MHz 'T' Array Project

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These notes were prepared to accompany, and to provide background for, the paper and digital materials pertaining to the Dominion Radio Astrophysical Observatory (DRAO)/Cambridge University 10-MHz T array project that I have placed in the NRAO's Historical Archives. Uncredited photos were taken by me in 1965 and 1966.

1. Motivation and pre-history

The original impetus for the Cambridge-based effort to study discrete radio sources and diffuse cosmic non-thermal emission at frequencies as low as 10 MHz in the mid-1960's came from Peter Scheuer and John Baldwin, both members of the Cavendish Laboratory's radio astronomy group led by Martin Ryle.

In the 1950's Peter Scheuer had written part of his Ph.D. thesis on the distribution of ionized hydrogen in the galactic disk. Observations by Shain in Australia at 19.7 MHz had shown that the free electrons in the interstellar gas, which are seen in emission at high frequencies, appear in absorption against the non-thermal galactic emission at low frequencies. Scheuer calculated the free-free absorption of ionized gas as a function of observing frequency, density and temperature, and had used this to derive its physical properties, as well as its distribution in galactic latitude and longitude. Pushing such work down to 10 MHz was expected to enable studies of more dilute ionized regions, perhaps giving extra insight into what processes maintain the ionization.

John Baldwin had taken over the supervision of an all-sky survey with a 38-MHz aperture synthesis telescope built at Lord's Bridge by Francis Graham-Smith's Ph.D. student Carman Costain in 1960. By 1963, the 38-MHz survey had shown that a few discrete radio sources, all of small angular diameter, showed turnovers in their radio spectra below 81.5 MHz (the '2C' survey frequency). Observations at still lower frequencies were seen as a possible way to identify unusually compact radio sources from their spectra alone. Interest in this topic increased when several such sources were shown to be quasars at high red shifts (and thus to be among the most luminous extragalactic objects then known).

Scheuer had studied several effects that could produce low-frequency turnovers in radio source spectra: free-free absorption, the Tsytovich-Razin effect, deficits of low energy electrons, and synchrotron self-absorption. While self-absorption was seen as the leading contender for causing the spectral turnovers, Scheuer was eager to find more examples. His goal was to find new quasars by purely radio means, and to try to distinguish the different turnover mechanisms by their spectral shapes, and thus to begin to explore physical conditions in the radio-emitting regions.

Cambridge itself was ill-suited for high-resolution work at frequencies below 38 MHz, however. Although the night-time ionosphere over Cambridge became sensibly transparent above about 13 MHz once the daily rise in the D layer's ionization recombined, scintillation and refraction made it hard to use good angular resolution at low frequencies, even if enough real estate could be found on which to build the necessary large antennas. It was thought that the 38-MHz aperture synthesis array had pushed the low-frequency limit about as far as was practicable at Lord's Bridge for work at about 1º FWHM resolution. To study discrete sources at such resolution at even lower frequencies would require observing sites where typical night-time critical ionospheric frequencies (f0F2) were significantly lower than those over England.

Ideas for possibly better sites for such work came to Cambridge from two main sources, both Canadian. Carman Costain, who had returned to Canada after making the observations at Lord's Bridge for his Ph.D., had begun to plan a new T-shaped array to work at 22 MHz at the DRAO near Penticton, British Columbia. Unlike his 38-MHz aperture-synthesis array, the 22-MHz array at the DRAO formed its pencil beam in real time, so it could make full use of single nights when observing conditions were best. Early results from the new array suggested that ionospheric conditions over the DRAO site (at intermediate latitude both geomagnetically and geographically) were promising. Martin Ryle had visited the DRAO and was aware of Costain's progress.

Scheuer also had a chance encounter on an airplane with Canadian ionospheric physicist Theodore 'Ted' Hartz who was making "topside sounder" studies of the ionospheric electron content from the Canadian "Alouette 1" satellite. Hartz had found that the ionospheric reflection became hard to detect North of the auroral zone (where radio source scintillation was well known to be severe). Hartz's data held out the hope that lower-frequency observing might be possible at far Northern "polar cap" sites where the lines of sight to many radio sources would pass through the ionosphere at geomagnetic latitudes above those of the auroral region.

2. Diversion: Polar cap radio astronomy

In 1963 Scheuer sought Ryle's support for exploratory low-frequency work at such high geomagnetic latitudes. The first site they considered was in Greenland, but the logistics of setting up a new observing station there were daunting. It seemed more practical to try to use the existing research station operated by the Canadian Defense Research Board (DRB) at Resolute Bay (74°41′ N, 94°52′ W) on Cornwallis Island in the Parry Channel, where radio scientist Jack Belrose ran an ionosonde and backscatter experiment.

Scheuer was funded to visit Resolute Bay in the late summer of 1963. After first visiting DRB in Ottawa, he went to Resolute and built a 4.5-MHz dipole (usable from 3 to 7 MHz) and an interferometer with pairs of dipoles usable from 7 to 13 MHz on a 900-m East-West baseline.

The practical difficulties facing radio astronomy in the polar cap environment were soon apparent. The ground was permafrost: rock hard and impossible to dig into, so the dipole supports had to be mounted in rock piles encased in the only readily available containers – discarded oil drums. Impedance measurements on Scheuer's dipoles then showed that permafrost was a nearly-perfect absorber. The dipoles therefore had no "ground screens" and were effectively in free space, reducing their forward gains. This effect, and the long cable runs needed to bring signals from the dipoles to the base station, required the use of battery-powered pre-amplifiers at the dipoles.

Chris Purton, a Ph.D. student from Toronto who was working in the Cavendish group under Francis Graham-Smith on diode noise sources for the absolute calibration of low-frequency observations, went to Resolute in January 1964 hoping to observe the bright source Cassiopeia A with Scheuer's antennas. Further difficulties ensued: one of the coaxial cables between the dipoles and the base station disconnected when its central conductor shrank in the extreme cold. That cable had to be mended *in situ* as it had become too stiff to coil up. The batteries for the pre-amplifiers at the dipoles also had usable lives of only a few hours at the prevailing low temperatures, so they had to be replaced frequently. That task was difficult in the constant dark and cold and was also hazardous in the presence of polar bears. To make matters worse, Cas A was never seen with the original interferometer, presumably due to a combination of severe scintillation and absorption. Purton had to improvise a shorter-baseline interferometer for 28 MHz in order to study the observing conditions at all. He eventually detected Cas A through severe scintillations but with unexpectedly high absorption. At the time, it had not been realized that the D layer's ionization in the polar cap is maintained not by sunlight, as it is at lower latitudes, but by direct exposure to cosmic ray particles, which at high geomagnetic latitudes arrived along magnetic field lines connected to a distant, and particle-rich, level of the Earth's magnetosphere. Belrose's data taken while Purton was at Resolute showed that on one occasion the D layer came all the way down to ground level, and was so dense that the ionosonde saw no return at all.

It had become abundantly clear that Resolute Bay was a very unsuitable site for low-frequency astronomy, but Purton's experience there allowed him to write what is probably the most entertaining Ph.D. thesis chapter ever produced by a Cambridge radio astronomer.

3. Windfall funding

Fortunately for the progress of astronomy at 10 MHz, by the time Chris Purton returned to Cambridge from Resolute in the Spring of 1964 the alternative of working at a lower frequency at the DRAO had suddenly become real.

In 1964 the DRAO was part of the Canadian government's Department of Mines and Technical Surveys, which had just canceled a program to run a network of seismic stations in the North-West Territories. The funds allocated for the canceled project became available elsewhere in the Department at short notice. The (then) DRAO Director Jack Locke had seized the opportunity to apply the windfall to fund construction of a 10-MHz array near White Lake, about 1 km West of Costain's 22-MHz array.

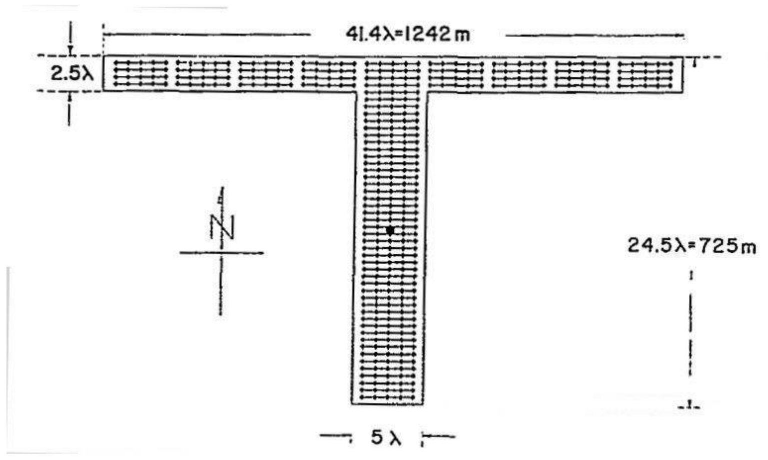
Aerial view of the 10-MHz T array site near White Lake in 1965
taken by Lockwood Survey Corp of Vancouver B.C.

From the outset, the 10-MHz project was a “crash” program that was done as rapidly as possible in order to take data during the expected solar activity minimum in the winter of 1964-1965. The DRAO had the funding and the real estate, and access to contractors who could erect the poles, antennas and transmission lines for a large array, but it lacked the personnel to build the new array’s phasing system and electronics, and to operate it once built. (The DRAO's own low-frequency effort was already fully committed to bringing the 22-MHz T into full operation by the winter of 1964, which was expected to be the prime time for low-frequency work at the end of Solar Cycle 19.)

When Ryle's group became aware of this situation, they were able to obtain funding from the Royal Society to help outfit and staff the 10-MHz array for one “start-up” year. The 10-MHz T project thus became formally a joint DRAO/Cambridge effort, to be overseen by John Galt on-site with most of the back-end and observing effort to be supplied from the Cavendish Laboratory – initially by Scheuer and Purton, fresh from their experience at Resolute Bay.

4. Doing it fast, and all at once

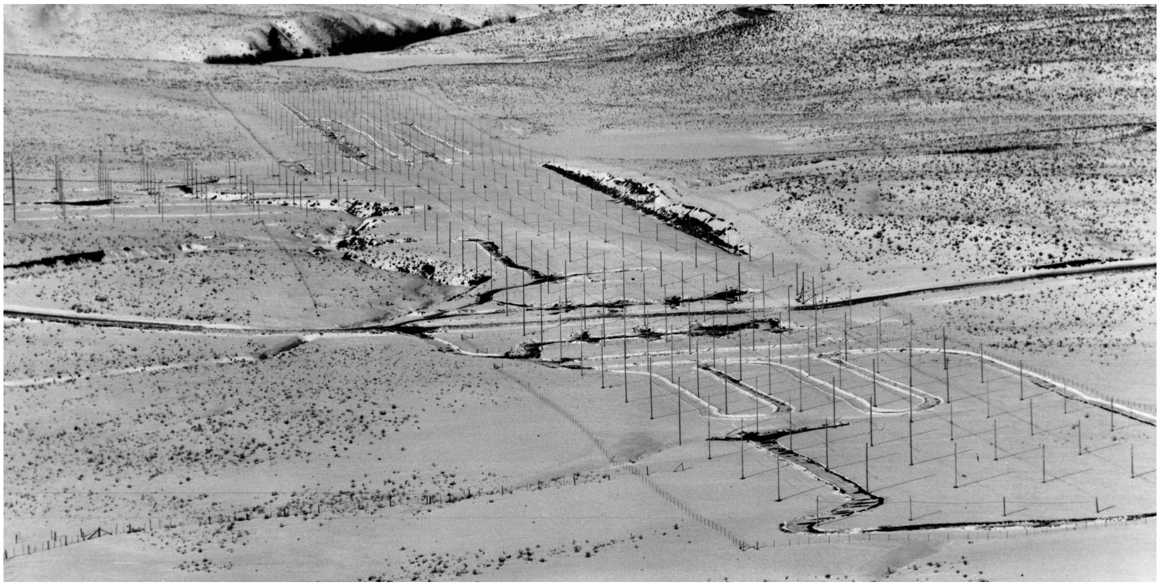
When the 10-MHz T project began in the summer of 1964, it was expected that studies of discrete sources would be limited to winter nights close to minimum solar activity, when the ionosphere should be optimally thin and quiescent. Speed of construction was paramount, as the 11-year activity minimum was expected to occur that winter. Speed of observation was also to be an even higher priority for the new array than for the 22-MHz array.



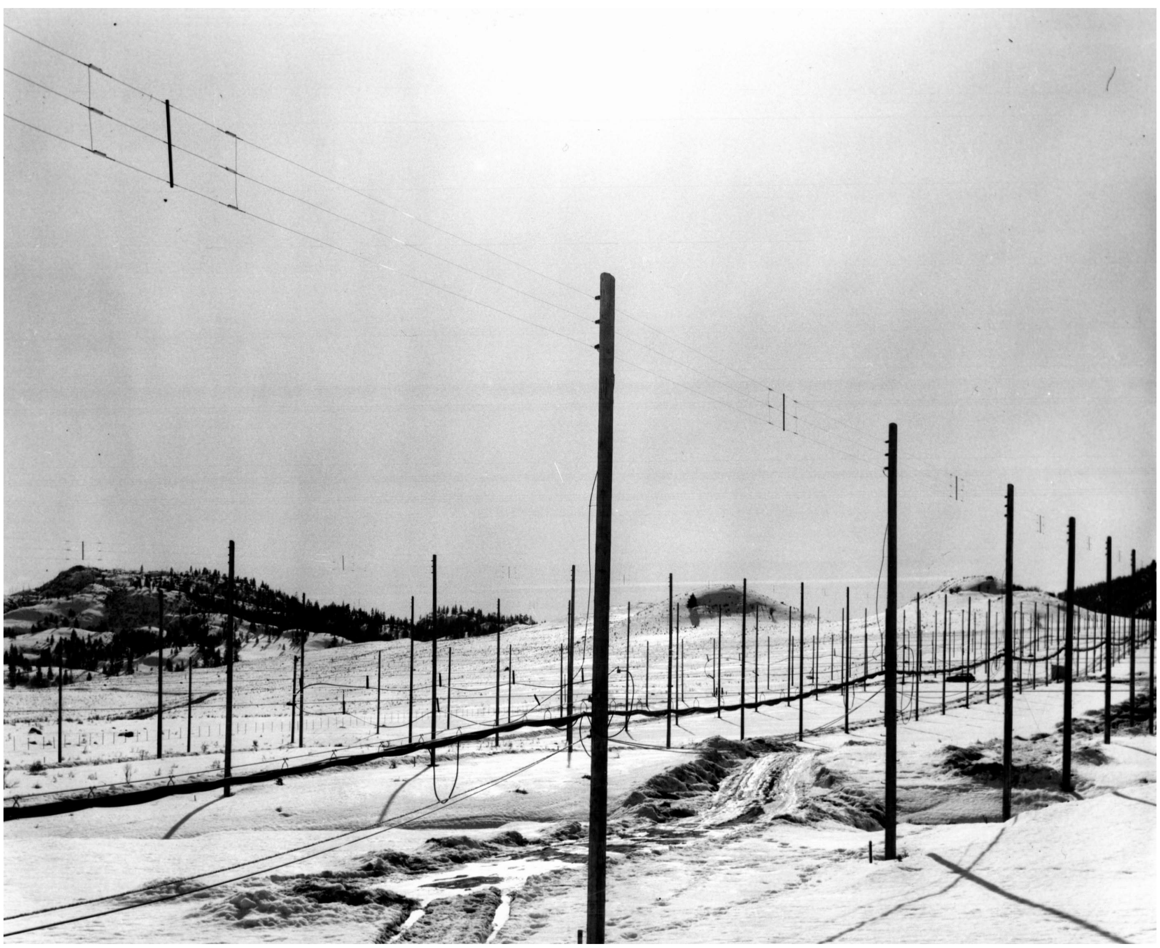
Dimensions of the 10-MHz T array - after Galt, Purton and Scheuer (1967)

The 10-MHz design (see above) was for a filled-T of 400 dipoles located λ/8 above a planar reflecting screen of area 192,000 sq.m. The signals from 20 dipoles in the overlap region of the two arms were shared between the arms, allowing the real-time formation of a pencil beam with FWHM about 2.5º on the array's meridian.

Dipoles at the East end of the 10-MHz array's East-West arm
(Dominion Observatory photo)



10-MHz array from the East, showing crossover region and public road passing through it.
(Dominion Observatory photo)



View along the 10-MHz array's North arm, from near the crossover
(Dominion Observatory photo)

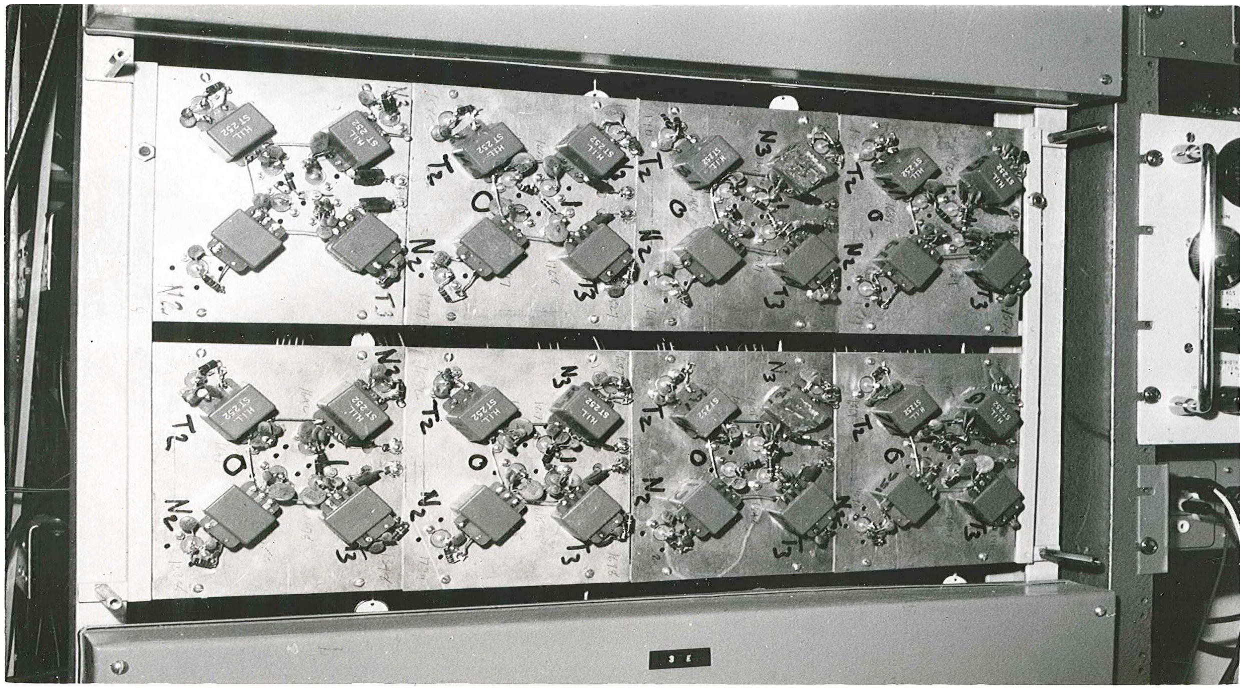
Scheuer proposed to take real time beam formation by the 10-MHz T one step further than at 22 MHz by simultaneously forming many beams on the array's meridian at different declinations using a Butler matrix. (The architecture of this matrix is described in detail by Galt, Purton and Scheuer in 'A Large 10 MHz Array for Radio Astronomy', Publications of the Dominion Observatory, vol 24, pp 294-304 (1967) so I will not repeat it here), If enough back-end receivers had been provided, the 10-MHz design could have surveyed the entire Northern sky in just three nights of good observing conditions (one night for each different declination phasing of the East-West arm).

This attractive concept was ahead of its time relative to affordable commercially-built technology, however, so its practical implementation became problematic. The 10-MHz project's receiver budget also only allowed for up to five simultaneous systems: four could be used to record data from simultaneous pencil beams at different declinations on the meridian while the fifth was used to record the total power from the North-South arm to provide a Relative Ionospheric Opacity Meter ('riometer'). Even this more limited beam-forming capability was valuable, as observations of discrete sources under conditions of moderate ionospheric refraction and scintillation could be corrected for the effects of refraction empirically during data analysis. This feature of the 10-MHz array's design was, indeed, vital to the success of its discrete source measurement program.

The 590 wooden support poles, 400 dipole array elements, and the transmission lines for the array were set in place near White Lake under a contract with Canadian Westinghouse in the summer of 1964. Unfortunately, the installers were telephone linemen who were unused to the concept of maintaining phase relationships while connecting the array elements. As a result, John Galt and his helpers had to spend significant effort determining which dipoles in the array as delivered were connected in the wrong phase relationship before the array was usable for astronomy.

A more permanent problem, which accelerated the 10-MHz array's demise about ten years later, was that the construction contract had not specified that the bases of the wooden support poles should be creosoted before insertion into the ground (unlike those of the cedar poles in the 22-MHz T). This omission speeded construction in 1964 but it hastened the eventual decommissioning of the array in 1975 when the bases of its poles deteriorated from direct contact with the soil.

A more subtle design decision that complicated calibrating the 10-MHz T's output was that of orienting the dipoles North-South (I.e, *along* the beam-steering phase gradient) instead of East-West as in the 22-MHz array. Any simplification achieved by this orientation during construction came at the expense of increasing the sensitivity of the array's beam shape, and hence its gain, to mutual interactions between currents in adjacent dipoles. The problem of computing the array's gain as a function of its phasing in declination was never solved fully satisfactorily, so a semi-empirical gain calibration based in part on theory and in part on the statistics of radio source spectra was eventually adopted (see Section 13 below).



Eight “nests” of balun transformers forming part of the 10-MHz T array’s
Butler matrix phasing system (photo by John Galt)

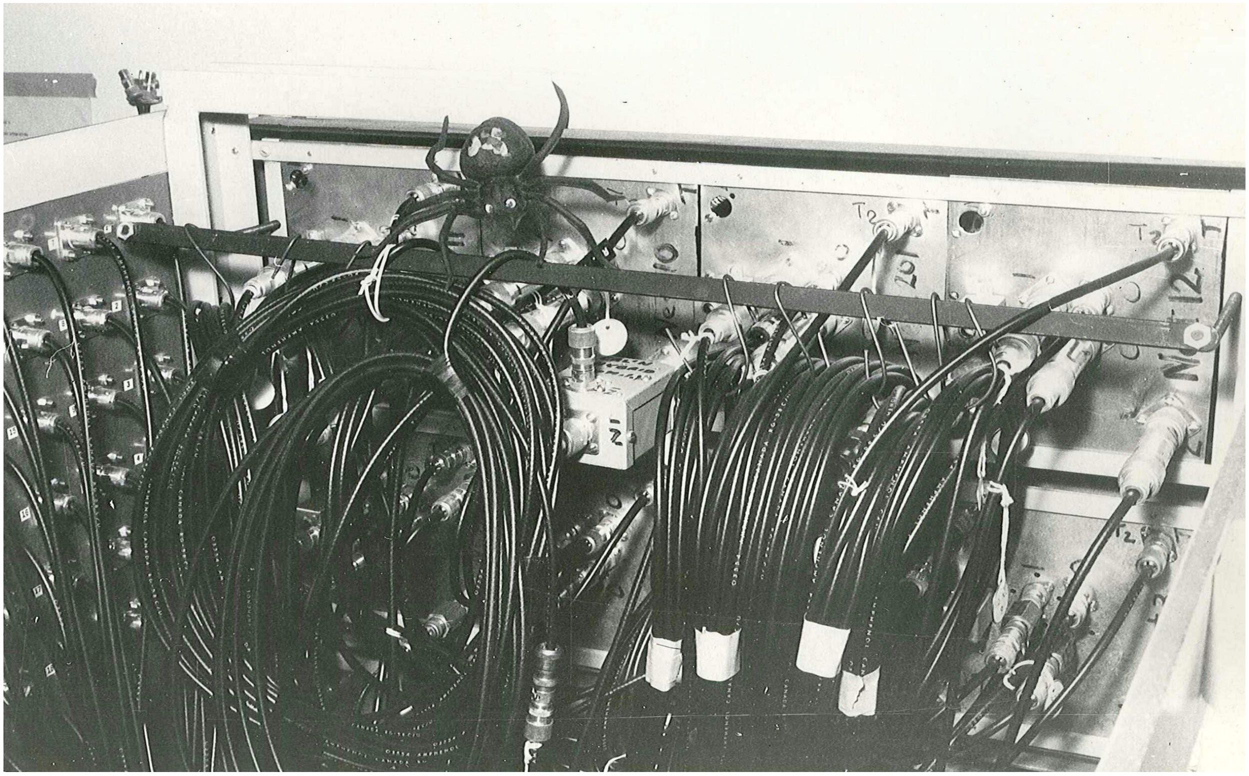
The urgency to bring the 10-MHz array on-line by the winter of 1964 was compounded by practical difficulties with the implementation of its Butler matrix phasing network.

The Cambridge group had purchased commercial broad-band balun transformers (see picture above) to form the matrix. This reduced the total quantity of coaxial cable needed for this purpose so it was an attractive option … in principle.

In practice the manufacturer's quality control on the 260 transformers needed to phase the 10-MHz array was poor. Not only were the input and output ports of the balun transformers poorly soldered, but the attenuation and phase shifts associated with them had unacceptably large variance between transformers. All the ports had to be re-soldered, and individualized attenuators and phase shift networks had to be added for each transformer.

This lengthy (and tedious) task was carried out by Scheuer at the DRAO and by Purton at the Cavendish Laboratory in the summer of 1964.

The North-South arm's phasing matrix – an assembly of balun and cable “nests” known as the “Rookery” - eventually occupied a space about 2 feet square and six feet tall in the array’s operations trailer, containing 256 baluns and their associated RG58U phasing cables … and a rubber spider that could be made to jump out of the cables by squeezing an air bulb. The spider (mysteriously named “Olivia”) was installed by Peter Scheuer, who enjoyed using it to startle visitors as they peered into the “Rookery”.



Phasing cables in the 10-MHz array's 'Rookery', attended by Peter Scheuer's rubber spider (photo taken by John Galt)

Scheuer also devised a "buzzer", a device that rapidly switched between open and short-circuit terminations of a cable to send a square-wave signal into the array to diagnose reflections from improper terminations in the transmission-line feeder system.

5. The 1964-1965 observing season

Chris Purton arrived at the DRAO from Cambridge in September 1964 and briefly overlapped with Peter Scheuer who returned to Cambridge that Fall to resume his teaching duties there. Purton and John Galt did most of the remaining testing of the 10-MHz array that winter.

By the time that Purton returned to Cambridge in July 1965 to write up his Ph.D. thesis, he had taken enough good quality data to map the diffuse "background" radiation at 10 MHz between declinations -15º and +65º (his contour map is shown in Appendix A below) and to measure flux densities for about 20 bright discrete sources, including 3C 84 (NGC 1275, Perseus A).

The first publication of results from the 10-MHz project was a paper by R.S.Roger, C.H.Costain, and C.R.Purton, 'Spectrum of Low-frequency Radio Emission from *NGC* 1275' Nature, vol. 207, pp, 62–63 (1965) showing that the emission from this unusual

Seyfert galaxy in the Perseus Cluster exhibited a low-frequency "excess" flux density at both 22 MHz and 10 MHz as well as the high-frequency excess that had been found by W.A.Dent and F.T.Haddock, in "A New Class of Radio Source Spectra", Nature, vol. 205, pp. 487-488 (1965)). The newly-discovered low-frequency component of this source was a hint of things to come from the two DRAO arrays.

By the time that Chris Purton began writing his Ph.D. thesis it was clear that favorable observing conditions at the DRAO were continuing beyond the expected solar activity minimum. Also, that the commissioning delays had not left him with enough time to carry out all of the work of which the 10-MHz array was capable. The high flux density he had found for NGC1275 also held out the promise that further 10-MHz studies of discrete sources might turn up "new" components in other sources: this increased interest in using the array for more spectral work than the search for turnovers in prospective quasars.

6. Funding a second Cambridge year at DRAO

When Chris Purton returned to the Cavendish Laboratory on 16 July 1965 he immediately began lobbying for another student to go to the DRAO to take as much data as possible while the good ionospheric conditions lasted – both to extend the 10-MHz discrete-source measurement program and to obtain further drift scans for the sky survey.

I had just returned to Cambridge from a vacation I had taken after finishing the part of my thesis work dealing with the galactic radio spectrum and the intensity of the integrated extragalactic (Olbers) emission using small scaled arrays at 13.2, 17.5 and 81.5 MHz. Martin Ryle and John Baldwin were already reading the draft of a paper I had written about my results – and I still had a year left on my Ph.D. research schedule. I was therefore an obvious candidate to follow Chris Purton on the 10-MHz project – provided funding could be found for a second Cambridge student to go to the DRAO.

Chris Purton and Peter Scheuer gave a joint colloquium at the Cavendish Laboratory on 22 July 1965 describing the status of the 10-MHz project and emphasizing the need for further effort from Cambridge to realize its full potential. Extending the Cambridge contribution to exploit the continuing good observing conditions required both Martin Ryle's approval and further funding.

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Ryle's approval came quickly, but securing more funding at such short notice was not easy. Peter Scheuer applied for a second year of funding from the Royal Society but it was unclear from the outset whether they could continue to support an already-built project. Ryle's enthusiasm was enough for me to start preparing to go to Canada, but on 5 August the Royal Society formally declined to provide a second year of support for the 10-MHz array, which no longer met its criteria as a "start-up". On 11 August Peter Scheuer applied for internal funding from the Cavendish Laboratory. On 17 August, John Galt confirmed that the DRAO wanted me to go there until increased solar activity made 10-MHz observing impractical, or until the discrete-source project was finished (whichever came first). Needing to take enough research materials and personal effects for a stay in Penticton that might last several months, I booked passage on the next available voyage to Montreal of the Cunarder "Franconia", paying my fare with a personal check that Peter Scheuer wrote in (characteristically optimistic) anticipation of the Cavendish funding coming through.

7. The 1965-1966 observing season

I arrived at the DRAO on 20 September 1965 and immediately began work with John Galt on a second (and, we hoped) final round of checking the array's integrity and the phasing of its dipoles, as well as searching for any residual errors in the “Rookery” matrix.

John Galt working with a probe used to check impedances and connections in the 10-MHz T in the Fall of 1965

Five weeks later, on 29 October 1965, I received official permission from Cambridge University to go to Penticton “for the Michaelmas and Lent terms”, with Carman Costain acting as my local Ph.D. supervisor. The Cavendish Laboratory had also agreed to fund my trip! (Peter Scheuer told me much later that he could not recall when, or even if, they reimbursed him for his personal funding of my sea voyage.)

The 1965-1966 10-MHz observing season began on Sunday 17 October 1965, before all the final array checks had been done, with an experiment that was not in the original plan but could be done with the array “as it was”. The previous winter's observations had shown that Jupiter, the brightest object in the night sky at 10 MHz, was such a persistent source of radio bursts that about 95 per cent of its transits made it impossible to observe anything else near its right ascension. John Galt had been contacted by Tom Clark, who was then a Ph.D. student working at the National Bureau of Standards in Boulder, Colorado, suggesting a joint study of the bursts. Clark was using a 4,800 sq.m. segment of a small 10-MHz 'T' near Boulder to investigate how the intensity of the bursts varied with Jovian longitude and with the orbital phase of Io. He was also interested in finding out if there was any correlation of the burst arrival times between his observing station and White Lake, which were separated by about 1,700 miles.

John Galt put the recording and timing system together with great speed at the last moment and both arrays observed at 10.03 MHz, recording Jupiter bursts and time stamps on high speed chart recorders. This was, in effect, one of the world' s first Very-Long-Baseline Interferometer (VLBI) radio astronomy experiments (in our case with post-detection correlation). I recall going outside the 10-MHz trailer to watch Jupiter rise towards transit, excited by my first experience of international collaboration in radio astronomy. Tom Clark telephoned us about 3 a.m. each night to compare our visual impressions of the burst activity at the two arrays. The charts were later shipped to Boulder where he and George Dulk searched systematically for any correlations between them. They found none of significance on this long baseline (consistent with similar results obtained by observers in Tasmania). Both John Galt and Tom Clark went on to help the development of centimeter-wavelength VLBI using tape recorders and maser clocks in Canada and the USA.

After this, John Galt and I, assisted by technician Mike Robinson, did the final tests on the 10-MHz array's dipoles and phasing networks. I then moved on to the array's planned program - drift scans for the galactic background survey on “poor” observing nights and targeted discrete-source flux-density measurements on “good” nights.

8. Calibrating the flux-density scale

The relative gain of the array’s receivers was monitored by injecting a noise signal into the cables from the North-South and East-West arms to the trailer. Zero levels were checked by replacing the array inputs with 50-ohm loads. More difficult aspects of calibrating the array's output were (a) converting the power measured by the receivers into source flux densities as a function of beam phasing and (b) correcting the measurements for time-variable ionospheric absorption.

Two approaches to absolute calibration of the array gain had been envisaged, but only one proved practical. The first approach used a half-wave dipole situated $\lambda/8$ above the surface of White Lake. The absolute gain of this dipole could , in principle, be calculated from theory, so observations of a strong source with the dipole replacing an arm of the 'T' could theoretically be used to calibrate the effective area of the other arm in the phasing for that source.

White Lake with standing water, Spring 1966

In practice, using the White Lake dipole this way was difficult because (a) it would be necessary to measure different strong sources under good conditions to calibrate every array phasing and (b) no provision had been made for compensating the 12.7 db loss and phase shift in the cable between the dipole and the 10-MHz trailer. There was also concern that without a wired screen under the dipole, its gain might change appreciably with conditions at the lake surface. These varied from a dry salt flat in summer to a snowfield in winter, to standing water in the spring (there were times when a boat was needed to access the dipole). John Galt and I agreed that the series of different setups and measurements that would be needed to calibrate the array using the dipole would not be the best use of good observing conditions in the coming winter. We chose instead to use the alternative approach of measuring the absolute flux densities of Cassiopeia A and Cygnus A using a separate phase-switched 10-MHz interferometer near the main DRAO building. That interferometer's elements were pairs of half-wave dipoles mounted $\lambda/2$ apart and $\lambda/8$ above wired ground screens, with an East-West baseline separation of 30λ The interferometer had its own instrumentation, so the calibration could be done alongside source observations with the main array.

I used the interferometer to observe Cas A and Cyg A for most of November 1965. By December, twelve relatively scintillation-free transits of Cas A had been recorded. After correction for relative ionospheric opacity (using total power drift scans with the T's North-South arm as a 'riometer') the Cas A scans repeated with a variance about 2 per cent. Those of Cyg A were of poorer quality - only four usable transits, with repeatability (after a less well-determined 'riometer' correction) about 20 per cent. Cyg A had transited closer to sunset, when ionospheric effects and interference were worse, but the Cas A data were good enough to set a flux-density scale.

Losses in the cables between the dipoles and the DRAO building were measured by injecting noise at the dipoles, and the absolute power levels at the recorders were calibrated using one of Chris Purton's diode noise standards. These data, along with a computation of the two-dipole element gain carried out by Carman Costain with the Department's computer in Ottawa, yielded an absolute flux density for Cas A of 28,000 ± 2,800 Jy and for Cyg A of 13,500 ± 3,500 Jy. These results, published in Bridle, A.H., "Flux densities of Cassiopeia A and Cygnus A at 10.05 MHz", The Observatory, vol. 87, pp. 60-63 (1967), suggested that both sources were seen through absorption in the ionized interstellar medium, with an optical depth of about 0.9 towards Cas A and 1.2 towards Cyg A.

The ionospheric issues encountered in the interferometer measurements supported our impression that calibrating the array gain using the White Lake dipole would be difficult - so we put that approach aside in favor of using the array for targeted observations of as many discrete sources as possible. The absolute measurement of Cas A allowed us to calibrate the array's gain in the phasing for its declination, and we hoped that the calibration could then be transferred to adjacent array phasings (i.e. near the array's zenith) satisfactorily from theory (see more below in Section 13)

9. Practical details of 10-MHz observing in 1965/1966

DRAO Travelall on the 10-MHz array access road in the winter of 1965-66

I had arrived at DRAO not knowing how to drive a motor vehicle: a bicycle was my only means of transport in Cambridge. Operation of the 10-MHz 'T' required me to go back and forth from the main DRAO building to the trailer, so John Galt tasked DRAO's mechanic Bud Orge with teaching me to drive the observatory's well-aged Travelall.

John then issued me a Canadian government vehicle operator's permit, with strict instructions to use it only to drive between the control building and the 10-MHz site, as I had no legal license. Although the public part of the road was only lightly traveled, an accident involving me could have bad repercussions, both for me and for him.

Carman Costain and I adopted a protocol whereby he assessed and told me what the early evening ionospheric conditions were like at 22 MHz after watching strong sources scintillate on the real time output of the 22-MHz 'T'. Unless the 22-MHz conditions looked favorable, discrete source observing at 10 MHz, where ionospheric effects were typically about five times worse, was pointless. Before I learned to drive, someone would take me to the 10-MHz array trailer at the end of the normal DRAO workday and Carman would telephone me there to give me his assessment. After I was able to drive myself I would stay in the main DRAO building until we saw the 22-MHz conditions improve. If they did not, I would only go out to the 10-MHz trailer to check on the equipment, while on "good" nights I stayed at the array all night switching its beams from declination to declination to record as many short-duration source transits as possible.

I learned much from Carman about the ionosphere and antennas on the "bad" nights when he was running the 22-MHz array, as well as getting his guidance about writing my thesis. We also had many discussions about ways to make steep-spectrum radio emission, as it was becoming clear that the low-frequency 'excess' from NGC 1275 was only one example of this effect. Another clear example was evident in the Coma Cluster, whose transits at 22 MHz looked like an unresolved source sitting atop a broader 'pedestal' of emission with a scale closer to that of the cluster as a whole.

The idea that both arrays might be sensitive to a previously unseen class of steep-spectrum source in galaxy clusters began to compete with using spectral turnovers to identify quasars as a high priority.

10. Comparing with the 4C survey

Shortly before I left Cambridge, I had seen a preprint from Bill Erickson reporting "not previously cataloged" (NPC) radio sources detected by his 26.3-MHz array at Clark Lake in San Diego County, California. I had found examples where emission near the reported 26.3-MHz position had been detected at 178 MHz in the then-unpublished Cambridge 4C and 4C'T' surveys. Carman Costain had also found examples of NPC emission at 22 MHz, as had Chris Purton during the 1964-1965 10-MHz observing season. We speculated, among alternatives, that such steep-spectrum sources could be "old" sources in which synchrotron aging progressed in a cluster environment where the emitting regions were kept unusually well confined for a long time. Clearly, access to the 4C source flux densities and positions would help us to locate and identify further steep-spectrum sources better than we could from the low-frequency data alone.

The 4C source list was, however, confidential at this time – the copies distributed within the Cavendish Laboratory radio astronomy group were individually numbered. Martin Ryle's secretary kept track of who had which copies, and I had been required to give mine back to her before I left for the DRAO. John Galt, Carman Costain and I soon hatched a scheme for getting a copy of 4C to the DRAO.

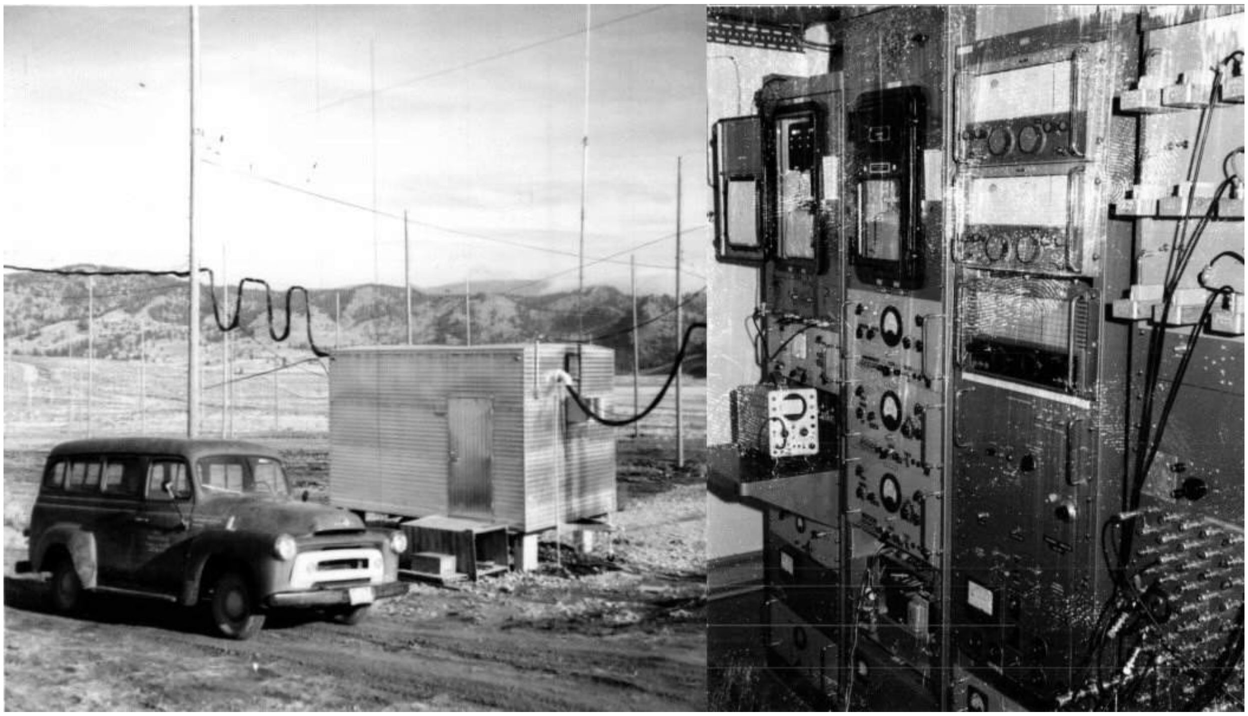
The key to our scheme was Malcolm Longair, then a Ph.D. student in Cambridge with whom I had become friends while we discussed how to use my estimate of the integrated non-thermal extragalactic emission for cosmology. Malcolm was building models of the evolution of powerful radio sources to explain Ryle's source counts, and his models used my data as a constraint (e.g., M.S.Longair, "On the interpretation of radio source counts", MNRAS, vol. 133, pp. 421-436 (1966)). Malcolm's thesis also included optically identifying compact radio sources for which accurate radio positions had been measured. He had identified several with blue stellar objects that proved to be quasars, and his success at this had earned him an invitation to a conference in Miami, Florida in December 1965. (The speed with which he had done this was another factor lessening the urgency to use low-frequency spectral turnovers as a way to find more quasars.) Malcolm had told me that he planned to spend Christmas with a relative in Ottawa before he returned to Cambridge in the New Year.

Our scheme was for John Galt to invite Malcolm to the DRAO to give a colloquium between Christmas and the New Year, bringing his copy of 4C with him, with the promise that I would later return that copy to him in Cambridge. Malcolm agreed to this idea, but - like other aspects of the 10-MHz project - the scheme proved harder to implement than we envisaged. This time the problem was Penticton's winter weather. Air service to Penticton in 1965 was on DC-3's which flew lower than some of the mountain peaks under visual flight rules so winter flights were often canceled. Malcolm had planned to arrive in Penticton from Vancouver on December 27th, well before his colloquium on the 29th. That leeway turned out to be barely enough, however: both Vancouver and Penticton airports closed on the 27th and heavy snow fell in the Okanagan on the 28th. A trip to DRAO in David Lacey's car on the 28th had required Rob Roger and me to ride part of the way hanging onto the car's trunk lid to provide hill-climbing traction.

Stranded in Vancouver since December 26th, Malcolm Longair finally gave up the idea of reaching Penticton by air and bought a ticket for an overnight Greyhound bus that delivered him (sleep-deprived) in downtown Penticton at 6 a.m. on the 29th. We fed him breakfast before dawn, then again slithered out to the DRAO where we toured him around both T-arrays on snowshoes. He somehow summoned the mental and physical resources to give his talk, then we spent an enjoyable evening at Carman Costain's house swapping stories about life in Cambridge.

Malcolm left Penticton early on December 30th having spent less than 10 hours with us at the DRAO after what had become several days of traveling from Ottawa - but his travel saga was not over! The DC-3 on which he left Penticton flew higher than usual to clear the mountains safely, and the crew had to bring bottled oxygen to the passengers in its unpressurized cabin. Malcolm's numbered copy of 4C had come to the DRAO at a cost that he reminded me of for a long time afterwards!

11. Lights in the sky

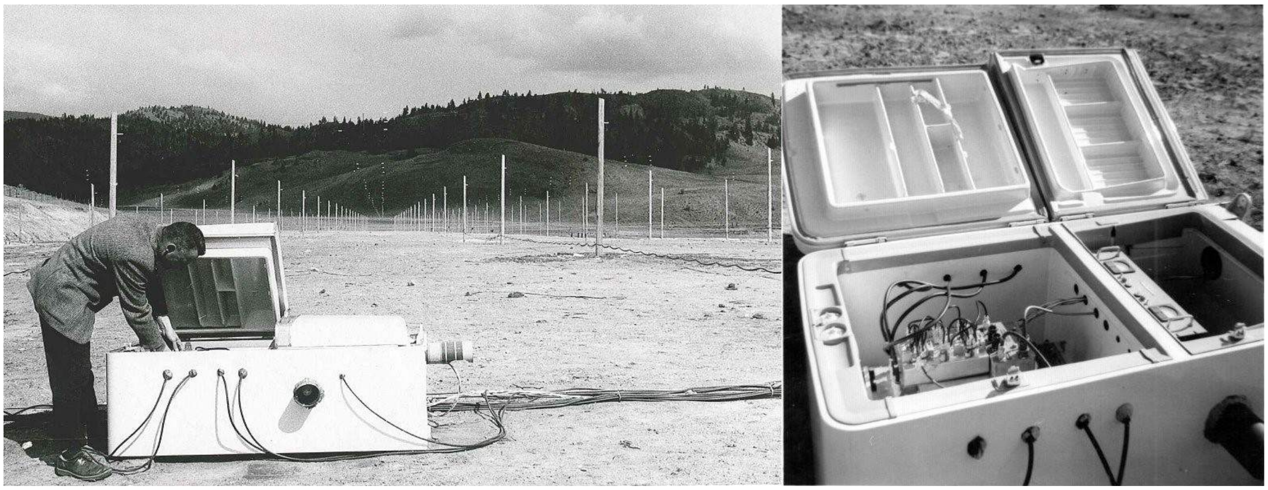


Outside and inside the 10-MHz T operations trailer in 1965

The 10-MHz T's operations trailer, located about half-way down the North-South arm, was a strangely isolated place in which to work all night. Packed with receiving equipment and the phasing system for that arm, it ran comfortably warm on cold winter nights, but it had no windows. The operator's only interface to the outside world was a telephone link to the main DRAO building. There were two occasions on which the visual isolation of this trailer had amusing consequences.

On the night of March 31 1965 a carbonaceous chondrite meteor broke up explosively in the sky over Southern B.C. and parts of it fell noisily to Earth near Revelstoke. As described in the *Meteoritical Bulletin*, “An extremely bright bolide giving off sparks was observed to travel for 100 km (8 seconds) at 15° inclination; blue white at high altitudes, it exploded at 30 km with a brilliant flash of white light, and travelled onward as two or more distinct reddish fireballs which went out at an altitude of 12 km over a very wild and desolate range of glaciated mountains and spruce forest. Violent detonations were heard up to 130 km from the fall area and were recorded on four seismographs as much as 400 km distant.” This spectacle was seen and heard by much of the population of the area, some of whom then telephoned the DRAO to try to find out what had just happened. The only person at the observatory that night was Chris Purton, alone in the windowless 10-MHz trailer, who was therefore totally unaware of the whole phenomenon - but still had to handle the barrage of urgent phone calls asking for an explanation! (John Galt and Ed Argyle from the DRAO became involved in trying to find fallen meteoritic material. They successfully turned citizens' visual observations of the skyfall into a model of the track the meteor had taken, which ultimately led to the recovery of several small pieces along the path they had plotted).

About a year later I was in the middle of a night's observing with the 10-MHz array when all of its receiver outputs suddenly plunged from their normal values towards zero. As it was obvious that nothing had happened to the systems inside the trailer, my reaction was that some array-wide disaster had occurred outside, perhaps in the old refrigerator that housed the phasing network and pre-amplifier for the East-West arm at the T's crossover.



John Galt and the 10-MHz array crossover refrigerator (left photo DRAO archives, right photo mine)

This simple (but effective) housing for the crossover equipment was a possible single point of failure for the array, so I suited up to go out to the crossover on the cold winter night to investigate. As soon as I opened the trailer's door I was greeted by a spectacular display of the Aurora Borealis, with shifting green curtains and light pulsations. Neither the 22-MHz T nor the 10-MHz T were able to collect data for over a week after this, but we were delighted to find that when the electrons causing the massive low-frequency absorption finally dissipated, there were several days of almost interference-free observing. The main sources of 10-MHz interference, which we understood to be Japanese fishing trawlers, had given up using their 10-MHz equipment during the event, leaving us with a brief window of (almost) perfectly "clean" observing.

12. After 1966

A few weeks after the big auroral event, observing conditions began to deteriorate so I switched from the all-night-attended multi-source observing to recording drift scans for the 10-MHz sky survey This let me sleep at night (!) and reduce data by day. There was no digital output so data processing was done by hand from the chart records. At this stage some administrators in Cambridge became anxious about when I would return there as I had now gone past their formal permission to be away for two academic terms. John Galt was understandably reluctant to let me depart from the DRAO carrying all of the project's chart records, so Carman Costain wrote letters to the Cambridge authorities assuring them that my time was still being well spent (I had saved enough on accommodation that stretching my original budget was not in fact a problem). Carman, who had written his own Ph.D. thesis after he had returned home from observing in Cambridge, encouraged me to reduce only as much data as I would need to get my degree, and also to focus on the discrete-source data as they would be easier to interpret than the sky survey As a result, only one small region of the 1965-

1966 survey (around the supernova remnant HB3 where there was absorption from the nearby HII region IC1805) was fully reduced when I finally left the DRAO in August. When I returned to Cambridge, John Baldwin and Peter Scheuer agreed that writing up the 10- MHz source work would be enough for me to submit my thesis (along with the galactic spectrum and integrated emission work I had done before going to the DRAO). My part of the 10-MHz survey data was put "on hold" apart from the HB3 region, which I wrote up after finishing my thesis: it was published as Bridle,A.H., "The non-thermal emissivity of the Galactic disk near l=140º", MNRAS, vol. 138, pp. 251-258 (1968),

Cambridge was unable to send another Ph.D. student to the DRAO to complete the remaining survey work A better solution emerged in 1967 when Jim Caswell, who had done the 4C'T' pencil-beam aperture-synthesis survey at 178 MHz for his thesis, and also had a strong interest in extended galactic sources, was awarded a Canadian NRC post-doctoral fellowship which he held at the DRAO from late 1967 until the end of 1969.

Jim Caswell resumed observations with the 10-MHz array in November 1967 after it had been equipped with an eight-beam recording system developed by John Galt and Fritz Bowers, a frequent collaborator with the DRAO staff from the University of British Columbia. Although Jim's observations were made further into Solar Cycle 20's rise than mine and were therefore subject to generally worse ionospheric conditions, the ability to take data from eight phasings of the North-South arm allowed him to make fuller use of the nights when conditions were good. He also observed during two winters, from November 1967 to February 1968 and again from November 1968 to March 1969. His data yielded a higher-quality survey, with better checks on the repeatability of the measurements, but over a more restricted range of right ascension than were possible in Chris Purton's survey or in mine. Caswell's scans also allowed further measurements of many discrete sources that had been observed in the 1965-1966 season. He also adopted a different approach to calibrating the array gain when phased away from the zenith, as described below.

13. Gain vs zenith angle for the array

The absolute measurement of Cassiopeia A in 1965 let us determine the gain of the 10-MHz array when it was phased for Cas A's declination, but we still needed to transfer the calibration to all the other beam phasings. Chris Purton had planned to do this theoretically, using the known properties of the phasing network along with data on the mutual interactions (impedances) within the array. This was a non-trivial task with the computer resources of the time, made worse by the strong interactions in the phase gradient direction due to the North-South orientation of the 10-MHz array's dipoles.

For my thesis I had finessed this calculation after I found that the spectra of an identifiable group of sources down to 10 MHz near the declination of Cas A (where the gain corrections should be small) appeared to be continuations of their higher-frequency power laws. Out of 55 sources with zenith angles less than 15º at transit, I found that 9 identified with ordinary elliptical galaxies at galactic latitudes above 10º had preliminary flux densities consistent with extrapolating their power-law spectra down to 10 MHz. I therefore adopted the extrapolated flux densities of 13 sources with similar optical identifications and galactic latitudes as "secondary" calibrators for higher zenith angles. Little was known about the detailed radio structures of these sources at the time. The restriction to elliptical galaxy identifications was adopted both empirically and as a way to exclude quasars whose structures were more likely to be dominated by compact, and thus possibly self-absorbed, components.

Nineteen sources were in common between Chris Purton's data calibrated using the theoretical gain vs zenith angle - G(z) - curve and mine based on the power-law spectrum extrapolation. The agreement between our flux-density estimates was good to within the errors of measurement, so my thesis was written (in late 1966) using the G(z) curve derived from the "elliptical galaxy" calibration.

In the Fall of 1967, Chris and I (both by then back in Canada) revisited this analysis with his updated estimates of the theoretical G(z) curve, eventually drawing the same conclusion. The G(z) relation adopted in A.H.Bridle and C.R.Purton, "Observations of Radio Sources at 10.03 MHz", Astronomical Journal, vol. 83, pp 717-726 (1968) used the form of the curve from the theoretical calculation with its amplitude normalized to agree in the mean with that from spectral extrapolation for the "secondary calibrators".

The absolute flux-density scale at 10 MHz was later revisited by R.S.Roger, A.H.Bridle and C.H.Costain (RBC), "The low-frequency spectra of nonthermal radio sources", Astronomical Journal, vol.78, pp. 1030-1056 (1973). RBC examined the spectral classification for 225 discrete sources between 10 MHz and 2 GHz using all available high-quality data. We then identified an improved set of 12 secondary calibrators at galactic latitudes above 20º whose structures were not known to contain compact components (which might be self-absorbed at 10 MHz) and whose spectra were consistent with power laws between 22 and 1400 MHz. The extrapolated 10-MHz flux densities of those secondary calibrators suggested that the scale used by Bridle and Purton should be raised by 20%. The scale corrections suggested by RBC have since been widely adopted for observations at frequencies below 200 MHz.

In his analysis of the eight-beam sky survey, Jim Caswell, in "A Map of the Northern Sky at 10 MHz", MNRAS vol. 177, pp.601-616 (1976) took a different approach to the G(z) calibration. He used power-law extrapolation of high-galactic-latitude *diffuse background* intensities to 10 MHz from 38-MHz and 178-MHz surveys at the same resolution. As there is diffuse background emission in every beam, this calibration can be carried out using data from large regions of the high-galactic-latitude sky. It is also independent – both in its assumptions and in its database - of the discrete-source-based approach. It was reassuring that Caswell's G(z) solution was, as his paper puts it, "broadly compatible with that of Bridle and Purton". His derived flux densities for 30 sources in common with our earlier work were also (mostly) consistent with the earlier values to within the errors of measurement, including the interpretation of background gradients and confusion of sources with other features.

In their 1973 study of the low-frequency flux-density scale calibration, RBC found good agreement between the DRAO 22-MHz flux densities and those measured at Clark Lake by Bill Erickson and his associates at 26.3 MHz, regardless of the flux-density level of the sources being measured.

There was also good agreement at *high flux densities* with results from the Grakovo UTR-1 telescope in Ukraine obtained by S.Ya.Braude and his colleagues, but that agreement did not persist for faint sources, for which the discrepancies also became worse as the frequency decreased. The Grakovo flux densities were as much as 40% higher than those measured at the DRAO or at Clark Lake for 100-Jy sources. The reason(s) for these systematic discrepancies with the Grakovo measurements never became clear, but a comparison by A.H.Bridle and J.L.Caswell ("Decametric Variability of Cas A and 3C84", Nature, vol. 225, pp. 356-357 (1970)) of 10-MHz measurements made at Grakovo and DRAO at similar times suggested that data were taken and used at Grakovo under ionospheric conditions that were considered too poor to make reliable measurements with the DRAO array.

In the end, not using the White Lake dipole to calibrate G(z) for the 10-MHz array did not appear to have impaired the science done with it, while the overall flux-density scale derived by Roger, Bridle and Costain from analyzing spectra measured with both DRAO arrays eventually offered the best available calibration for this frequency.

14. Interstellar electron gas

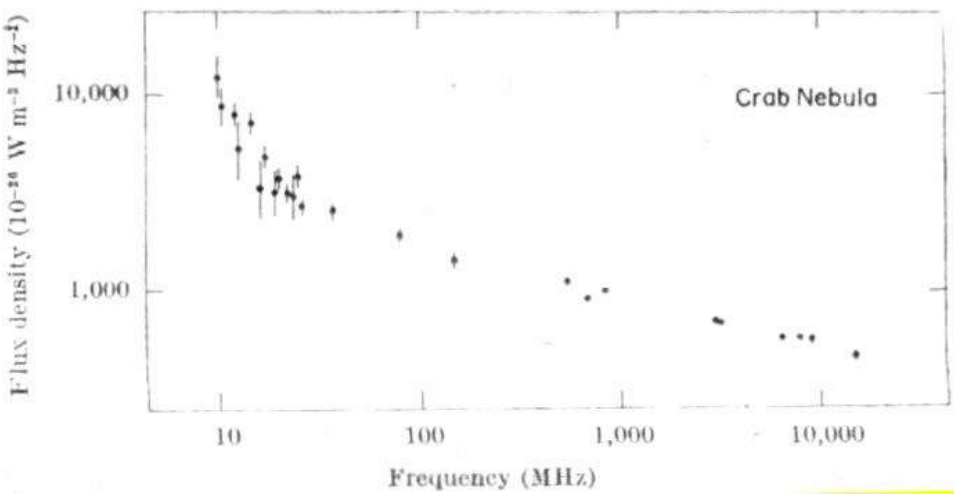
Jim Caswell's survey of the Anticenter region with the eight-beam receiver provided excellent data for studying absorption by discrete HII regions that produce local absorption features, and thus for improving constraints on the distribution of non-thermal emissivity in the galactic disk. By analyzing 10-MHz absorption data for 17 individual large-diameter HII regions whose distances were known, Caswell was able to infer that the non-thermal emissivity is largely confined to the spiral arms, with lower emission from the inter-arm regions.

10-MHz absorption of extragalactic sources at low galactic latitudes also gave information about more diffuse interstellar ionization. After a typically lively discussion in the DRAO's coffee/lunch room in the summer of 1969, the 10-MHz data for low-latitude extragalactic sources were combined with dispersion measures of (then newly discovered) pulsars at known distances, and with other data, by A.H.Bridle and V.R.Venugopal, "Distribution and Temperature of Interstellar Electron Gas", Nature, vol, 224, pp. 544-547 (1969). This paper was the first to argue for a thick (equivalent width 600 pc) free-electron disk in the galactic Anticenter, similar to that previously deduced from absorption of the galactic nonthermal background in the inner Galaxy by G.R.A.Ellis and P.A.Hamilton, "Ionized Hydrogen in the Plane of the Galaxy", Astrophysical Journal, vol.349, pp. L17-L19 (1966).

The thick ionized disk was later confirmed in very low-level Hα emission. The energetics of maintaining the diffuse ionization far above the galactic plane, whether by ultraviolet light from hot stars, or by supernovae, are unclear - e.g., R.J.Reynolds, "The Power Requirement of the Free Electron Layer in the Galactic Disk", Astrophysical Journal, vol. 349, pp. L17-L19 (1990).

15. The low-frequency source in the Crab Nebula

The evidence for free-free absorption in the spectra of extragalactic sources at low galactic latitudes, and for a thick disk of free electron gas, made it notable that the measured spectrum of the Crab Nebula showed no sign of such absorption, unlike that of IC443 at a similar galactic position and distance. By 1970 the Crab Nebula was known to contain a steep-spectrum radio source, probably associated with the pulsar (and perhaps formed by blending of its pulses in a wide bandwidth after dispersion). In A.H.Bridle, "Low-frequency spectrum of the Crab Nebula", Nature, vol. 225, pp. 1035-1037 (1970) I showed that if the Nebula's observed low-frequency spectrum is corrected for the *expected* free-free absorption along its line of sight using the thick-disk model derived from the extragalactic source spectra, there is evidence that the low-frequency component dominates below about 30 MHz (see Figure below).



Spectrum of the Crab Nebula corrected for free-free absorption (from Bridle 1970)

The spectral index of the inferred low-frequency component was 1.76 between 10 and 1400 MHz, similar to that of 2 measured for the mean pulse profile of the pulsar near 200 MHz. This increased the likelihood that the steep-spectrum low-frequency source and the pulsar emission are indeed the same. Jim Caswell's 10-MHz sky survey paper also pointed out that the flux densities measured for the Crab Nebula during his survey differed from those measured in 1964-1965. The source was weaker (mean value 3880 Jy) in 1967-1969 than the 5830 Jy measured in 1964-1966, consistent with variability of the pulsar.

16. Postscript

It was perhaps ironic that the 10-MHz T array contributed essentially nothing to the new astrophysical topic that had originally motivated Peter Scheuer to advocate working at such a low frequency - the discovery of new quasars, whose radio spectra did not in fact generally show turnovers between 38 MHz and 10 MHz. It found only one clear new spectral turnover (in 3C 380) at a time when direct optical identifications with stellar objects based on accurate radio positions had proceeded apace. That part of the original motivation for working at 10 MHz turned out to be only a minor footnote to the science eventually done with the array - but one of its major contributions was to a topic that had been part of Peter Scheuer's Ph.D. thesis work – the spatial distributions of the free electron gas and of the non-thermal emission in the galactic plane. That the 10-MHz array found systematic absorption in extragalactic source spectra at low galactic latitudes was of course not unexpected - the array was the most sensitive detector for interstellar free electrons that existed in its time.

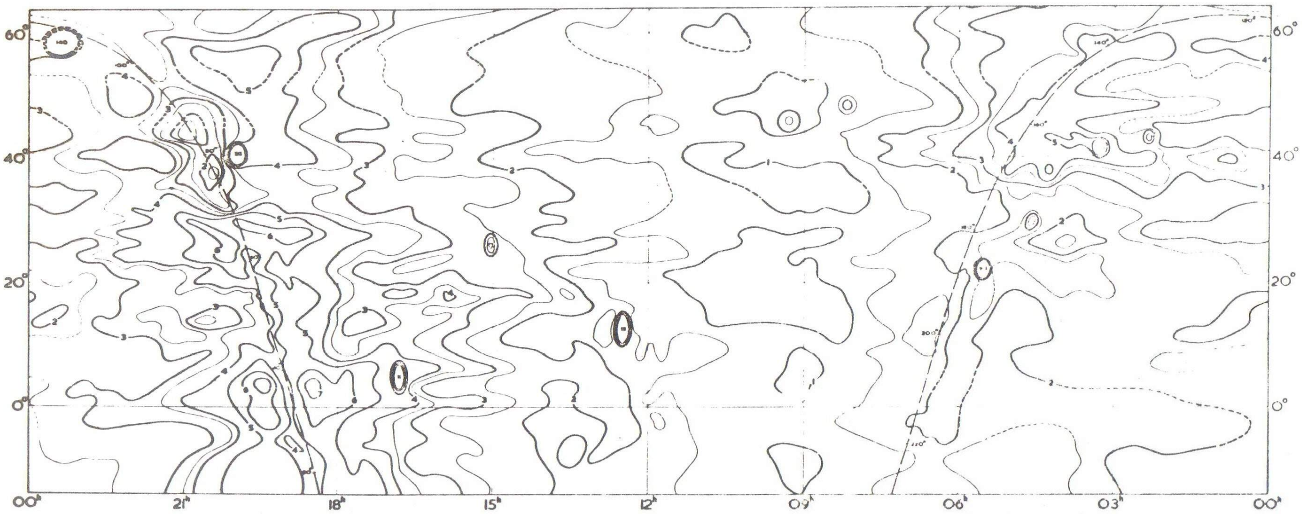
The fact that most extragalactic sources do *not* in fact show spectral turnovers by 10 MHz increases their minimum energy requirements over those estimated by integrating their spectral flux densities only as far down as 10 MHz, as is common in “equipartition” calculations. Especially for steep-spectrum sources, it remains important to find out how much lower in frequency the power-law spectra extend before they turn over.

The array’s other main discovery, especially when its data were partnered with those from the 22-MHz T, was to document new sources with unusually steep-spectrum low-frequency components. Radio galaxies with these components are often associated with rich clusters. The phenomenon is now understood in some detail as arising from the accumulation of synchrotron-aged ejecta from active galaxies in dense intracluster media that can be studied by their X-ray bremsstrahlung emission. The steep-spectrum components, whether they are “cluster halos” or “dead sources”, are now among the prime targets for study with the next generation of low-frequency radio telescopes.

Acknowledgements

I thank Chris Purton and David Routledge for reading earlier drafts of this account, for suggesting improvements, and for correcting details that I had mis-remembered. Any mis-statements that remain are entirely my own responsibility, however. I am forever indebted to the late Carman Costain and to the late John Galt for their guidance, patience and friendship during what was a pivotal time in my career.

Appendix A: Chris Purton's 10-MHz survey contour map



The 10-MHz sky from Chris Purton's Ph.D. Thesis (1967) – galactic plane is shown dashed
The brightness contour interval is 100,000 K

Appendix B: More photos of the 10-MHz array site

View of the main DRAO site and 22-MHz T through poles of the 10-MHz T (October 1965)

Sunrise over the 10-MHz array – often the end of my workday

Mike Robinson working at the 10-MHz array’s most common failure point – soldered joints at the individual dipole baluns, which needed constant monitoring

The 10-MHz array in January 1966

Sunset view of the 22-MHz array – taken on my way to start a night's observing at 10 MHz

WInter view ew of the 10-MHz array from the North-East

10-MHz array dipoles, trailer and diesel generator fuel tank, January 1966