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Abstract

The status of development and characterization tests of integrated infrared detector array technology for astronomical applications is described. The devices under development include intrinsic, extrinsic silicon, and extrinsic germanium detectors, with hybrid silicon multiplexers. Laboratory test results and successful astronomical imagery have established the usefulness of integrated arrays in low-background astronomical applications.

Introduction

To advance the capabilities of integrated infrared (IR) detector arrays for low-background astronomical research from space, a technology development program is underway at Ames Research Center. Integrated IR arrays are expected to be a central feature of the focal plane instrumentation in the Space Infrared Telescope Facility (SIRTF)[1,2] and in the Large Deployable Reflector.[3] SIRTF (Fig. 1) is planned to be a 0.8-m-aperture long-duration observatory, with internal optics and instruments cooled to liquid helium temperature. For most of its 1.8 - 700 μm range, and throughout most of its life on-orbit, SIRTF will provide the potential for making extremely sensitive measurements, with limits imposed only by natural astrophysical backgrounds. Our objective is to provide a technological base from which a number of IR array-based instrument concepts can be drawn for both near-term and future applications. Three SIRTF instrument concepts are presently under definition study.[2] In both the Infrared Array Camera[4] and the Infrared Spectrograph,[5] integrated arrays have been proposed. (In the Multiband Imaging Photometer for SIRTF,[6] smaller arrays of optimized detectors with multiplexed JFET readouts were proposed.) The demonstrated high sensitivity and excellent imaging characteristics of these arrays make them highly attractive for use in a number of future astronomical cameras, spectrometers, and polarimeters.

Among the critical performance parameters for low-background applications are sensitivity (in terms of noise and responsivity), dark current, the effects of energetic particle events, uniformity and linearity, and overall imaging characteristics. For SIRTF, the requirement is for optimum performance at very low backgrounds, extended wavelength coverage, and extended integration times. In this technology development program, devices are obtained through industrial or academic sources, and testing and characterization of these critical parameters are performed either at Ames or in outside laboratories.

This paper describes the status of the various elements of the program, taken in order of increasing wavelength. Summary comments are also included to indicate expected future trends in technology developments for the low-background space astronomy application.

Program Status

32 x 32 CCD and 58 x 62 DRO InSb arrays

A very productive research program to study and utilize integrated InSb arrays has been underway at the University of Rochester. A 32 x 32-element charge-coupled device (CCD) array from Santa Barbara Research Center (SBRC) has been evaluated in the laboratory and incorporated into an astronomical instrument for ground-based observing. Laboratory data include values of dark current down to 0.1 fA, or 1000 e$^-$/s (cf. Fig. 2), and a quantum efficiency of about 60%.[7] This instrument has been used in a number of investigations and has produced excellent images of outflows near star-forming regions (Fig. 3). Significantly, this array has been proven to have a lower noise equivalent power (NEP) in ground-based observations than the best discrete-detector InSb instrument presently in use. A limiting sensitivity of +20.9 magnitude/pixel (1σ) has been achieved with this array, in a 1 hr integration time at 2.2 μm, with a bandpass of 0.23 μm.[8]

The testing capabilities and software developed for this project are now being modified for a 58 x 62-element direct readout (DRO) InSb array. This device is presently being developed by SBRC. The DRO multiplexer will allow random-access readout and the ability to sample the charge accumulated during an intergration without destroying it (nondestructive read). Figure 4 illustrates the basic DRO circuit and Figure 5 shows the hybrid array assembly. In a DRO, charge produced by either photon absorption or leakage (dark current) is stored on the gate of a low-capacitance (~0.1 pF) MOSFET. In addition to its larger array size, the InSb DRO is expected to have a read noise of <400 e$^-$ (more than 3 times lower than that of the CCD), and allow measurements of InSb dark current at temperatures well below the threshold (~45 K) where the CCD multiplexer freezes out.

Si:Bi CID arrays

Two-dimensional accumulation-mode charge-injection device (CID) arrays from Aerojet ElectroSystems Company, with 16 x 16 and 2 x 64 formats, have been tested in the laboratory at Ames and used in astronomical applications.[9,10] Images in multiple infrared wavelengths have been obtained with a cooled circular variable filter wheel. Although charge-trapping effects limit the attractiveness of CID arrays for low-background astronomy, this system has achieved good sensitivities from the ground and has provided useful image processing information. The 16 x 16 CID array camera and recent results obtained with it are described in detail elsewhere in this volume.[11]

10 x 64 Si:As DRO array

At the University of California Space Sciences Laboratory, DRO arrays from Hughes Aircraft Company (Carlsbad) are under evaluation.[12] The goal of this work is to establish the low-background, low-temperature characteristics of DRO multiplexer and extrinsic silicon detector technology. As of this writing, the experimental apparatus for these measurements is still under development. However, the devices have been used in field tests, and astronomical images have been obtained.[13]

Si:As blocked impurity band arrays

Two projects are now underway to develop and characterize the Rockwell International Science Center Si:As blocked impurity band (BIB) IR detector technology for low-background astronomical applications. This technology offers the promise of superior sensitivity, linearity, and radiation-hardness over conventional bulk extrinsic photoconductors.[14]

Two-dimensional, backside-illuminated BIB arrays, in 10 x 50-element formats, are being designed and fabricated for potential use in SIRTF. These arrays will include switched-FET multiplexers modified to allow non-destructive readout of charge (see Fig. 6). The program will include characterization of presently available detectors and optimization of backside-illuminated BIB arrays specifically for low-background applications. Preliminary test data are quite encouraging. At 4.2 K, integration times of 300 s have been achieved, and an upper limit of 140 e$^-$/s has been established for dark current. After removing synchronous noise pickup from the recorded noise spectrum, a read-noise level of about 200 e$^-$ was estimated.

Tests of dark current of a 10-element front-illuminated Si:As BIB array are also underway. Dark current down to about 7×10^{-16} amp (~4000 e$^-$/s) has been measured with a transimpedance amplifier circuit at 5.2 K. (However, we believe this result is dominated by the instrumentation rather than by the device.) An improved integrating JFET-circuit with capacitive feedback is under development which allows us to resolve leakage currents below 10 e$^-$/s.

Si:As solid state photomultiplier (SSPM) development

A program has recently been initiated at Rockwell International Science Center to invesitigate the applicability of their discrete SSPM devices to astronomical applications. These devices, with their ability to count single-photon events at wavelengths out to about 28 μm, appear to have tremendous potential for use at low backgrounds. The program will analytically and experimentally explore the nature of the dark counts (which would limit sensitivity in a cooled telescope such as SIRTF), and expand the data base for device operation in this regime.

58 x 62 Si:Sb DRO array

To extend the spectral coverage of extrinsic silicon integrated arrays to 30 μm, arrays with Si:Sb detector material hybridized to the CRC 228 DRO multiplexer, have been produced and tested at SBRC. These arrays, with 75 μm pixels, are packaged in leadless carriers (Fig. 5). These arrays are being characterized at Ames using the low-background test dewar (Fig. 7) and electronics and data acquisition system (Fig. 8) described in Reference 15. Preliminary data taken at SBRC indicate that good performance has been achieved.[15] On the first array tested, all but 6 of the 3596 pixels were optically active. Uncertainty in the spectral response of the devices created uncertainty in the calculated responsivity, but values fell in the range 1 - 6 A/W. Upper limits on read noise (<600 e$^-$) and dark current ($<3 \times 10^4$ e$^-$/s) were established at 7 K and 1.5 V bias. Figure 9 shows the NEP histogram for this array, with an average of about 5×10^{-18} W/√Hz. Again, these data are preliminary and were obtained in a nonoptimum test configuration. Recently, the operability of the hybrid array at a device temperature of 4 K has been demonstrated. At this temperature, the signal/noise ratio is only slightly lower than it is at ~7 K.

1 x 8 Ge:Ga array modules

At Aerojet ElectroSystems Company, modules of Ge:Ga detectors with switched-FET readouts have been developed. This project explores the feasibility of adapting low-noise integrated array technology to long-wavelength extrinsic germanium detectors. The approach is to produce 1 x 8-element modules with integral multiplexer/readouts that can be stacked into two-dimensional (e.g. 8 x 8) formats.[16]

Two versions of these modules have been produced. The first includes a readout made of hand-wired discrete transistors; the second utilizes FETs taken from a 16 x 32 integrated-circuit version of the readout. Initial data on the second unit indicate a readout noise of <600 e^-/sample (with 1.8 pF capacitance) and a responsivity of >10 A/W at 0.39 V bias. We plan to characterize the performance of the modules under low-background conditions at Ames in the near future.

Future Directions

While substantial progress has been made in demonstrating the applicability of integrated arrays for space-based IR astronomy, a number of areas require additional development or optimization. For arrays to reach the background-noise limit in a cryogenic telescope such as SIRTF, continued improvements in readout noise and dark current will be required. The question of particle effects on integrated astronomical arrays has not been adequately addressed; one needs to understand the effects of particle hits, to optimize the properties and operating points of devices for this environment, and to develop efficient means of removing (annealing) residual charge deposited by energetic particles. Impurity band conduction arrays, with their inherent radiation-hardness, may provide a means of minimizing these effects. Additional development and demonstrations with arrays are needed to provide better understanding of their imaging properties and flat-fielding or image processing requirements. Furthermore, ultra-low-background test dewars with known radiometric characteristics need to be developed, particularly for applications of arrays in high-resolution (i.e. very low photon arrival rate) instruments in SIRTF.

Summary

A variety of development and test projects are underway to provide a broad technology base for application of integrated infrared arrays in space astronomy. The switched-FET readout offers low read noise, random-access, and nondestructive readout, and represents the most promising multiplexer technology for low-background astronomical arrays. DRO arrays incorporating a number of extrinsic silicon materials (Si:As and Si:Sb under this program, and Si:In and Si:Ga under closely-related SIRTF work), extrinsic germanium (Ge:Ga), and intrinsic detector materials (InSb) are actively being developed and evaluated. Si:As impurity band conduction arrays may provide superior linearity and sensitivity advantages in astronomical applications when compared to conventional bulk photoconductors. Performance parameters of prime interest for space IR astronomy include readout noise, dark current, responsivity, and temporal stability.

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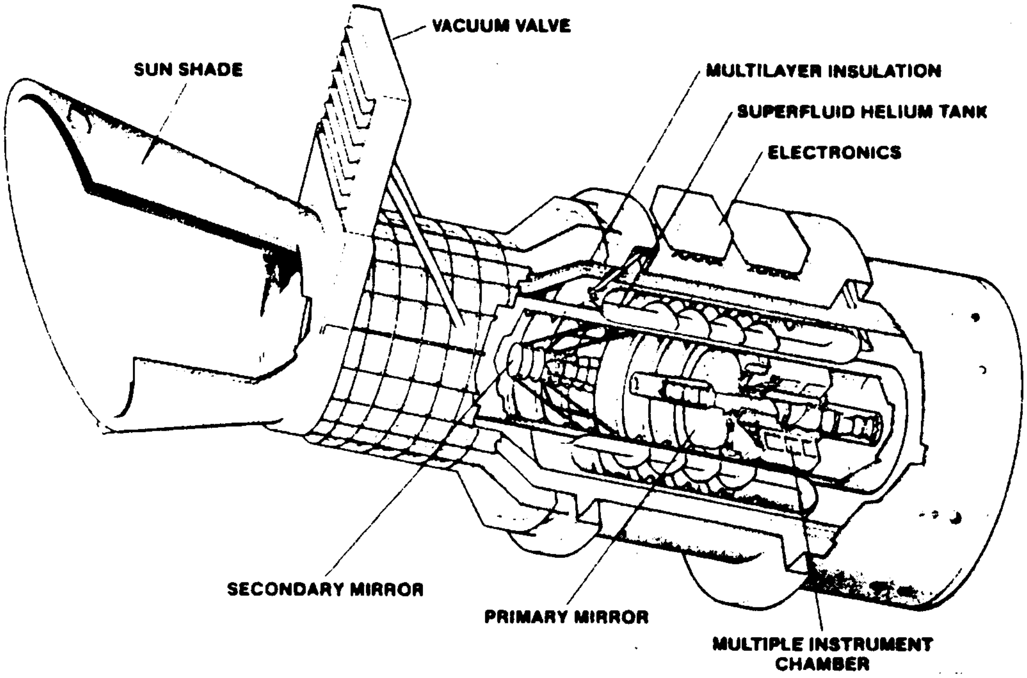

Figure 1. Cutaway view of the Space Infrared Telescope Facility (SIRTF) telescope concept.

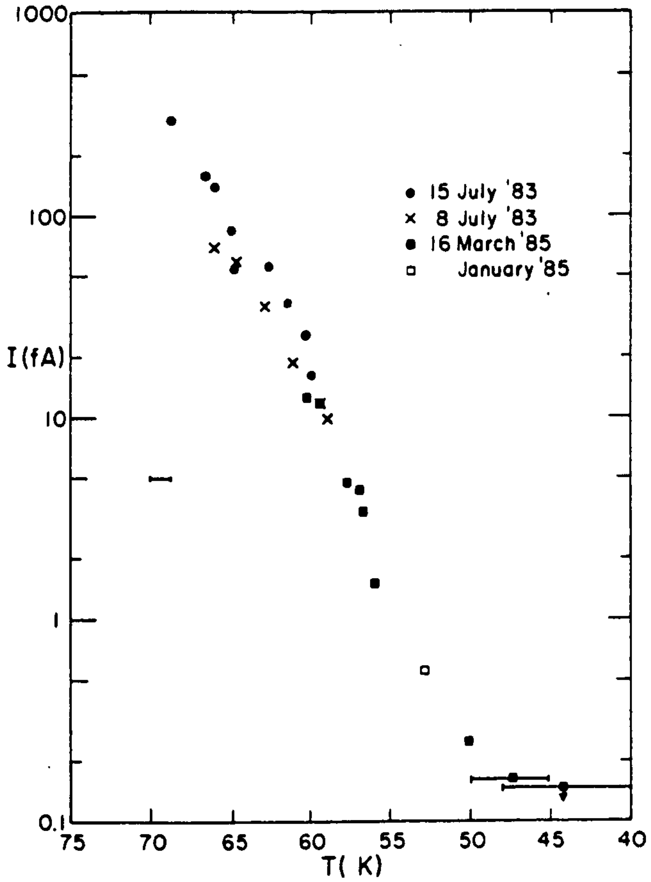

Figure 2. Measured dark current of typical elements in a 32 x 32 InSb CCD array, taken at the University of Rochester. To ensure a good charge injection efficiency, a back-bias of 30 mV was applied.

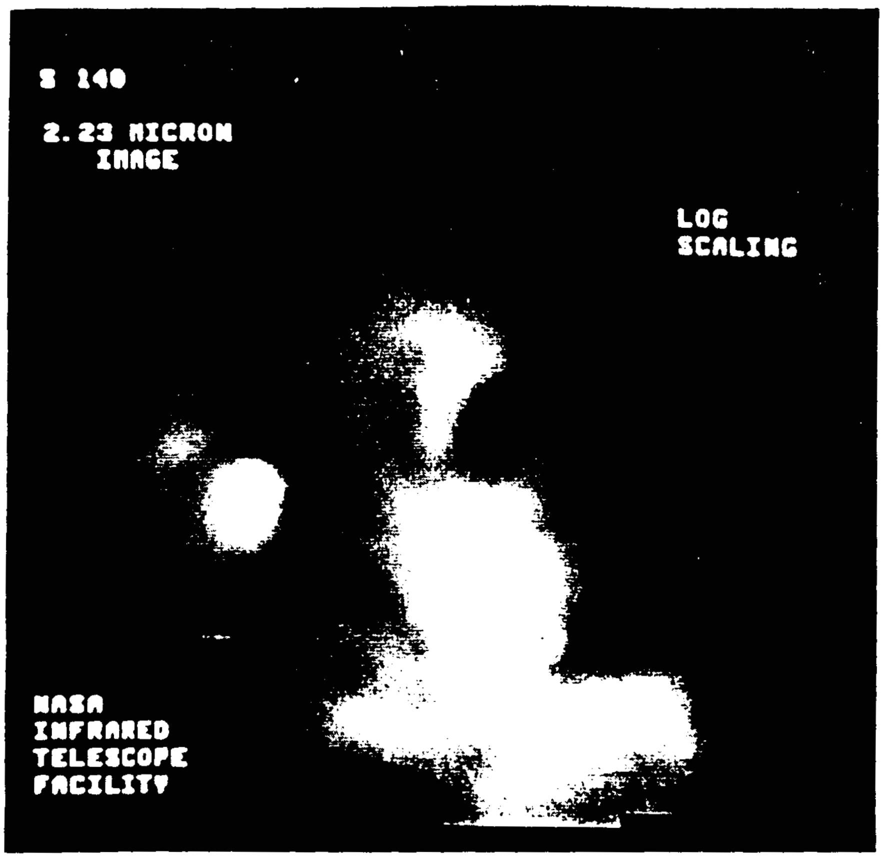

Figure 3. 2.23 μm image of the Sharpless 140 complex taken with the 32 x 32 InSb array in July 1985 at the Infrared Telescope Facility.

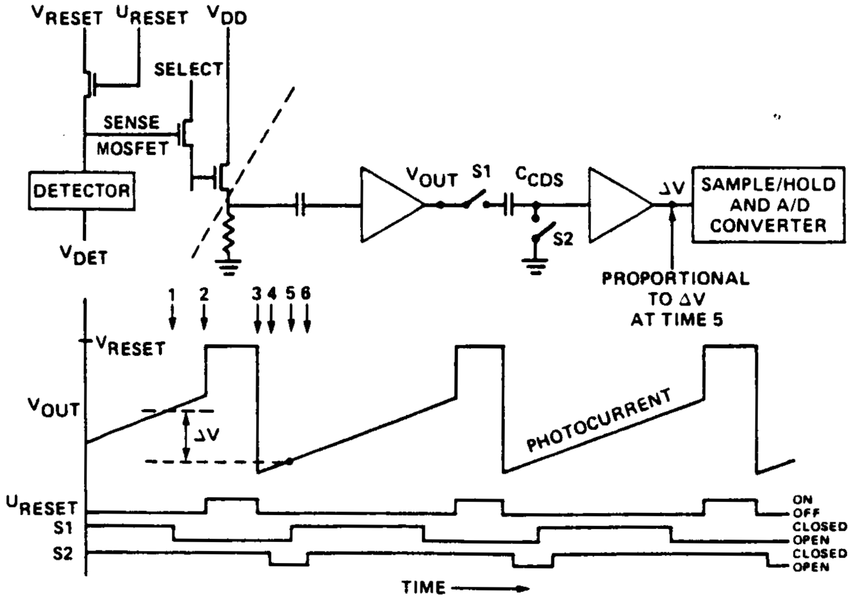

Figure 4. Schematic drawing of direct readout multiplexer and correlated-double-sampling electronics. The "delta-reset" scheme is illustrated, with the signal proportional to the difference between voltage samples 1 and 5.

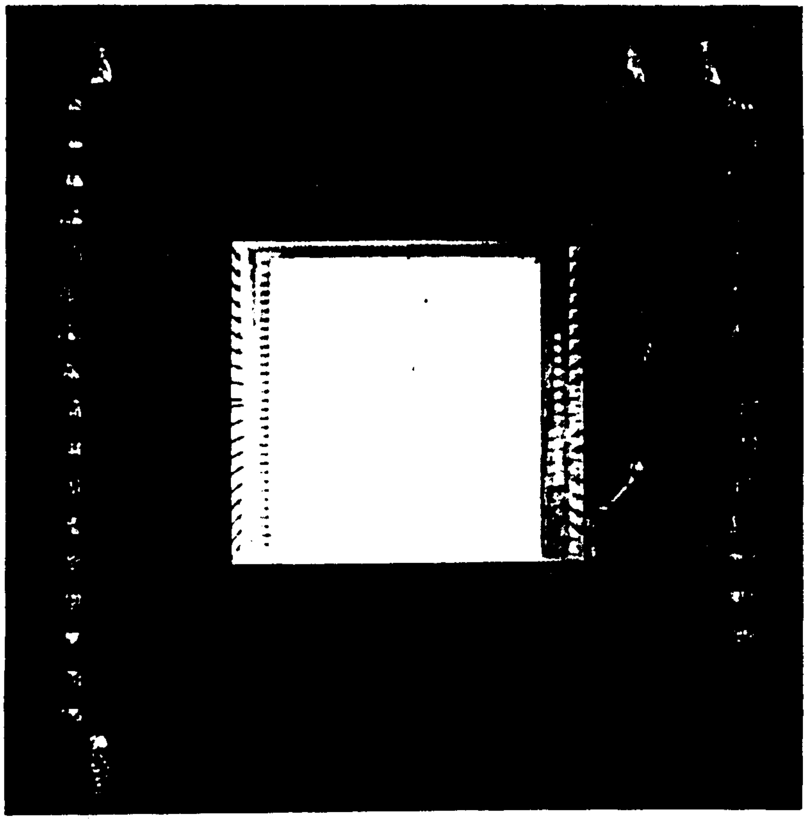

Figure 5. Photograph of InSb DRO array in 68-pin leadless carrier.

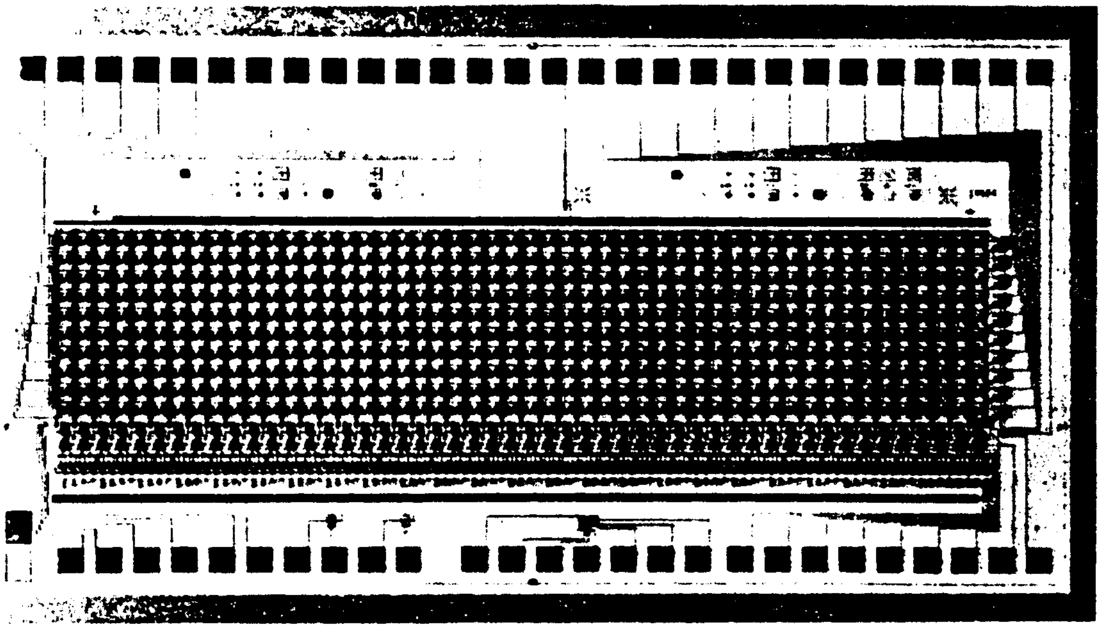

Figure 6. Photograph of 10 x 50-element multiplexer for backside-illuminated Si:As blocked impurity band array.

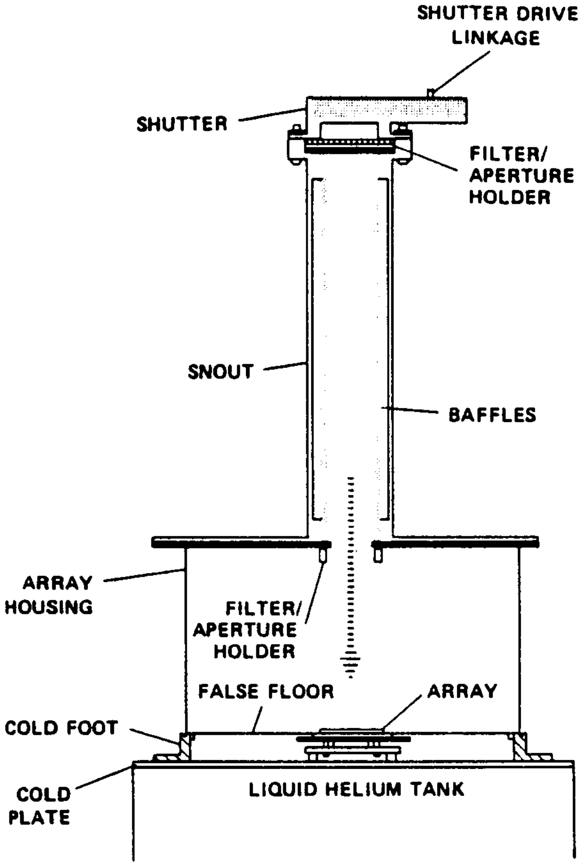

Figure 7. Cross-sectional view of low-background test dewar.

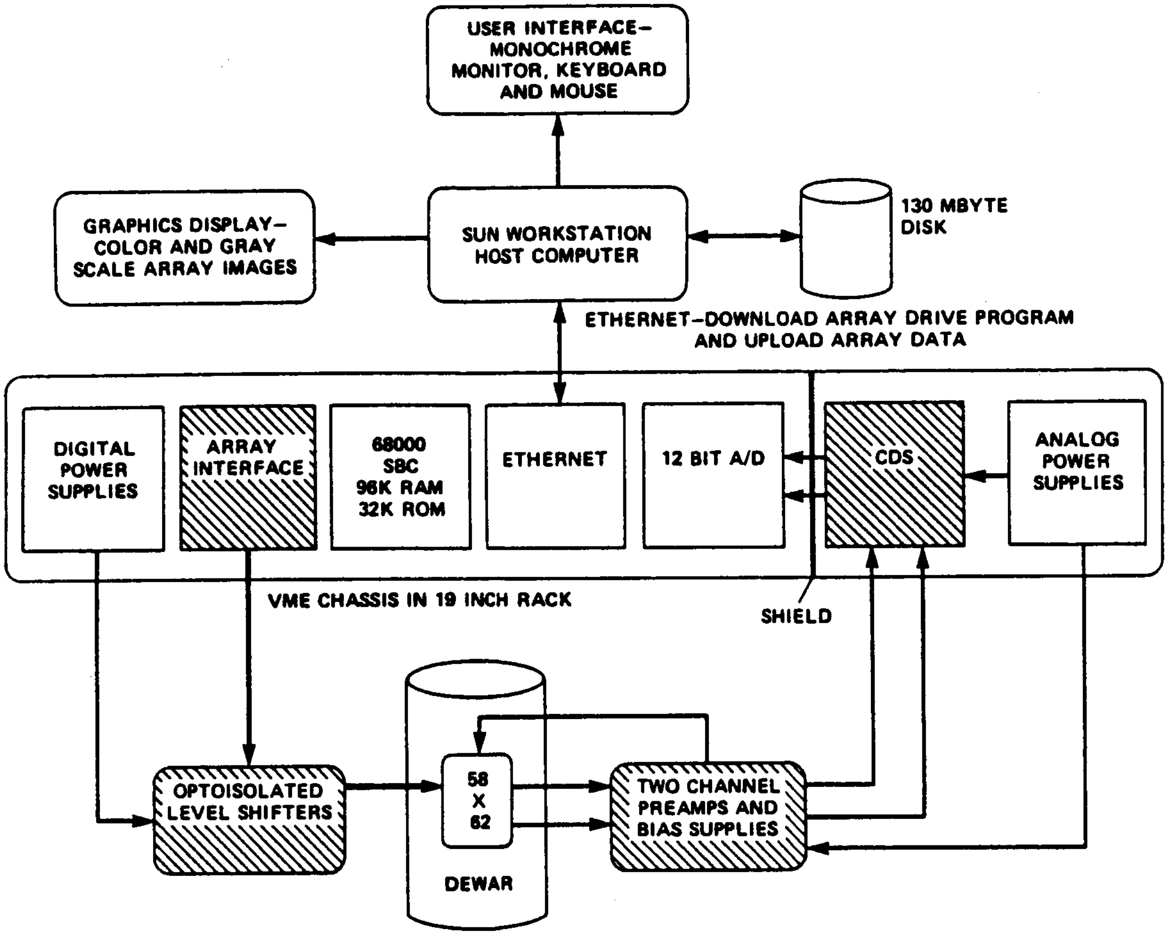

Figure 8. Block diagram of data/electronics system for DRO array.

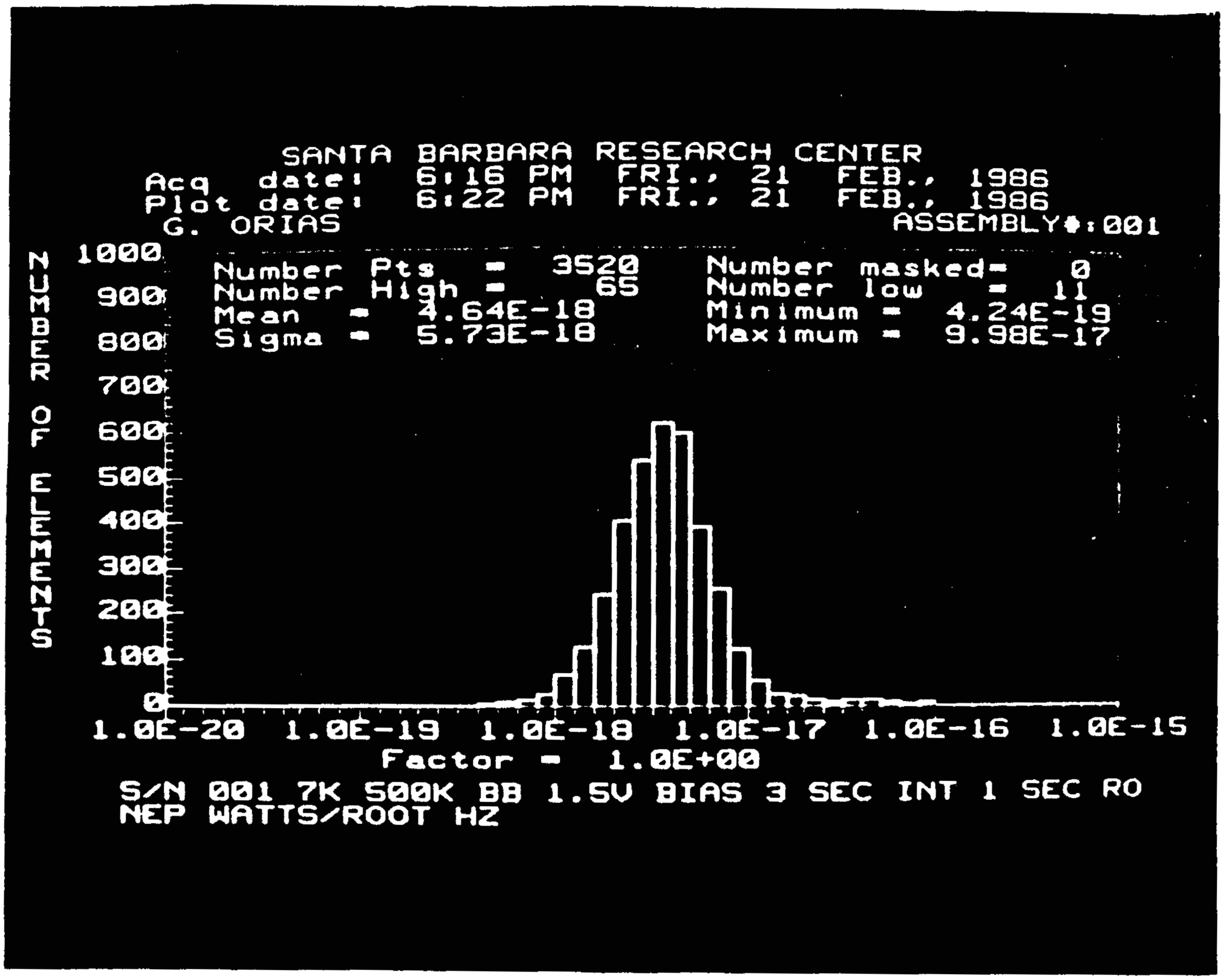

Figure 9. Histogram of noise equivalent power for 58 x 62 Si:Sb DRO array.

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15. Supplementary Notes

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16. Abstract

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