Pentodes, Power Patterns, Pliers, and Parsecs: Pioneering Radio Astronomy at Queen's University

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"There is a tide in the affairs of men," Shakespeare said, "which, taken at the flood, leads on to fortune." What follows is the story of how Queen's University's Physics Department attempted to catch such a tide in the 1950s, at the moment when astronomy was expanding into the electromagnetic spectrum beyond the visual window.

First Radio Telescopes and Observations

In early March 1958, in a hayfield south of the hamlet of Westbrook west of Kingston, two antennas made of aluminum tubing stared upward into the Milky Way (see Figure 1). Inside a hut midway between them, a pen connected to the output of a sensitive receiver jittered across a chart, scribing a ragged red line. Together, the antennas and receiver constituted the first of several radio telescopes that would be built—primarily by graduate students—during the next decade and a half in that hayfield, the nascent Queen's Radio Observatory (QRO).

The two Yagi antennas, aimed to centre on Cassiopeia as it transited, were absorbing faint radio power at six metres wavelength. Thousands of times weaker than required by TV sets, the voltages they fed to the central receiver nevertheless interacted, producing an interference pattern—a joint reception pattern of north-south pancake-shaped beams when seen from a distant object in the sky—through which the Galaxy would sweep as the Earth rotated. The multitude of beams, the radio analogue of the optical interference pattern in a double-slit experiment, formed a radio-wavelength "fringe" pattern. This reception pattern resembled a peacock's tail on display.

Extending across several cycles of the oscillatory fringe pattern, the broad smear of radio emission from the Milky Way could not affect the receiver. Why, then, was this pen tracing out interference fringes?

Precision interferometry at Cambridge had recently pinpointed a small-diameter radio powerhouse in Cassiopeia—it had to be small or interferometers would not see it—blasting out power across the radio spectrum. What sort of bizarre object was this, and how far away? Next door? Distant but inside our own galaxy like M1, the Crab Nebula? Or hundreds of millions of light-years from us like the faint galaxy—no, two galaxies, apparently, colliding—recently identified as another strong radio source, in Cygnus?

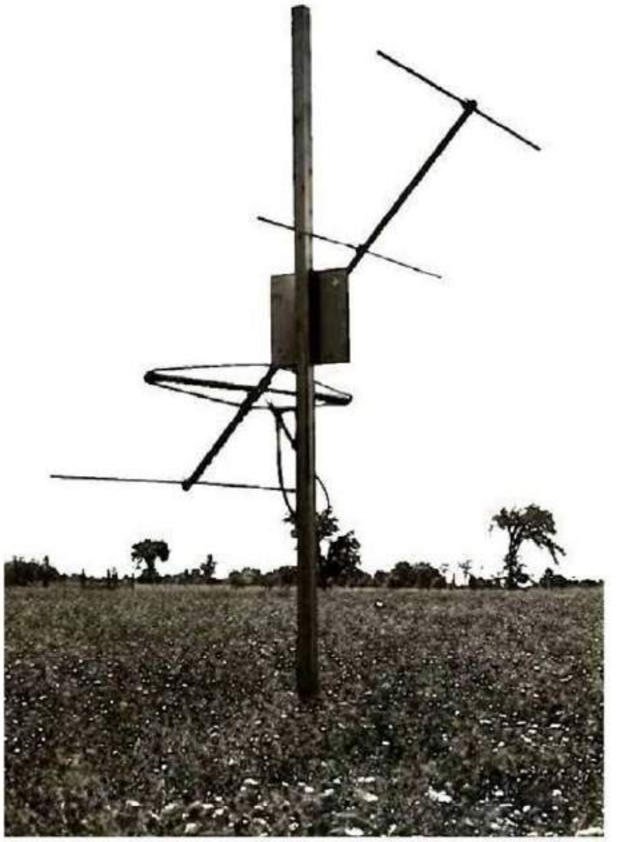


Figure 1 – Half of Queen's University's first radio telescope at Westbrook in 1958—one of two Yagi antennas comprising Arnold Matthews' east-west interferometer for recording scintillations of Cas A at 6m wavelength. The three metal rods (one "reflector" dipole and two "director" dipoles) are 3m long. The diamond shape (a dipole "folded" to raise its impedance) is connected by coaxial cable to the receiver in a central hut. The loop of cable hanging down (a "balun") prevents currents from flowing on the outside of the cable and disturbing the shape of the Yagi's reception beam (its "power pattern").

Most optical telescopes pointed at that spot in Cassiopeia would reveal nothing spectacular. However, the Palomar 200 inch (in 1958 the world's largest) had detected faint red wisps of nebulosity. Astonishingly, these wisps were moving, racing through space at up to 7,400 km per second. Comparing their transverse and line-of-sight motions, the distance of those wisps had to be 3,400 parsecs—a parsec being 3.26 light-years.

Radio interferometery at Manchester, meanwhile, had shown this brightly radiating object (labelled Cassiopeia A) to be a shell, four arcminutes wide and thus four parsecs in diameter.

It might be an exploded star, a supernova remnant like the Crab Nebula but younger—a mere 350 years old.

However insignificant Cas A appeared at optical wavelengths—because of obscuration in what most people took to be a vacuum, the interstellar medium—to radio telescopes, this "radio star" came booming in, weaker only than the nearby Sun. Why should such an optically underwhelming object transmit powerful radio waves?

An explanation by a Soviet astrophysicist, Ioseph Shklovsky, had emerged: electrons hurtling through the interstellar medium at nearly the speed of light could be deflected into spiral trajectories by weak magnetic fields. This produced "synchrotron" radiation. His theory had been validated in observations of the Crab Nebula when both its radio and optical emission had been found to be partially linearly polarized. Synchrotron radiation could be the mechanism lighting up Cas A as well.

The pen at QRO continued to jitter across the chart, the fringes decreasing in amplitude after Cas A's transit an hour before midnight. In the afternoon, a young man arrived to check the interferometer and tend the chart recorder. This was Arnold Matthews, the first of a dozen and a half graduate students in the Physics Department who would build and operate radio telescopes at QRO (see Table 1). He had been attending classes in the morning and this was his experiment, conceived by his thesis supervisor, Dr. George A. Harrower[1] but implemented according to his own calculations and by his own handiwork.

After examining the chart, Matthews might have decided that everything was running well and all he had to do was replenish the ink and paper in the recorder. If not, he had to trouble-shoot the problem and if possible, repair it on the spot. Perhaps calculations—done by slide rule of course—would show that something required modification. If so, and the work could be performed in the field, he would open his tool

Table I — Theses in Queen's U. Physics Department Based on Work at QRO and ARO, 1958-72

NAME	DEG	SUP	YR	SUBJECT
Matthews	**M**	**GAH**	**58**	**Period spectrum of radio star scintillations**
Hogg	**M**	**GAH**	**59**	**Short-lived solar radio bursts in the range 88-128 Mc/s**
Ryan	**D**	**GAH**	**59**	**Scintillation of four radio sources at upper transit**
Black	**M**	**GAH**	**61**	**Scintillations of radio stars related to earth's magnetic field**
MacDougall	**M**	**GAH**	**61**	**Upper atmospheric irregularities by radio star scintillations**
Srivastava	**M**	**GAH**	**62**	**Spectrum analysis of radio star scintillations**
Gibbons	**M**	**GAH**	**62**	**Scattering elements for the 146 Mc/s reflection array**
Kronberg	**M**	**GAH**	**63**	**Variable-spacing interferometer for radio astronomy**
Sandqvist	**M**	**GAH**	**63**	**Sidelobes of a synthetic aperture**
MacDougall	**D**	**GAH**	**63**	**Ionospheric Irregularities by Radio Star Scintillations**
McCutcheon	**M**	**GAH**	**64**	**Design and construction of the random reflection array**
Butler	**M**	**GAH**	**65**	**Theoretical and experimental investigation of reflection arrays**
Gregory	**M**	**GAH**	**65**	**Phase-switching receiver for variable-spacing interferometer**
Hesse	**M**	**GAH**	**65**	**Preparation for a sky survey with variable-spacing interferometer**
Routledge	**M**	**VAH**	**66**	**Radio polarimeter for galactic continuum**
Potter	M	VAH	67	*Observations of small diameter radio sources*
Blackwell	**M**	**VAH**	**67**	**Long baseline interferometer**
Miller	M	VAH	69	*Galactic background at centimeter wavelengths*
Routledge	D	VAH	69	*Radio observations of the galactic plane*
De Kock	**M**	**VAH**	**70**	**Commissioning a 60 foot radio telescope**
MacDonell	M	AHB	71	*Microwave spectra and variability of radio sources*
Guindon	M	AHB	71	Radio spectra of sources in 1400 MHz catalogue [Observed at Green Bank]
Butler	D	VAH	71	*Observations of selected galactic radio sources*
Bradford	D	VAH	71	Spectra of type III solar radio bursts detected by Alouette I
Retallack	**M**	**VAH**	**72**	**Radio pulses from direction of Galactic Centre**
Woodsworth	M	VAH	72	*Observations of radio stars at 2.8 cm*

Legend: M—M.Sc.; D—Ph.D.; GAH—George A. Harrower; VAH—Victor A. Hughes; AHB—Alan H. Bridle. **Boldface** *indicates research was carried out at Westbrook;* ***Italics:*** *research required ARO 46-m observations. Graduate students working in theoretical astrophysics are not included here.*

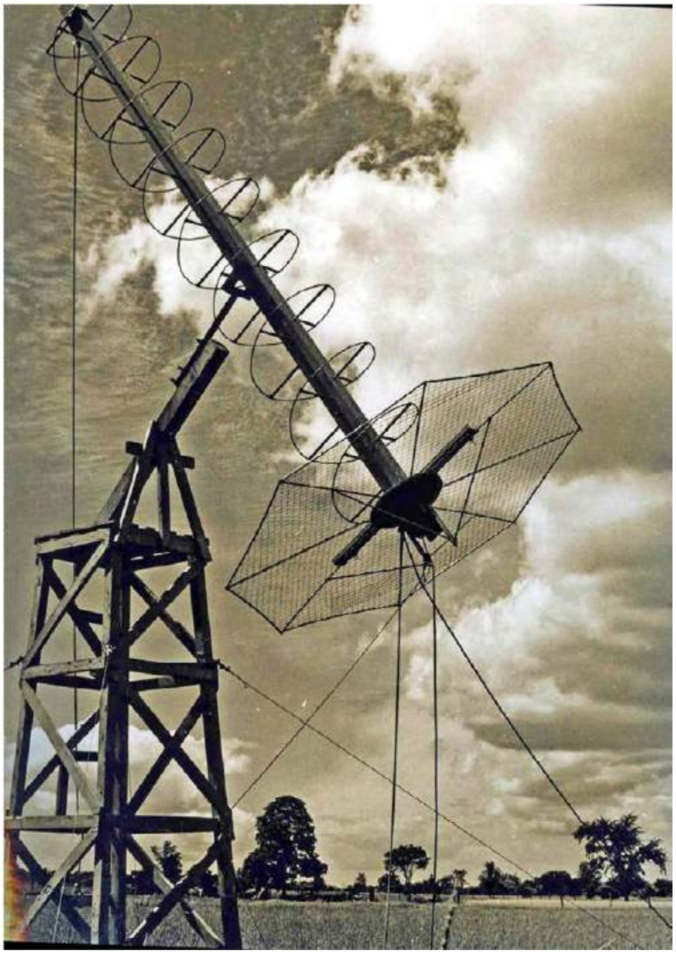


Figure 2 — David E. Hogg's M.Sc. project—studying transient bursts of radio noise from the Sun by scanning repetitively in wavelength from 3.4m to 2.3m at 5-second intervals. The antenna is an equatorially mounted 9-turn helix of length 6m, with a reflector of diameter 3m. The receiver output is recorded directly from an oscilloscope screen by a camera.

box and reach for pliers, a wrench, soldering gun, electrical tape, hacksaw, screwdriver,... and replace a connector, shorten a cable, adjust an antenna pointing, replace a vacuum tube, resolder a connection, or whatever he deemed necessary. This was hands-on training in self-reliance and experimental science. He was the experimenter, answerable to no users' committee, no time allocation committee, no head of engineering. When in doubt, he could confer with Harrower, but ultimately this telescope was his to design and his to operate, and the data would be his to analyze while writing his M.Sc. thesis. At the oral examination, he would be the one standing alone in front of the examining committee, defending every word and number in that thesis, and "just losing weight," as P.G. Wodehouse would put it.

The chart in his hands now, though, showed a far from smoothly oscillating fringe pattern. The fringes were torn by irregular excursions, showing variations in the power incoming from Cas A. Far from making Matthews frown, however, that irregularity was essential, for he wished to study not the supernova remnant itself, but the jaggedness of the recording, the time structure of the irregular variations in radio power—in other words, the way that Cas A "scintillated."

How the incoming waves could vary so rapidly in intensity was the question. An object four parsecs in diameter could not flicker like a candle—no coordinating signal could cross it in less than 13 years. These fluctuations could not be intrinsic to the source but must be imposed during propagation of the waves through the intervening space. Most of the variation, in fact, was already known to occur in the last few hundred kilometres, caused by distortion of the wavefront by irregularities in the Earth's own ionosphere.

Ionospheric physics was, in fact, a primary area of Harrower's expertise. For two years he had been collaborating with T.R. Hartz of the Defence Research Telecommunications Establishment (DRTE) in Ottawa, analyzing radio-source scintillations and ionospheric data.

Despite sitting near a city of more than 50,000, QRO did not experience appreciable man-made interference. Runways left behind after WWII lay four kilometres to the southeast, used sporadically by the Kingston Flying Club. Two TV stations served the area—channel 7 at 1.7m wavelength and channel 11 at 1.5m. Cell phones lay decades in the future. In March of 1958, only four satellites had ever been launched into orbit. *Sputnik I* had already burned up. *Sputnik II* and *III*, massive but now derelict, still orbited; both would burn up in April. *Explorer I*, tiny but the one spacecraft still functioning, transmitted only milliwatts at 2.8m wavelength. Not being in a polar orbit, it could not pass overhead at QRO. (In four years' time, Canada would enter the space age with the launch of *Alouette I*, designed and built in Ottawa and intended to probe the ionosphere from the "top side" at wavelengths from 25m to 300m.) In the broadcast bands, CKWS, CKLC, and CFRC transmitted at 312m, 217m, and 201m (AM) and at 3.11m, 3.03m, and 3.26m (FM). QRO had plenty of empty spectrum for future radio telescopes to use.

In 1958, the field of radio astronomy was burgeoning, as scientists and astronomers worldwide rushed to peer through the new long-wave window into the Universe. A dozen octaves wide—compared with the single octave of wavelengths spanned by human vision—the radio window was already revealing bizarre and unanticipated phenomena. At the end of July, 159 astronomers and radio scientists would convene in Paris to present more than a hundred papers in radio astronomy.

Queen's University was catching the radio tide on the rise—by the time Matthews shut down his scintillation telescope to write his thesis, another was already on the air. This telescope tracked the most powerful radio source in the sky—an immense ball of roiling ionized gas, a cauldron of thermonuclear reactions, origin of a seething atmosphere laced by writhing magnetic fields, site of powerful eruptions and storms, unpredictable and only 500 light-seconds from us: the Sun.

David Hogg's solar radio telescope used a single antenna, mounted equatorially for tracking the Sun (see Figure 2). His thesis supervisor was again George Harrower. Unlike ionospheric scintillation, the phenomenon under investigation this time—transient solar radio bursts—was intrinsic to the source, not the propagation path... or was it? At the Paris Symposium on Radio Astronomy that would commence in a month, out of 107 scientific papers by scientists from 12 countries—including A.E. Covington from the National Research Council (NRC) in Ottawa—40 percent would be on solar radio phenomena and attempts to understand the physics behind them. Of those, over half would include observations or analyses of "radio bursts" that shifted in wavelength as if beams or clumps of charged particles were speeding through the coronal plasma, perhaps in the grip of tortured magnetic fields. The radio waves the particles launched would then have to propagate through an inhomogeneous magnetized plasma—the corona itself—to reach the Earth.

In Hogg's three months of observations from QRO, he recorded several radio bursts from the Sun, using a highly modified commercial receiver. He scanned from 88 to 128 MHz by motorizing the frequency tuning of the receiver. With a camera mounted to view the screen of an oscilloscope, he synchronized the oscilloscope's horizontal sweep with the tuning sweep of the receiver. The instantaneous spot brightness showed the solar radio power reaching the antenna. With this he photographed many transients, from which he selected ten to study their frequency drift with time.

Matthews' and Hogg's telescopes were examples of special-purpose instruments built on very low budgets. Nor would these be the last of this type to be built at QRO (see Table 1). John Black, for example, built and operated two interferometers for his M.Sc. scintillation work, so as to monitor Cas A continuously, as well as Cygnus A, the Crab Nebula, and Virgo A (M87) as they rose, transited, and set.

Elsewhere, however, by the summer of 1958 huge multi-purpose radio telescopes were being designed, funded, and constructed. A 26-m steerable paraboloid would be operating at Penticton in B.C. by 1960, a 64-m steerable paraboloid would see first light at Parkes in Australia in 1961, and a 91-m meridian-transit paraboloid would come into service at Green Bank in West Virginia in 1962. But of course in Britain, in 1957 the world had seen the first giant telescope lumber into action, at the time of *Sputnik I.* This massive telescope—it

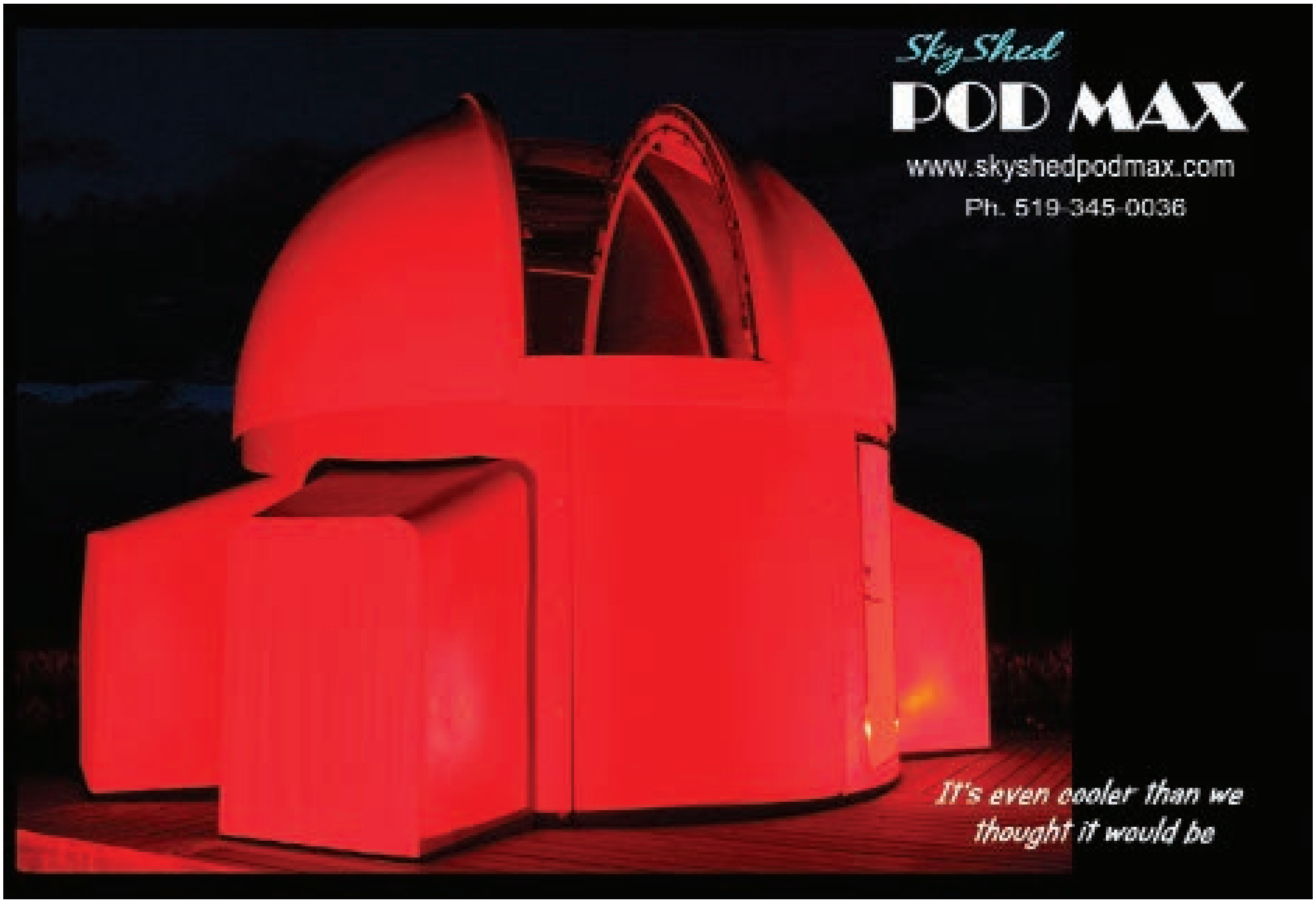


Figure 3 — The reflection-array telescope for 2m wavelength in 1964. The two-element Yagis are reflecting elements mounted on 5m poles for height adjustment. Through the door of the small hut can be seen the rack of receiver electronics. At 53m height, the tower (base visible here) is an aviation hazard and has to be painted in red and white bands, besides carrying a red light at the top.

required bearings from WWI battleship gun turrets—had instantly become an icon, the 76-m steerable paraboloid south of Manchester at Jodrell Bank.

The cost of such general-purpose instruments was shocking, however. Including cost overruns, expenditure on the Jodrell Bank telescope had risen to £700,000. (In 2019 terms, that is $11,000,000 CAD.) How, Harrower asked himself, could researchers at individual universities compete?

To answer that, he first pinpointed the fundamental difficulty with radio astronomy at the time—that good angular resolution (that is, imaging with good detail) requires antenna structures hundreds or thousands of wavelengths wide. The human eye, for example, can resolve a single arcminute because a pupil of 2mm diameter is 4,000 wavelengths wide at 500 nanometre wavelength. To achieve the same resolution at two metres would still take a telescope aperture 4,000 wavelengths across, but that is eight kilometres. Even the Jodrell Bank telescope spanned only 38 wavelengths at two metres, so its images would contain detail no finer than 1.7 degrees. Its gigantic collecting area of over 2,000 m^2 would be largely unneeded for imaging the radio sky at 2m wavelength—the faint sources it detected would be lost in the huge, fuzzy blobs that were the strong sources. Though excellent at centimetre wavelengths, e.g. the atomic hydrogen spectral line at λ21cm, its 76-m diameter was inadequate for imaging at metre wavelengths, where the tonnes of steel forming the dish surface and backup structure were mainly wasted.

And thus, was born, in about 1960, Harrower's idea of the porous reflecting array—an inexpensive technique for metre wavelengths of achieving the same angular resolution as a complete paraboloid, but without unnecessary collecting area. He would use a large number of individually small reflecting elements just above ground level, distributed throughout a circular area so that incoming radio waves would be reflected from them to a focal point above. The heights of the reflecting elements would be adjusted to mimic the paraboloidal surface of an actual dish, minus an integral number of wavelengths near the "rim" to keep all elements near the ground. By placing the reflectors at random within the area of the circle, sidelobes (unwanted responses at large angles from the main beam) could be kept low. The density of elements—the porosity—within the circle would determine the effective area. This idea produced three M.Sc. theses (see Table 1). Michael Gibbons optimized and tested the reflecting elements, settling on Yagi antennas with short-circuited terminals. Richard Butler calculated the expected power pattern of the array and compared that against measurements on a scale model at 9cm wavelength. William McCutcheon constructed a full-size array at 2m wavelength at QRO, and made further computations of the power pattern.

The full-scale reflection-array telescope at QRO consisted of 100 two-element Yagi antennas within a 120-metre diameter circle. (See Figure 3.) Cables carried signals from the "feed"

at the top of the tower to the receiver in a small hut at the base. The feed consisted of a pair of crossed dipoles so the "background" power received directly from the sky could be subtracted from that reflected from the Yagis.

The new telescope would have a beam width of two degrees. Steering the beam, however, would require repositioning all 100 reflecting elements, so that tracking an object was impossible, and even using it over a range of declinations as a transit instrument would be physically arduous. Furthermore, it was found that achieving adequate collecting area (sensitivity) required more elements than first envisaged. The concept was not pursued further.

The Moving Tee

Undeterred, Harrower still desired angular resolution competitive with behemoth single-dish telescopes, but without their superfluous collecting area and immense steel backup structure. He realized that with a new technique called "aperture synthesis," detailed images of the radio sky could now be made—using angle iron, wire mesh, cable, etc., plus student expertise and labour—for a tiny fraction of the cost.

Besides providing a new look at the sky, an aperture synthesis telescope could address a question of high importance at the time: at a given wavelength, how many radio sources can be counted of given strength or brighter? This was the "source count" issue, important for cosmology and a bone of contention between Martin Ryle's Cambridge group and Bernard Mills's Australian group. The Cambridge source counts—from sky surveys made with interferometers—appeared to be systematically higher than those from Sydney, with the Sydney group alleging that a fraction of the Cambridge "sources" were actually duplicates, sources being counted more than once as they appeared in successive interference fringes.

Why should Queen's not contribute to this debate, Harrower asked himself, and perhaps even help settle the disagreement with independent data from a new telescope at QRO?

Philipp Kronberg, an M.Sc. student, undertook design and construction of a synthesis telescope, supervised by Harrower. An operating wavelength of two metres was selected—more precisely, 2.05 metres, in the radio amateur "two metre" band, to take advantage of commercial components such as frequency-heterodyning "mixers." And why not do better than even the world's biggest single dish at that wavelength, with a beam of one degree at QRO?

The project got underway in 1961. What, then, was this new technique of "aperture synthesis"?

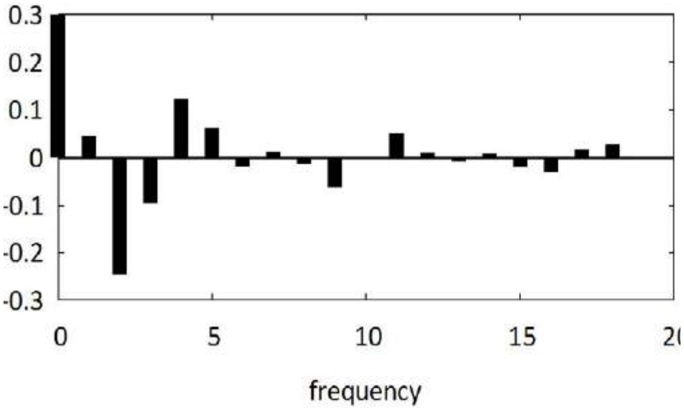
Briefly put, synthesis imaging is a way to produce a sharp reception beam with a pair of cheap antennas, computing power, and tenacity instead of a huge steerable paraboloid.

The enemy of ever-larger single-dish telescopes is gravity. Not only does the moving tonnage become gigantic, but the mirror sags away from the desired parabolic shape. Also, how it deforms depends on the direction of pointing. The cost goes up typically as the cube of the diameter, and the sounds of collapsing budgets and buckling steel echo across the years. The foundations had been poured, for example, for a steerable 183-m dish at Sugar Grove in West Virginia before sanity prevailed in 1962 and the project died.

To achieve sharp angular detail, a telescope still has to be many wavelengths across, however. How to solve the conundrum?

Enter Jean Baptiste Joseph Fourier, born the son of a tailor in France in 1768. Analyzing how heat flowed through an object—this was the era of steam engines—he made a stunning mathematical discovery: you can build up ("synthesize") nearly any mathematical profile—a city skyline, for instance—out of simple sine-wave oscillations of different rates ("frequencies" with their corresponding wavelengths), strengths ("amplitudes"), and timings ("phases"). And conversely, you can disassemble nearly any profile into such sine-wave oscillations. Fourier was awarded the rank of baron.

To demonstrate the power of Fourier synthesis, suppose we add together waves of increasing frequency having the amplitudes shown in Figure 4(a). The result is the waveform in Figure 4(b), a pair of rectangular humps. As we see, summing higher and higher harmonics of the fundamental frequency,



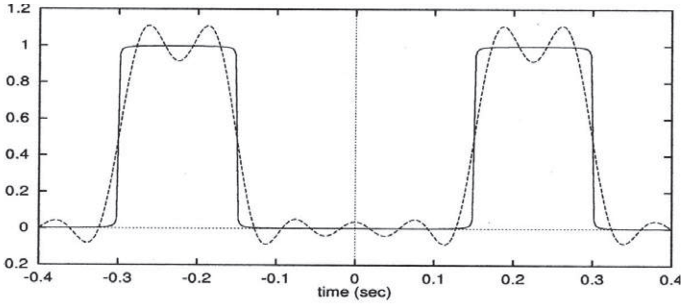


Figure 4(a) — Amplitudes of sine-wave oscillations used to build up the double-hump shape below.

Figure 4(b) — Double-hump shape synthesized by adding sine-wave components with amplitudes shown in Fig.4(a) above. The dotted line is the sum of seven harmonics, while the solid line is the sum of five hundred. This resembles the brightness profile along Cygnus A.

the less crude the rectangles become, i.e. the sharper the detail portrayed.

However, the shapes of astronomical objects are profiles in terms of angle across the sky, not time. Therefore, instead of oscillations in *time* we imagine instead oscillations in *angle*. Variation along the time axis becomes variation with angular position across the object, and in place of the word "frequency" we use "spatial frequency." The process in Figure 4 becomes synthesis of an image in one dimension.

But how to know what amplitudes to use—as in Figure 4(a)—at the various spatial frequencies? Surprisingly, we have already seen an instrument for measuring the amplitudes of sine-wave components of objects in the sky. This instrument picks up only one spatial frequency at a time, and it consists of two cheap antennas, plus amplifiers and some cable to carry the incoming signals to a receiver. There they combine and interfere, which is why it is called an interferometer.

The larger the number of wavelengths between the antennas, the more rapidly the interference fringes oscillate with angle. Therefore, lengthening the antenna spacing (baseline) day by day will pick out successively higher spatial frequencies from the brightness profile across the object. Day by day we record the amplitudes—and phases—of the oscillating output (the fringes on the chart), *assuming* that the object in the sky does not change from day to day.

When we have enough recordings, we can add oscillations together of the required amplitudes, keeping the phases correct. Result: an image of the object as in Figure 4(b), containing detail as sharp as the fastest oscillation (highest spatial frequency) used in the summation.

Using this technique, in fact, by the late 1950s the radio source Cygnus A had been found—amazingly and inexplicably—to be double, with a brightness profile along its length something like Figure 4(b). The interferometer measurements—performed at 2.4m wavelength by working westward from Jodrell Bank with transportable antennas—were reported at the 1958 Paris Symposium[2]. Cygnus A looked like a dumbbell, which defied explanation.

One-dimensional profiles were useful, but detailed two-dimensional images would be actual radio *pictures*. (These would one day reveal that far from being unique, Cygnus A was the prototype double radio source; there are thousands of extragalactic sources like it, even more distant, all incorporating beams of relativistic particles powered by massive black holes.)

Two-dimensional synthesis had already been achieved, by Ryle's group at Cambridge, with first results in 1957 by Blythe—sky maps with a 2.2° "pencil beam"[3]. Sharper images—0.8° resolution—at the same wavelength came three years later from a second Cambridge synthesis telescope[4]. This was progress—to achieve 0.8° at 7.9m, a single-dish telescope would have to be two-thirds of a kilometre in diameter.

Figure 5 shows the fundamental concepts of two-dimensional synthesis. The performance of a large rectangular aperture could be achieved with a cross, or more efficiently with a "tee," or more efficiently yet with just two antennas, placed at locations that would form a tee if one had extreme patience.

At QRO—as at Cambridge—the compromise approach would be taken, with the long east-west arm of the tee being constructed as a "corner reflector" (see Figure 6), but the half-length north-south arm being formed with a shorter, moveable, corner reflector. And patience.

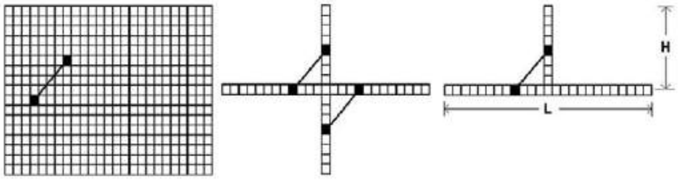


Figure 5 — From filled aperture to tee in three conceptual steps. In the rectangular aperture at left, the spacing (length and orientation) between two elements is usually not unique—in fact there is large redundancy for most spacings. In the cross, two linear antenna arrays are built and the two output voltages are multiplied together in the receiver. This product of two fan beams gives a pencil beam of the same sharpness as would the rectangular aperture. In the tee at right, even the small redundancy in the cross has been removed. The tee produces the same sharp pencil beam as the cross. In the extreme, even the linear arrays do not need to be physically constructed—two small antennas can be moved day by day to occupy positions forming a tee. In the QRO "moving tee" telescope, the long east-west arm (L = 117m) was constructed, but a smaller moveable antenna was used to form the north-south arm (60 positions over length H = 62m). The pencil beam of the QRO telescope was therefore the same as if the complete aperture of size L X 2H, i.e. 117m X 124m, had been built.

Figure 6 — The long E-W fixed arm of the 2m "moving-tee" synthesis telescope, under construction in 1962. The beginnings of the moving element are visible to the left. Professor George Harrower stands, while Philipp Kronberg climbs on the 60-degree corner reflector. Kronberg is holding one of the 96 end-to-end folded dipoles that together form a "line feed" for the corner reflector. The sides of the reflector are wire mesh, which acts as a mirror for radio waves. With mirrors 60° to each other, 5 images appear. The real line feed plus its five images act together as an array of long antennas, increasing the sensitivity of the telescope to incoming waves.

At the time, "two solitudes" existed in astronomy—optical and radio—with little communication between the two. Radio astronomy, the small brash upstart, consisted of radio engineering, receivers and antennas, soldering irons and pliers, and boring flux-density measurements and power-law spectra plotted on logarithmic axes. Optical astronomy, meanwhile, "real" astronomy, dealt with stellar atmospheres, photometry and spectroscopy and orbital parameters of binary stars, photographic plates, evolutionary plots of stellar magnitudes and temperatures and linewidths, *photos* of planetary nebulae, and so on. In other words, the two groups studied different objects, with different instruments and techniques, and worked at different angular scales. Optical images had arcsecond resolution and usually showed a field of view of a few arcminutes, while radio "contour maps" showed at best half-degree resolution, and covered several degrees of sky. To optical astronomers' eyes, these were just line drawings of blobs. The fuzziness of these radio maps would remain radio astronomy's biggest problem until aperture synthesis techniques were invented and then implemented in hardware and software, whereupon radio images would rapidly become as sharp and detailed as optical images had long been—sometimes much sharper with very long baseline interferometry (VLBI)—and radio astronomers would become more and more accepted by optical astronomers.

Harrower had seen that Queen's was positioned to build a world-rank telescope at metre wavelengths. Aperture synthesis could provide good angular resolution at low cost, without superfluous collecting area, and produce sharper images at 2m wavelength than those being produced elsewhere. He had every reason to believe that this goal was within reach.

Producing an image by Fourier synthesis required adding together many days' observations. At Cambridge, Ryle said later, if the digital computer had not been invented when it was, his group would have been forced to invent it themselves to accomplish this step. The observations recorded on charts had first to be digitized (punched onto cards or paper tape), then used as input for a program to perform the two-dimensional Fourier summation.

At Queen's, the university's computer was an IBM 1620, recently installed in Ellis Hall. This machine had core memory (RAM) storing 20,000 base-ten digits (expandable to 60,000), and a processor clock speed of 2 MHz. Even the fastest instruction took 10 microseconds. Input was done on punched cards.

Kronberg would write a program in FORTRAN to accomplish the Fourier summation. This program (the "source" deck of cards) had to be fed into the input hopper for the compilation step and then a new set (the "object deck," which the machine punched out in machine language) had to be fed in, followed by the data cards, in the execution step. The output appeared—eventually—on punched cards. The astronomer could now write the output numbers (the brightness of the radio sky point by point) in a two-dimensional array representing the sky, and draw contours by hand.

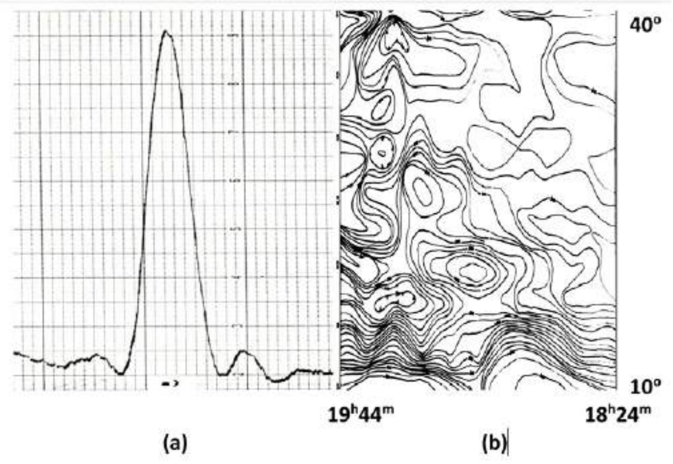


Figure 7 — (a) Chart recording at 2 metres by Hesse, as Cas A transits through the NS fan beam power pattern of the long arm of the moving-tee telescope. Chart speed is one large division per 15 minutes; hence the fan beam is 1º EW at half maximum. Sidelobes are visible on each side, of about 5%.

(b) Combining interferometer outputs from many days' observations in a Fourier summation, a pencil beam forms. Thirty degrees in declination of Kronberg's 1963 map is shown. Closed contours indicate individual sources, and broad emission from the Milky Way dominates the South and East.

Figure 6 shows the 2m "moving tee" under construction at QRO. By September 1963, Kronberg had produced a first-try contour map of a strip of the sky 1^h20^m wide in right ascension and 40° high in declination, with resolution 1° EW × 3.5° NS (see Figure 7(b)).

When Kronberg defended his thesis in 1963 and departed for Britain to continue his studies, he rightly believed he had accomplished a gargantuan task, and foresaw that subsequent students would accomplish a complete sky survey at 2m wavelength. As usual in science, however, the new instrument required tweaking before final data-gathering could commence. The fringe records must not be contaminated by phantom sources—the response of the telescope to radio sources in the sidelobes. And indeed, there might be sidelobes.

Aage Sandqvist checked on sidelobes—and solutions—for his M.Sc., under Harrower's supervision. He developed probes for measuring currents, including their phases, along the linear array of dipoles that formed the line feed of the long corner reflector. He concluded that the array needed to be "tapered" ("apodized" in optical terms) to reduce sidelobes.

If an antenna is used for transmitting, its power pattern has the same shape that its reception pattern would have if a receiver replaced the transmitter. In transmitting terms, the network of "twin-lead" transmission line connecting the 96 dipoles to form the line feed was providing equal currents to all dipoles. In antenna jargon, the linear array had a "uniform taper" (no apodization). Theory and experience predicted this

would produce strong sidelobes. When receiving, these could indeed pick up sources, "aliasing" them into the receiver output as indistinguishable from sources transiting the main beam—duplicates contaminating the data.

After studying various tapers, and methods of achieving them, Sandqvist decided to group the dipoles in sets of four, and add resistors to reduce the signals from the dipoles progressively toward the ends of the array. Time had elapsed since Kronberg's departure, and the feed now exhibited a taper worse than uniform, i.e. higher at the ends than the centre—possibly the first signs in the new telescope of that ceaseless degradation affecting all instruments exposed to the relentless effects of weather. (In the Kingston area, rain freezes, and snow melts and then freezes again, over and over, and these events are particularly troublesome—solder joints and metal pieces suffer continual breakages.)

Sandqvist applied a "Gaussian" (bell-shaped) taper along the feed array and found that the long arm by itself produced a fan beam 1.14° wide, with sidelobes no higher than 0.25 percent of the main beam.

The next students to work on this telescope were Helmut Hesse and Philip Gregory, again doing M.Sc. projects supervised by Harrower. Uncertainties in the performance of the receiver had arisen, as well as the necessity of calibrating it. Also, a modification could halve the number of days required for a survey. And again, the feeder system for the long corner reflector was giving trouble.

Gregory undertook to improve the receiver. This multiplied the voltage output of the long arm by that of the movable element and had to record the ever-changing complex product (the fringes from a north-south interferometer), in both amplitude and phase. Equivalently, it could record the real and imaginary parts, and this was what it had been built to do. Before Gregory, however, recording real and imaginary parts had taken two days' observations, the second being performed with an extra quarter-wave cable connected between the movable antenna and the receiver. Gregory twinned the receiver channels to measure both simultaneously.

The receiver now consisted of a pair of (ideally) identical receivers. Gregory established the bandwidths of these and ascertained how the bandwidths affected the accuracy of the output fringes. Devising tests of several receiver parameters, he then quantified the performance of the receiver. He concluded that the new receiver system was capable of detecting at least as many celestial radio sources as the telescope could resolve.

Hesse found that the flexible twin-lead transmission lines used to connect the dipoles feeding the corner reflectors were not standing up to the rugged environment at QRO. Grouping dipoles in sets of twelve along the long arm, he rebuilt the feeder system using coaxial cable where possible, as more robust and weatherproof, and incorporating baluns and impedance transformers where necessary. A scan with the improved feeder system is shown in Figure 7(a).

Hesse also designed and built a receiver calibration system. In preparation for the finally-imminent sky survey, he then wrote a new program for Fourier synthesis on the IBM 1620. This program, parts of which were in machine code and parts in FORTRAN, implemented the just-published Cooley-Tukey algorithm for Fast Fourier Transforms.

Gregory and Hesse submitted their theses and defended them. Sadly, these would be the last theses involving the 2m (146 MHz) moving-tee. As they left to continue their astronomical careers elsewhere, the telescope stood at last truly ready—for the moment—for its sky survey.

However, a major change had already occurred in the physics radio astronomy group.

New Leadership

At this point the breadth of interest in radio astronomy at Queen's should be made clear. George Harrower had joined the Physics Department in 1955 and launched Queen's into the field of radio astronomy as early as any university in Canada by establishing QRO in 1956. This was never a single-handed endeavour, however—he was collaborating closely with academic staff in other departments—Allie Vibert Douglas in Mathematics and Astronomy, John E. Hogarth in Mathematics, and Robin M. Chisholm in Electrical Engineering.

Chisholm brought expertise in antenna research and signal processing, including the new technique of aperture synthesis. He had spent some time in New South Wales, at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) radio astronomy field station at Fleurs. There, Mills's group had pioneered the cross-type telescope, one of which produced a 0.8° pencil beam at 3.5m wavelength. Now Chisholm was keeping his research links with Fleurs strong, travelling there often. By 1958 he and Harrower were designing a 3km-baseline "compound interferometer" for 3.5m which would synthesize a reception beam under 5 arcminutes wide. This was extremely ambitious, and the telescope would be the largest in the world. For tests they chose a tee configuration but scaled down in wavelength by a factor of ten for cost and practicality. The test-bed instrument would be a tee of two dipole arrays, with the bar of the "T" running north-south. Each scaled-down array would be 47m long. By 1962, the Electrical Engineering Department had begun construction of this 35cm tee at QRO.

The north-south arm was to be steerable in declination. However, difficulties with impedance changes arose, and the elements were changed to "long Yagis" with 40 directors, made of aluminum tubing. Even then the proposed electrical steering system remained intractable. The east-west array had been built, however, and produced a fan beam along the meridian. This array—actually a pair of E-W arrays mounted together—was tiltable to different declinations. It can be seen in Figures 8 and 10.

By now, however, the original compound interferometer project was far behind competitors and was abandoned. While it failed to yield astronomical measurements, the project had produced at least 11 MSc degrees in Electrical Engineering for receiver and antenna design. Chisholm had also become deeply involved in what would become the world's first successful VLBI project, and Electrical Engineering bequeathed the 35cm antennas and receiver to Physics.

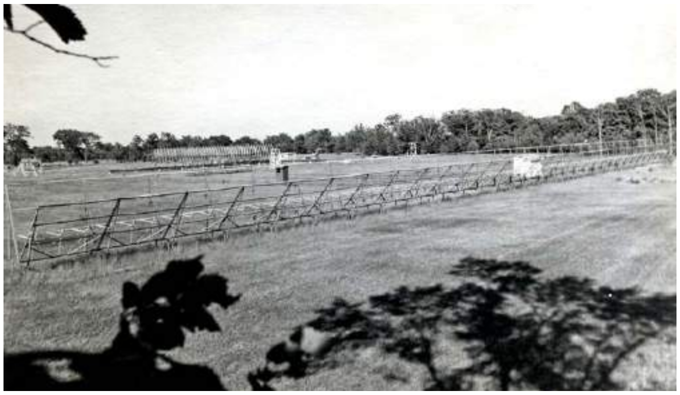


Figure 8 — Queen's Radio Observatory viewed from the South, in 1965. The long E-W fixed arm of the 2m-wavelength moving-tee synthesis telescope is in the foreground, with the white hut containing its receiver behind it. In the background to the North sit the 35cm-wavelength twin arrays built by the Electrical Engineering Department and transferred to the Physics Department. The rail-mounted movable element of the moving-tee is faintly visible between the long corner reflector and the 35cm twin arrays. Both corner reflectors of the moving-tee are tiltable in declination.

George Harrower, meanwhile, had come to a crossroads in his career. Queen's had offered him the position of Dean of Science, and he had elected to take it.

A successor had been found, fortunately, to take the helm of the radio astronomy group in the Physics Department. This was Victor A. Hughes, who arrived from England in September 1963, having done wartime work in telecommunications, graduate work in radio astronomy with Bernard Lovell at the University of Manchester, then radio and space research with James Stanley Hey at Malvern.

Having been part of the "pioneering" age of radio astronomical invention and discovery in England, Hughes was very happy to see the roll-up-your-sleeves-and-build-it tradition being inculcated in radio astronomers of the next generation at Queen's. He was pleased to continue the collaboration with Electrical Engineering, and assisted Harrower in supervising Gregory and Hesse in their work at Westbrook.

After Hesse and Gregory defended their theses and departed, however, the 2m moving-tee telescope entered a period of decay, including some vandalism, without being used for the "clean" sky survey it was capable of. Nonetheless, QRO would soon see another active period, involving other telescopes and arrays.

In 1964, Hughes obtained recordings of observations—including solar radio bursts—made with the *Alouette I* satellite. These came from T.R. Hartz of DRTE in Ottawa. Henry Bradford, a new Ph.D. student, used these to study "Type III" solar radio bursts (see Figure 9) in one of the first radio astronomy projects at Queen's not involving QRO—a sign of things to come.

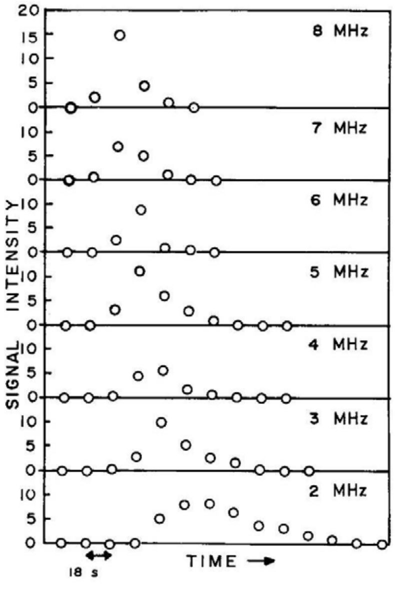


Figure 9 — Alouette I observations of a type III solar burst. Radio intensity has been sampled (dots) every 18 seconds by the swept-frequency receiver carried by the satellite. The burst arrives later at lower frequencies (longer wavelengths). Ground-based radio telescopes often miss parts of these bursts because of ionospheric reflection at long wavelengths.

Hughes also saw potential in the now-surplus 35cm-wavelength twin arrays at QRO and the two-channel correlation receiver which had been designed—and modified by successive Electrical Engineering graduate students—to be used with it. Why not use these, he asked himself, to measure the polarization of the radiation arriving from the Galaxy that surrounds us?

By this time, radio emission from the interstellar medium, separate from discrete sources within it, had been explained as the interaction of relativistic electrons with the pervading Galactic magnetic field—synchrotron radiation. As with the Crab Nebula, the emission should be partially linearly polarized and therefore mapping the polarization should reveal the distribution and orientation of the magnetic field throughout the Galaxy's spiral arms.

A new M.Sc. student supervised by Hughes, David Routledge, arrived in 1964 and took on the task of reconditioning and adapting the 35cm receiver for this project. Hughes had brought an interesting concept with him: by slightly offsetting the frequency-heterodyning "local oscillators" in the two channels of the receiver, the position angle of the system's maximum sensitivity to linear polarization could be made to rotate on the sky. The 35cm twin arrays consisted of 80 long Yagis each, with the two sets orthogonally polarized. Each array produced a fan beam along the meridian, of E-W width 0.7 degree. It would be as if the stationary 35cm arrays behaved like a single spinning antenna, so that a polarized signal from the sky produced a slowly oscillating receiver output, which could be measured.

This instrument did work, in the sense that the system, with its completely rebuilt receiver, did allow measurement of the polarization of test antenna transmissions. However, spurious polarization resulting from collimation errors between the two arrays (even after laborious reconditioning and adjustment) and —once again—sidelobes, foretold major difficulties in measuring Galactic polarization using these arrays. The twin 35cm arrays joined the ranks of retired telescopes at QRO.

The receiver, however, would see use in another incarnation. In 1966 Hughes obtained an 18-metre paraboloidal dish antenna from the Defence Research Board, where it had been used fastened to a tower. At QRO it was resurfaced, and a new M.Sc. student, Daniel de Kock, took on the task of designing a fully steerable alt-azimuth mount and indication system, and installing the dish on a wheeled triangular structure riding on rails (see Figure 10). The new telescope, commissioned in 1969 with a dual-polarized feed, used the 35cm receiver from the polarization project and produced a beam 1.4° in width.

A subsequent M.Sc. student, Donald Retallack, used this paraboloid—with a new 35cm receiver—to search the Galactic Centre, looking for pulses coinciding with gravitational wave pulses then being reported by Joseph Weber from his mass-interferometric detector in Maryland. Pulse timing data provided by Weber covering months of radio observing at QRO showed no timing coincidences had occurred, and his reported detections were later discovered to be artifacts of his data analysis. Nevertheless, the QRO paraboloid did detect pulsed radio emissions from the Galactic Centre and gave their positions[5].

Figure 10 — The QRO 18-m dish on E-W rails in 1969. Plans for a second dish to form an interferometer were never implemented. In the background to the East sit the twin arrays for 35cm wavelength built by the Electrical Engineering Department.

Technicians

Although much of the work at QRO and in the Physics radio astronomy lab was performed by graduate students, those students relied on the group's technicians. During the era 1957–1972, the group employed three in sequence, but never more than two at one time. These knowledgeable, hard-working, versatile repositories of experience and paragons of patience were Don Cooper, Joel Tarback, and Bob Baran. Tarback in particular laboured many weeks per year outdoors at QRO. In Hesse's thesis, for example, he says, "Research technician J. Tarback helped this project inestimably with his wide knowledge and the spirit with which he went about his work, and thus deserves special thanks." Tarback also carried out much of the heavy task of reconditioning the twin 35cm arrays both mechanically and electrically, and single-handedly installed a new double-layer wire mesh surface on the surplus 18-m dish.

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Vacuum-Tube Receivers

One well-intentioned graduate student working at QRO assembled the components of his receiver near his antennas for tests, but as evening approached realized that he had no weather-proof enclosure. Seeing rain clouds forming but wishing to run his telescope overnight, he borrowed an unused waterproof "cabinet" he spied. This was a refrigerator that at one time had been used in the main observatory hut but was no longer functioning. Acting responsibly, he moved the components of his receiver—many of them commercial units on loan from Electrical Engineering—into the refrigerator. Giving his receiver a final tweak for the night's observations, he closed his new cabinet and departed.

Returning in the morning, he found the receiver still running. However, he had forgotten about the First Law of Thermodynamics: "Energy can be transformed from one form to another, but can be neither created nor destroyed." As the temperature in the ex-refrigerator rose higher and higher overnight, plastic components in several electronic units had melted, including dials and light jewels. These had also obeyed the Law of Gravitation by drooling down the front panels.

Vacuum tubes did all the things transistors do now, but with a fundamental difference: they dissipated thousands of times more heat—a few Watts each. Packing even hundreds together—let alone millions—to build an integrated circuit would produce spontaneous combustion.

With three electrodes in the glass envelope—in addition to the filament that heated the cathode—the basic vacuum tube was the triode. The pentode (five electrodes plus filament) offered improved characteristics for some applications.

The montage in Figure 11 shows McCutcheon's receiver for 2 metres, and one of the four cabinets of the 35cm two-channel polarization receiver. In the 35cm receiver, the first cabinet contained two parametric amplifiers (adjusted for identical gain and bandwidth by postdoctoral fellow Carson Stewart) that were "pumped" by 3cm microwaves from a special vacuum tube—a "klystron"—beneath which sat its own massive vacuum-tube power supply. The fourth cabinet contained only such power supplies, each incorporating several high-power vacuum tubes. In the 35cm-receiver cabinet shown in Figure 11, 29 vacuum tubes reside inside cylindrical metal sheaths. Keeping receiver huts warm, even in winter, was never a problem.

New Academic Staff

The "supervisor" column in Table I reflects the transition of thesis supervision from Harrower to Hughes that occurred in 1964–1965.

Following Hughes's arrival, additional academic staff began to be added to the group. The first was theoretical astrophysicist Richard N. Henriksen from the University of Manchester, in 1965, bringing expertise in magnetic effects in astrophysics. In 1966, Alan H. Bridle also joined the group, from Ryle's group at Cambridge.

Bringing knowledge of decametre-wavelength astronomy and the broad-scale Galactic synchrotron radiation, Bridle instituted a weekly "literature review" in which all graduate students were expected to take part. Each was assigned two or more specific subjects of responsibility, spanning current astronomical papers in the international journals. Topics that Bridle assigned included the enigmatic quasi-stellar radio sources (discovered 1963) including the question of whether their redshift was cosmological, the ongoing discovery (since 1962) of extrasolar X-ray sources using rocket-borne instruments, discoveries (1963 onward) of radio spectral-line emission—including maser amplification—from interstellar molecules, and (1965 onward) the cosmic microwave background radiation and implications regarding the Big Bang.

Each week each student would present a précis of

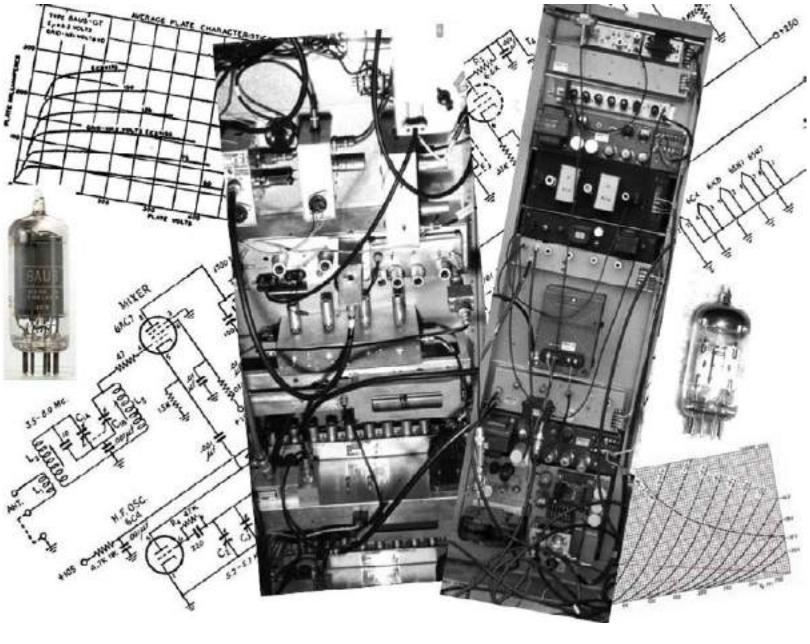


Figure 11 — A vacuum-tube montage showing the rack containing McCutcheon's receiver for the 2m reflection-array telescope on the right, and one of the four cabinets of the 35cm two-channel polarization receiver on the left. At far left is a pentode, and at far right is a triode. Racks are taller than a person, and cabinets are shoulder height. In the background appear anode current-voltage curves, and the schematic diagram for a shortwave receiver. Connections to its five vacuum-tube filaments appear at right.

a significant paper in each of his assigned areas. Beyond the advantage of keeping everyone abreast of developments in astronomy, this was excellent training for presenting papers concisely and clearly at scientific conferences. Penetrating questions were to be expected. Soon academic staff members, including from other areas of physics and other departments on campus, were attending the group's literature review sessions as well.

One topic assigned for the review was decametric-wavelength astronomy, advancing in Tasmania, California, Ukraine, and especially Canada, with construction of a huge synthesis tee for 13.5m wavelength[6] and another for 30m wavelength[7] at the Dominion Radio Astrophysical Observatory (DRAO) at Penticton. Both these telescopes had begun observations by 1965. Bridle, in fact, had already worked with the DRAO 30m-wavelength telescope, acquiring data for radio-source spectra[8].

In 1967, came the jaw-dropping discovery by Ryle's group at Cambridge—made not with their increasingly powerful cm-wavelength synthesis telescopes but with a wire-and-cable-and-wooden-posts antenna array for 3.5m built largely by graduate students—of the unforeseen phenomenon of pulsars. These would lead to better understanding of supernova remnants and the interstellar medium, and brought neutron stars, enormous magnetic fields, and interstellar radio beams into daily discussions.

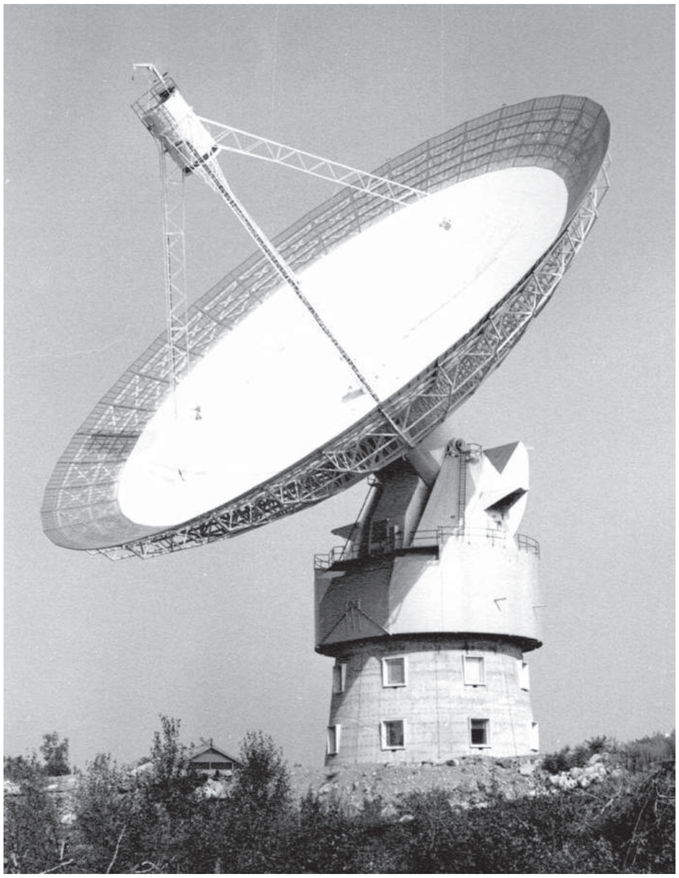


Figure 12 — The 46-m telescope and at left the control building, at ARO in 1968. Receivers are available at three wavelengths, offering increasingly sharp pencil beams: 9cm (9′), 4.5cm (4.2′), and 2.8cm (2.7′). When commissioned, this is the third-largest fully steerable telescope in the world, after Jodrell Bank and Parkes. Receivers may be mounted at both the prime focus and Gregorian focus.

Michael J. Kesteven arrived from Sydney, Australia, in 1968, with expertise in decimetre-wave observations of supernova remnants and in aperture synthesis. Wai-Yin Chau—a second theoretical astrophysicist—joined in 1969, bringing knowledge of general relativity and neutron stars.

Through the interval 1957–1972, postdoctoral fellows also joined the group and raised its activity level for various periods of time. These included Carson Stewart, Arthur E. Niell, Paul A. Feldman, Henry M. Bradford, Melvin R. Viner, and Andrew W. Woodsworth. These also augmented the audience at the literature review sessions, adding to the trepidation of the student presenters.

Second Major Change: Algonquin Radio Observatory

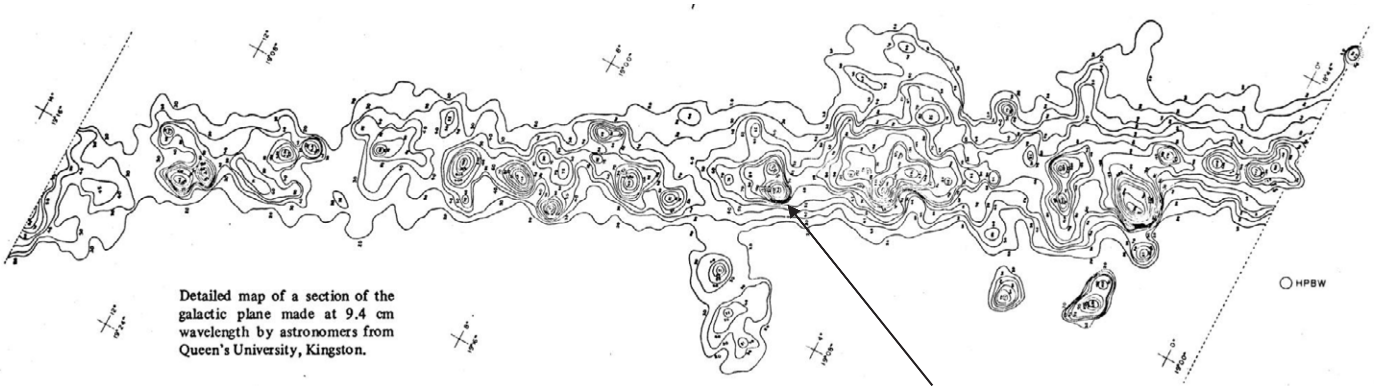
In 1966, 230 km north of Kingston at a radio-quiet site on Lake Traverse in Algonquin Park—henceforth known as Algonquin Radio Observatory (ARO)—a magnificent radio telescope saw first light. (See Figure 12.)

This 46-m telescope would be maintained by NRC electronics technicians and engineers. Observers would not be required to bring a pair of pliers or soldering iron near it. Designed by world-calibre radio engineers including NRC's own radio astronomers, it was intended for their use plus that of university astronomers and their students.

The effect on Hughes's radio astronomy group at Queen's was profound. As Table I shows, activity at QRO dwindled as students began choosing thesis projects based on observing programs at ARO, rather than construction projects.

The contrast between QRO and ARO could not have been stronger. QRO was "hands-on," which meant bringing tool boxes and whatever instrumentation might be required. ARO, conversely, was "don't touch." The observer had responsibility for changing paper in the chart recorder, setting the speed of the chart recorder, and setting the receiver-output filter preceding the chart recorder. Scanning or slewing or stowing the telescope remained strictly the domain of the operator, who sat at a control console before a set of digital displays and dials as intimidating to students as those of a nuclear power station.

Servicing the telescope and its receivers, e.g. riding the cherry picker to the prime focus with a dewar of liquid nitrogen, was likewise the domain of NRC technicians. Planning a night's observations, however—including pointing calibra-



NRAO 591 & 3C396 (Fig.14 below)

Figure 13 — Radio emisssion from 15 degrees of the Milky Way in Aquila observed by Routledge in 1968 using the ARO 46-m at 9cm wavelength. The angular resolution (width of the pencil-beam power pattern) is 9′. Knots of closed contours reveal individual sources embedded in the broad-scale emission from the Galaxy's interstellar medium. This image was made by scanning the single beam of the telescope across the survey area like a single-pixel camera, and recording the power received point by point.

tions, focal position calibrations, flux-density calibrations, etc., and of course scan positions, directions, and speeds—was the responsibility of the student. If a calibration source set before the telescope could slew to it, he had his own poor planning to blame. If atmospheric conditions deteriorated and he had not prepared fall-back observations at a longer wavelength, likewise. Luckily, NRC astronomers (Bryan Andrew, Norman Broten, Carman Costain, Lloyd Higgs, Tom Legg, John MacLeod, Wilfred Medd, and Christopher Purton) were establishing effective calibration and correction procedures (e.g. focal-position adjustment with zenith angle) and observing strategies, and Queen's students benefitted immediately from these.

Built on an alt-azimuth mount, the telescope converted to and from equatorial coordinates for the digital control console, but without using a digital computer. An analog device—an equatorial telescope—emitted a beam of light tracked by photoelectric sensors attached to the rear surface of the 46-m reflector. With arcsecond accuracy, analog feedback control systems and powerful motors drove the 800-tonne telescope to the right ascension and declination requested by the operator and scanned precisely as commanded.

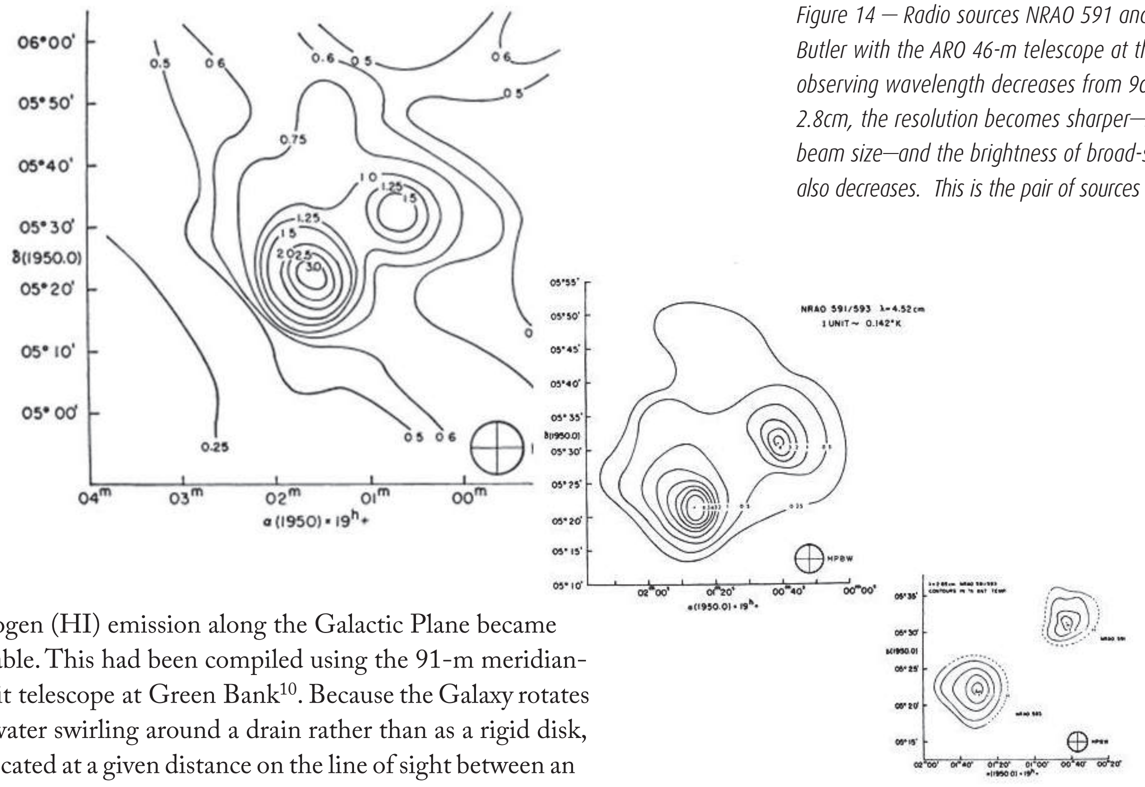
In 1968, tragically, the brilliant career of Robin M. Chisholm of the Electrical Engineering Department was cut short when he passed away in October. This occurred after the Canadian effort to achieve the world's first VLBI, of which he had been part, had succeeded. Fringes had first been achieved[9] on quasars at 67cm wavelength between the new ARO 46-m and the DRAO 26-m in May of 1967. Chisholm and the Electrical Engineering radio astronomy group had cooperated closely with the Physics radio astronomy group since Chisholm's arrival at Queen's, and his loss was felt deeply by both groups.

Examples of results from ARO that began appearing in student theses and in international journals are shown in Figures 13 and 14. The contours are drawn by hand.

At centimetre wavelengths, the radiation from the Milky Way and individual sources within its interstellar medium consists of a blend of "thermal" emission from ionized gas, and "nonthermal" synchrotron emission. Observations with the ARO 46-m at multiple wavelengths immediately began separating sources from the background, and thermal emission from nonthermal. The ionized gas is generally optically thin (translucent) but in spots may be optically thick (opaque). From their radio spectra, some sources were deduced to be HII regions like M8 (the Lagoon Nebula), consisting of gas ionized by young stars within them. Others were found to be synchrotron emitters, often supernova remnants like Cas A or M1.

A major problem in radio astronomy had from the beginning been the determination of distances to many radio sources. Fortuitously, however, a partial solution became available at just this time, for objects within our Milky Way Galaxy. As Queen's students began returning from ARO with observations to analyze , a spectral-line survey of λ21cm atomic

Figure 14 — Radio sources NRAO 591 and 3C396 imaged by Butler with the ARO 46-m telescope at three wavelengths. As observing wavelength decreases from 9cm, through 4.5cm, to 2.8cm, the resolution becomes sharper—see circles showing beam size—and the brightness of broad-scale galactic emission also decreases. This is the pair of sources marked in Figure 13.



hydrogen (HI) emission along the Galactic Plane became available. This had been compiled using the 91-m meridian-transit telescope at Green Bank[10]. Because the Galaxy rotates like water swirling around a drain rather than as a rigid disk, HI located at a given distance on the line of sight between an object and the telescope ought to absorb radio power from that object at a calculable line-of-sight velocity. Using the Doppler effect, that could be converted to a redshift or blueshift, and hence a precise wavelength. Conversely, by measuring its line-of-sight velocity, the distance to that concentration of HI could be deduced, giving a minimum distance to the object behind it.

Distance estimates to some brighter sources observed at ARO therefore became possible using the recently published Schmidt model of galactic rotation, the Doppler effect, and trigonometry. With plausible distances, furthermore, suddenly the physical phenomena occurring within radio sources also became accessible.

An example of a pair of sources positioned—was it by chance, or because of physical proximity?—on nearly the same line of sight is shown in Figure 14. The HI "absorption profile" toward 3C396 (the stronger, south following source) showed that it lies a huge distance from the Sun—certainly no closer than 7,800 parsecs. (The weaker source, HII region NRAO 591, was later shown to be at least as distant, likely 14,000 pc from the Sun[11].)

Observations in the new radio window were therefore opening new possibilities in Galactic astronomy. The region shown in Figures 13 and 14, after all, lay within the Serpens-Aquila Rift, an area of sky notorious for high visual extinction. Even in the red, optical dimming in the direction of 3C396 exceeds 25 magnitudes[12]. Yet observations and calculations by Queen's students were not only revealing the existence of unseen objects lying beyond much of that absorbing material but allowing some of their physical parameters to be deduced—e.g. for HII regions their ionization density, emission measure, and mass, as well as estimates of their exciting stars.

Last Work at QRO

In Table I, the transition in 1964–1965 from Harrower's thesis supervision to Hughes's supervision is sharp, whereas the migration from QRO to ARO is more gradual. Students of Hughes (VAH) and Bridle (AHB) carried out their research observations primarily at ARO, not QRO. The likelihood of a student's thesis work being publishable in scientific journals had become much higher using NRC's world-class 46-metre telescope than battling the unrelenting forces of weather and deterioration at QRO to perfect build-it-yourself apparatus in hopes of obtaining the same quality of data.

In Table I, hands-on projects undertaken at QRO are shown in bold font. After Harrower's last thesis students graduate in 1965, such entries become sparse. Thesis research in the radio astronomy group has switched to ARO.

The last thesis written on work at QRO, on observations with the 18-m steerable paraboloid (Figure 10), was by Retallack, in 1972.

Thus ended an era.

Conclusion

The authors were students in the Queen's University Physics Department's radio astronomy group during the decade and a half discussed here. We feel privileged and grateful to have had the chance to take part in the expansion of astronomy into the radio portion of the electromagnetic spectrum—an event that will occur only once in the advance of science—and to help catch the tide of discovery this would yield. ✶

Acknowledgements

We thank our fellow students in the Physics radio astronomy group—Henry Bradford, Philip Gregory, Helmut Hesse, David Hogg, Philipp Kronberg, and Aage Sandqvist—for permission to quote from their theses. Alan Bridle very kindly commented on the text, adding useful information. We also gratefully acknowledge the efficient and indispensible help of the Queen's University archivist, Paul Banfield, and his staff.

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New Horizons

Rick Stankiewicz, New Years Day, 2019

An old year ends with missions
complete,

We all look forward to new horizons.

New Year, new beginnings,
new threats to defeat,

We all look forward to new horizons.

New perspectives, new knowledge,
new missions conceived,

We all look forward to new horizons.

New dreams, new hopes, new views of
our world perceived,

We all look forward to new horizons.

New strength, new courage, new hope
not lost,

We all look forward to new horizons.

New discoveries, new challenges, new
success at all cost,

We all look forward to new horizons.

New visions, new futures, new goals
replete,

We all look forward to new horizons.

A new year starts with missions to
complete,

We all look forward to New Horizons.

NASA/JHUAPL/SWRI