

antennas and is called "supersynthesis."

The need for higher resolution has been long-standing in radio-astronomy instrument development. This led, in the 1950's and early 1960's, to the development and use of radio interferometers in Australia, the UK and the US. These instruments were useful, but they produced high sidelobe levels or fan beams that limited resolution. In the mid-1960's supersynthesis was used in the construction of radio telescopes at Cambridge, UK and the National Radio Astronomy Observatory that could chart radio sources with moderate angular resolution. These second-generation instruments were still hampered by a lack of speed and low sensitivity. At this time, the general concept of a very large array of antennas that could provide radio pictures of high resolution, sensitivity and speed began developing.

The design of the VLA is the result of a study completed at the NRAO. A map or image of a radio source made with the VLA will consist of over 10 000 picture elements with a resolution of one second of arc at 2695 MHz and 0.35 seconds of arc at 8085 MHz, two frequencies at which the radio telescope may operate.

The array is of particular interest to researchers because it will maintain a circular beam over most of the observable sky, including the region of the celestial equator, where most other arrays have resolution in only one dimension. Furthermore, the sidelobe

levels are low (only about 3%) permitting the study of complex sources, or of sources superimposed on a complex background.

Applications. Radio astronomers hope that the VLA will enable them to unravel some of the puzzling phenomena associated with radio galaxies and quasars. The quality of radio pictures that would be available permits closer study of the physical processes and laws relating to gravity, magnetic fields and plasmas. Extragalactic sources may be used as radio beacons on which cosmological studies could be based.

The VLA should also make it possible to measure the radio emission from novae and stars in the process of formation, providing clues to their structure and evolution.

Use of the array will be open to the scientific community with a minimum of 60% of the observing time allocated to researchers from institutions other than NRAO. A permanent staff of engineers and technicians will remain at the site to operate and maintain the array.

There were many constraints in choosing the site for the array. These include a large flat area, away from the radio interference of populated areas, a site high enough to minimize the effects of atmospheric water vapor and as far south as possible in the US (to achieve maximum sky coverage). The array is expected to go into partial operation in 1976 and to be completed by 1982.

To determine $\langle i^2 \rangle$ you measure the mean square output voltage together with an input-output calibration. The quantity L is more difficult to measure but is not necessary if a one-point calibration is allowed.

Wheatley's group is making different kinds of instruments with the system, and he feels that they will be useful for studying fluctuation phenomena in general, and for applications in chemistry and biology.

The system might turn out to be quite a good thermometer in the intermediate temperature range, say up to 20 K, Wheatley feels, but its greatest importance is at very low temperatures. "It gives us the possibility of measuring temperature where before we didn't really have an easy means to do it." A more fundamental method is to determine temperature using the formula $T \Delta S = \Delta U + W$, an approach used by William Giauque (University of California at Berkeley). Wheatley noted that this kind of thermometry requires tremendously careful, precise measurements. Another technique is nuclear magnetization (nuclear Curie law), but Wheatley believes that it has limited practicality for measuring helium at very low temperatures because of the thermal resistance between the nuclei and whatever you are trying to measure. He says that the noise thermometer may have a more rapid response time and be more reliable than the nuclear Curie law technique.

One point about the device is "kind of cute and interesting," Wheatley noted. The energy in the fluctuations is the same as the energy there would be in one of the degrees of freedom of a single gas atom at millidegree temperature—namely 10^{-25} joule at 10 millideg. Typical time constants are 1 sec, so that energy is exchanged with the lattice at a rate of 10^{-25} watts.

Kamper and his collaborators use as a resistor a small piece of silicon bronze—about 10 microohms. The resistor is connected in parallel with a Josephson junction in a circuit of very low inductance. If you pass a direct current through this shunt it biases the Josephson junction to about 10 picovolts. Then the current through the junction

Noise thermometers in millidegree range

John Wheatley is known for his work at very low temperatures. When we recently visited his laboratory deep underground in Urey Hall at the University of California in La Jolla, Wheatley told us that he is excited about a noise thermometer¹ that has its instrumental noise limit in the microdegree region. In work with Richard Webb and Robin Gifford this thermometer has measured 5 millideg K.

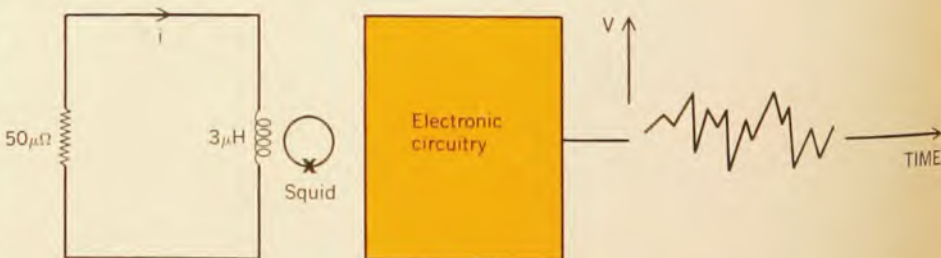
The La Jolla noise thermometer resembles a device built by Robert Kamper, James Zimmerman and their collaborators² at the National Bureau of Standards in Boulder, Colo. Both groups look at Johnson noise from resistors or resistive circuits and employ a Josephson device as a transducer. The inherent low-temperature limit is similar for both devices.

In the La Jolla device a small piece of Be-Cu (50-microhm resistance) is connected by superconducting wire to a 3-microhenry inductance. That inductance is coupled with a Squid, which is coupled to electronic circuitry. This "black box" enables you to sense minute

fractions of a flux quantum. Because of feedback, the output of the device is an exact mirror of what happens at the input; so the output voltage reflects the random current in the input circuit. The source of the random currents is completely analogous to the random motion of an ideal-gas atom; it is Johnson noise.

To measure temperature one uses the relation

$$\langle \frac{1}{2} (Li^2) \rangle = \frac{1}{2} (kT)$$



Noise thermometer used by John Wheatley and his collaborators. The "black box" can sense minute fractions of a flux quantum. The source of the random currents is completely analogous to the random motion of an ideal-gas atom; it is Johnson noise.

oscillates at about 5 kHz. Johnson noise on the resistor causes the voltage, and consequently the frequency, to fluctuate. You can relate fluctuations in frequency directly to the absolute temperature of the resistor. In fact, if you use a frequency counter, with gate time τ , the variance σ^2 of the fluctuations in the measured frequency is related to the absolute temperature T by

$$\sigma^2 = 2kTR/\tau\phi_0^2$$

where ϕ_0 is the magnetic flux quantum and R may be measured by noting the bias current and the average frequency of oscillation of the Josephson junction.

Recently Robert Soulen and Harvey Marshak (NBS, Washington) have compared Kamper's noise thermometer with other standard reference thermometers—by measuring the magnetic susceptibility of cerium magnesium nitrate, and by measuring the anisotropy of gamma rays coming from radioactive nuclei. These measurements show that the noise thermometer has an error of less than ± 1.0 mK for a temperature of 20.0 mK. To achieve this precision at lower temperature, measurements take many minutes, a time which Kamper feels is about as long as is practicable.

Kamper's thermometer has the re-

sistor connected directly to the junction, whereas Wheatley's is coupled by a superconducting transformer. This gives Wheatley the ability to get a bigger signal and to adjust the bandwidth. The statistical rms fractional error in measuring temperature is inversely proportional to the square root of the product of the time you're willing to spend and the bandwidth of the system. Because Wheatley's bandwidth is adjustable (Kamper's is not), he can achieve greater precision. On the other hand, Kamper points out, Wheatley has a calibration problem because he must determine the coupling ratio of the transformer and the bandwidth to specify the temperature. Kamper feels his approach is simpler and more direct.

—GBL

References

1. R. P. Gifford, R. A. Webb, J. C. Wheatley, *J. Low Temp Phys.* 6, 533 (1972).
2. R. A. Kamper in *Symposium on the Physics of Superconducting Devices*, Charlottesville, Va., Office of Naval Research, 1967, page M1; R. A. Kamper, J. E. Zimmerman, *J. Appl. Phys.* 42, 132 (1971); R. A. Kamper, J. D. Siegwarth, R. Radebaugh, J. E. Zimmerman, *Proc. IEEE* 59, 1368 (1971); *PHYSICS TODAY*, August 1971, page 36.

Liquid-xenon proportional counter

Luis Alvarez and his collaborators¹ at Berkeley have built a proportional counter filled with liquid xenon. When we recently discussed the new counter (while flying over the Bay Area in Alvarez's twin-engine Cessna), he told us that the new counter will be useful for cosmic-ray satellite experiments, for ground-based high-energy particle detection and as a medical gamma-ray camera.

The counter works just like any other proportional counter—the ionizing radiation impinges on the filling material, which is normally a gas, but in the Berkeley device is liquid xenon. Because the xenon is liquid its higher density permits the improvement of spatial resolution by a factor of maybe 100 over that of a gas, Alvarez said. At the present time a spatial resolution better than 10 microns has been observed, and that value is limited by the width of the "signal generator." An advantage over solid-state counters is that because there are no grain boundaries in the liquid xenon, you can make as large a volume of liquid xenon as your pocketbook will stand, he went on. Typical condensed counters of germanium or silicon are limited by the size of the furnaces that do the purification, typically 2–3 inches.

The other very high-class, large-volume condensed-state counting material

with good gamma-ray detection properties is cesium iodide, and Alvarez says that the liquid xenon is considerably cheaper in the sizes they want.

The Berkeley group has planned to use spark chambers in a cosmic-ray experiment on HEAO (High-Energy Astronomical Observatory)-B, scheduled for launch about 1976. One of the reasons for studying liquid xenon was to improve upon the spatial resolution of the spark chambers (about a fifth of a millimeter). The experiment is primarily designed to measure the very-high-momentum electrons and positrons in cosmic rays to look for evidence of the inverse Compton effect on the 3-K blackbody radiation. The electrons can be identified, but the positrons have to be distinguished from protons. To do that, the experimenters use the fact that positrons make showers in cesium iodide with a much shorter build-up distance than protons. You measure the particle's energy in a magnetic field (produced by a superconducting magnet) and you remeasure it in cesium iodide; if the two numbers agree there's a good chance that the particle is a positron. Now Alvarez feels that the liquid xenon is also a promising substitute for the cesium iodide. He would need 10–20 gallons of it to operate a total absorption shower counter.

Alvarez says that many people think of liquid xenon as being too expensive compared with most materials—it's about a dollar per gram, the same as gold. But this cost is less than that of putting the satellite in orbit in the first place, he points out.

Because the liquid-xenon detector can be used as a high spatial-resolution substitute for a spark chamber, it should be quite effective at the energies at which the Batavia accelerator will be running. This ability to detect and measure very small magnetic deflections should lead to great savings in the cost of bending magnets. In such an application, you would use a thickness of only a few thousandths of an inch over a square meter.

In the early development of the liquid-xenon counter the Berkeley group was troubled with some unknown impurities that had an enormous appetite for electrons. To cure the ailment the experimenters use the central wire with potentials reversed as a very copious supply of electrons (produced by field emission from the very thin wire). These electrons are drawn over to the outside cylinder, which is normally a cathode, but in the clean-up mode acts as an anode. The impurities capture the electrons and are then swept out towards the wall by the electric field. Then the potentials are reversed back to normal counter operations. The ionization electrons can then multiply in the intense electric field, producing an avalanche. The clean-up is so effective that no impurities are normally seen for several hours. An unexpected bonus is that the energy resolution of a liquid-xenon counter in the gamma-ray detecting mode is now better than that of a sodium-iodide crystal.

—GBL

Reference

1. Richard A. Muller, Stephen E. Derenzo, Gerald Smadja, Dennis B. Smith, Robert G. Smits, Haim Zaklad, Luis W. Alvarez, *Phys. Rev. Lett.* 27, 532 (1971).

Batavia accelerator

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and the first 200-MeV beam was achieved two years later. The 7-GeV booster became fully operational in May 1971. On 1 July a 7-GeV beam was injected from the booster into the main ring and made to execute one full turn; by early August the beam was able to execute 10 000 revolutions.

Despite these early achievements it became apparent during the second half of 1971 that many modifications and improvements were needed in the main ring and that even minor changes to