A Ten-Decade Logarithmic Current-to-Voltage Converter

The DN120 logarithmic I/V converter is capable of translating the entire dynamic range of current (10 fA–100 µA) produced by various sensors into a buffered output voltage that can easily be measured and recorded by a data acquisition system.

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Logarithmic current-to-voltage (I/V) converters are called for when current over a large dynamic range is to be measured without the use of gain adjustment. Until recently, converters could operate only over a six-decade dynamic range (1 nA–1 mA) of input current. Sensors such as photodiodes, ionization chambers, and photomultipliers, however, often have current outputs far below 1 nA.

Theory

The DN120 logarithmic I/V converter is capable of measuring current from ±10 fA to ±100 µA. The input stage of this device (see Figure 1, page 52) is a transimpedance amplifier consisting of a pnp and an npn low-leakage silicon transistor and an ultra low current op amp. The output voltage V_A comes from the idealized intrinsic transistor equation for silicon [1]:

$$V_{BE} = \frac{kT}{q} \ln \left[\frac{I_C}{I_S} + 1\right] = -V_A \qquad (1)$$

where:

$I_C = I_{IN}$, if $I_{IN} >> I_B$

V_{BE} = base-to-emitter voltage of conducting transistor

I_C = forward collector current of transistor

I_S = reverse saturation current of transistor

k = Boltzmann's constant (1.38×10^{-23} joules/kelvin)

T = absolute temperature in kelvin

q = unit electron charge (1.6×10^{-19} coulomb)

This equation shows that the conducting transistor's base-to-emitter voltage is proportional to the natural logarithm of the collector current. If the op amp leakage current I_B is small compared to the input current, the amplifier output voltage V_A is proportional to the logarithm of the input current I_{IN}. This fundamental property of a transistor is used in almost all logarithmic I/V converters.

Although it is not apparent from Equation 1, temperature has a strong influence on diode characteristics. The reverse saturation I_S roughly doubles with every 10°C increase in junction temperature [2]. As a result, the temperature coefficient of V_{BE} is approximately −2mV/°C. Conventional logarithmic I/V converters use temperature compensation techniques to reduce this effect, but these devices are generally limited to a six-decade dynamic range.

The DN120 differs from other logarithmic converters in that the diodes are mounted on a thermoelectric cooler stabilized to 23°C (296.2 kelvin) to prevent ambient temperature variations from affecting the diode characteristics. The equation relating the output voltage V_A to the input current I_{IN} for the amplifier in Figure 1 is then:

$$V_A = -25.5 \bullet 10^{-3} \ln \frac{I_{IN}}{I_S} \qquad (2)$$

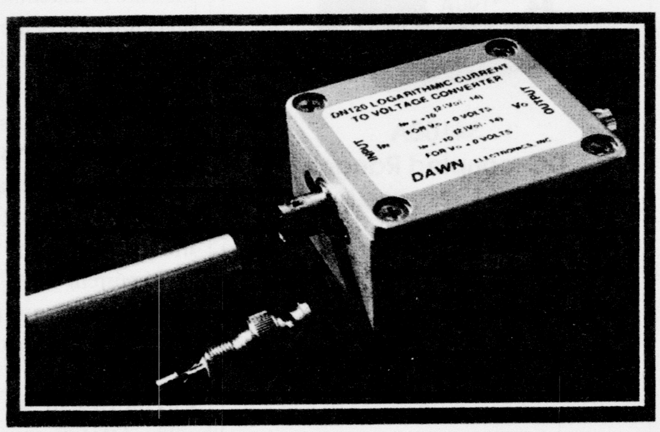

Photo 1. *The current-to-voltage converter's dynamic range was tested on a radiometer. Shown here before final assembly, the equipment consisted in part of the converter, the cylinder (left of the converter) that kept direct sunlight from striking the photodiode, and the photodiode (below the cylinder).*

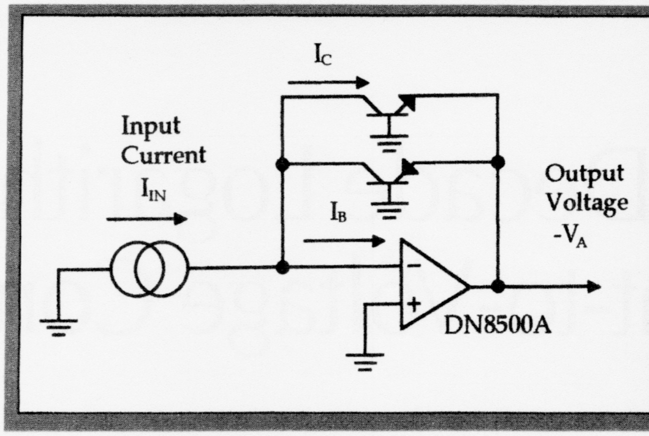

Figure 1. *The transconductance amplifier in the first stage of the DN120 produces an output voltage that is the logarithm of the input current.*

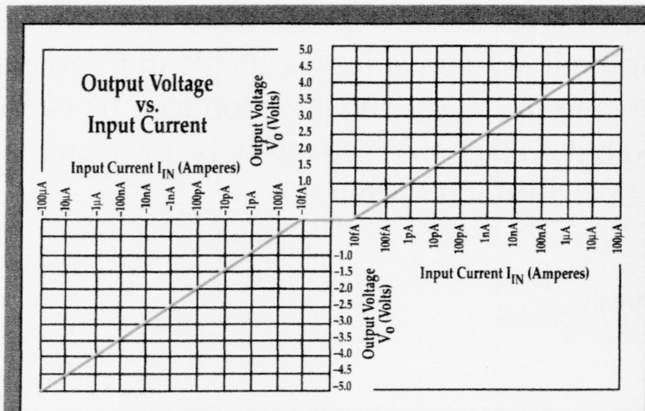

Figure 2. *The output voltage of the DN120 is zero when the input current is greater than –10 fA and less than +10 fA.*

where:

$I_{IN} = I_C$, and

$I_{IN}/I_S >> 1$

And the change in output voltage per decade change in input current is:

$$V_{A2} - V_{A1} = -25.5 \bullet 10^{-3} \ln \frac{I_{IN2}}{I_{IN1}} = -58.8 \text{ mV} \qquad (3)$$

for $I_{IN2} = 10 \bullet I_{IN1}$

The smallest current the converter can measure is determined by the reverse saturation current I_S of the transistors and the input leakage current of the op amp. The reverse saturation current I_S is <0.5 fA at 23°C for the DN120's transistors and the input leakage current of the DN8500A, an ultra low current op amp available from Dawn Electronics, is typically <2 fA. The low reverse saturation current of the transistors and low input current of the op amp enable the converter to measure input current down to 10 fA and to resolve current changes of <1 fA.

Circuit Design

The DN120 was designed to produce an output voltage that increases 0.5 V/decade change of input current, and to deliver ±5.0 V when the input current is ±100 µA (see Figure 2). When the input current is positive, transistor Q1 conducts; when it is negative, Q2 conducts. The output voltage V_A from this stage, which increases 58.8 mV/decade, is fed into two active rectifier circuits that have independent full-scale and gain adjustments for positive and negative input current (see Figure 3, page 53). Recombining these signals produces the output voltage. Equations 4.1 through 4.4 define the converter's I/O characteristics:

Positive Input Current	Negative Input Current
(4.1) $I_{IN} = +10^{(2\lvert V_O\rvert - 14)}$ For 5 V > V_O > 0	(4.3) $I_{IN} = -10^{(2\lvert V_O\rvert - 14)}$ For –5 V < V_O < 0
(4.2) $V_O = +\left[7 + \frac{\log\lvert I_{IN}\rvert}{2}\right]$ For $10^{-4} > I_{IN} > 10^{-14}$A	(4.4) $V_O = -\left[7 + \frac{\log\lvert I_{IN}\rvert}{2}\right]$ For $-10^{-4} < I_{IN} < -10^{-14}$A

Application

A simple radiometer incorporating a 1.2 mm^2 silicon photodiode from Centronic Inc. (Newbury Park, California) was constructed to demonstrate the converter's dynamic range (see Photo 1, page 51). The photodiode was connected to the input of the DN120 as shown in Figure 4 (page 53). Photodiode current I_{IN}, which is directly proportional to the incoming radiation, flows

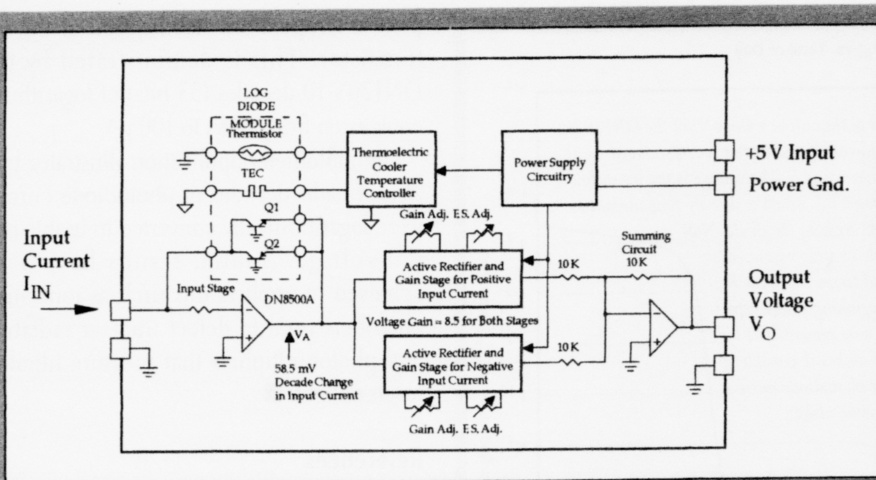

Figure 3. *The two different signal paths for positive and negative input current are necessary to ensure that the output voltage goes to zero when the input current is between –10 fA and +10 fA, and to compensate for slight differences in transistor characteristics.*

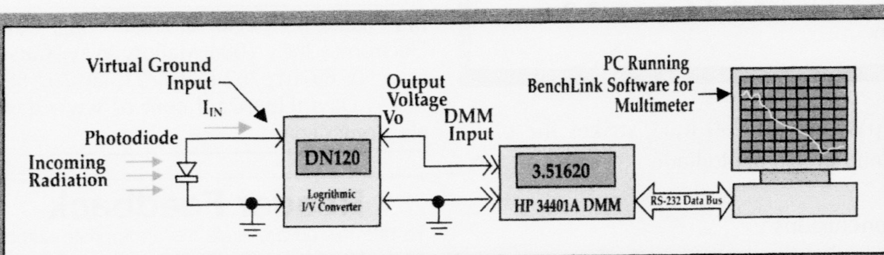

Figure 4. *A data acquisition system was used to measure the logarithm of the photodiode current (light intensity) in the radiometer experiment*

into the converter's virtual ground input. This produces an output voltage V_O that is proportional to the logarithm of the current (Equation 4.2).

The radiometer (see Figure 5) was pointed vertically to measure the intensity of the light radiating from the sky. The photodiode was placed in a tube to prevent direct sunlight from entering the aperture. A data acquisition system incorporating a Hewlett-Packard 34401A DMM and a PC running HP34812A BenchLink software measured and recorded the converter's output from 1:16 p.m. to 10:27 a.m. the following day. This time period exposed the photodiode to the maximum radiation of midday and the minimum radiation of early morning. Measurements were made every 30 s. The recorded data were transferred to a Microsoft Excel file.

Figure 6 (page 54) plots the output voltage V_O as a function of time. This voltage is the logarithm of the photodiode current, which can be calculated using Equation 4.1, and is shown on the right Y axis. Note that the DN120 measured nearly eight decades of photodiode current; the highest light level occurred at the beginning of the test when there were clouds in the radiometer's field of view, and the lowest level in the early morning hours of the experiment. These extremes occurred at 1:34 p.m. and 2:28 a.m. and produced photodiode currents of 7.08 μA and 165 fA respectively. ▶

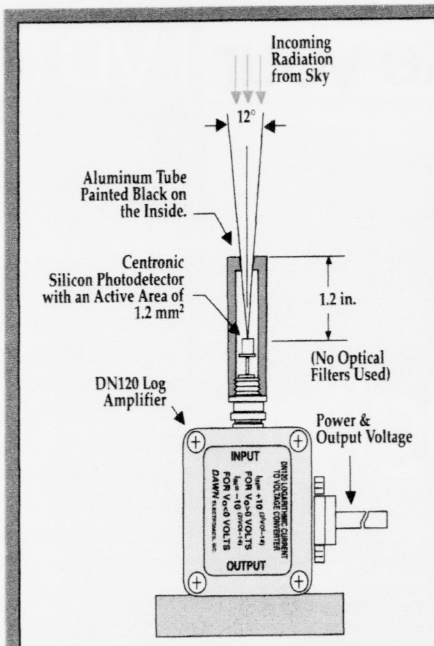

Figure 5. *This simple radiometer, using a silicon photodiode, was constructed to demonstrate the dynamic range of the DN120 logarithmic current-to-voltage converter.*

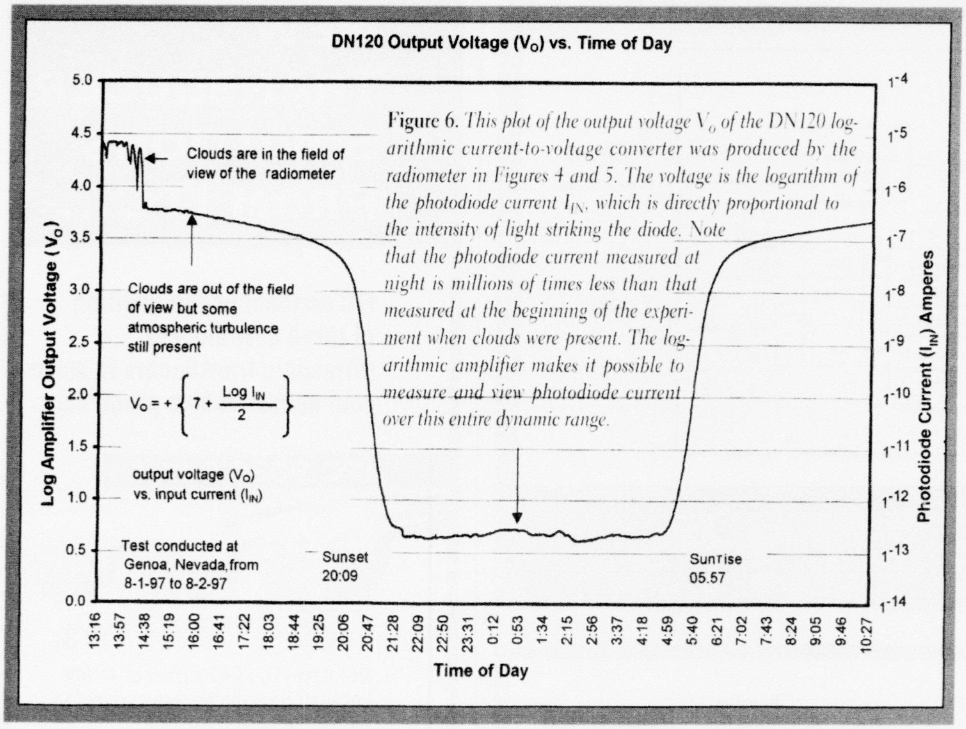

Figure 6. *This plot of the output voltage V_o of the DN120 logarithmic current-to-voltage converter was produced by the radiometer in Figures 4 and 5. The voltage is the logarithm of the photodiode current I_{IN}, which is directly proportional to the intensity of light striking the diode. Note that the photodiode current measured at night is millions of times less than that measured at the beginning of the experiment when clouds were present. The logarithmic amplifier makes it possible to measure and view photodiode current over this entire dynamic range.*

It must be noted that the radiometer was not calibrated to determine a scale factor between the radiant energy striking the photodiode and the resulting photodiode current. It can be estimated, however, that ~6 nA of photodiode current is produced when radiant energy, with flux density of 1 μW/cm^2 (at 900 nm), strikes the Centronic silicon photodiode.

Conclusions

The base-to-emitter vs. collector current relationship of a transistor can be fully exploited in logarithmic I/V converters by precise temperature stabilization of the log transistor. This is demonstrated by the DN120's 10 decades (33 bits) of logarithmic conversion from 10 fA to 100 μA.

The radiometer application illustrates how almost eight decades of photodiode current were logarithmically converted to usable output voltage. Similar results have been achieved in applications such as ionization chambers used to detect nuclear radiation and photomultipliers that measure ultralow levels of light. ■

References

1. *Burr-Brown Linear Products IC Data Book*. 1996/97.
2. *Motorola Silicon Rectifier Data Manual*, Series A. 1980.

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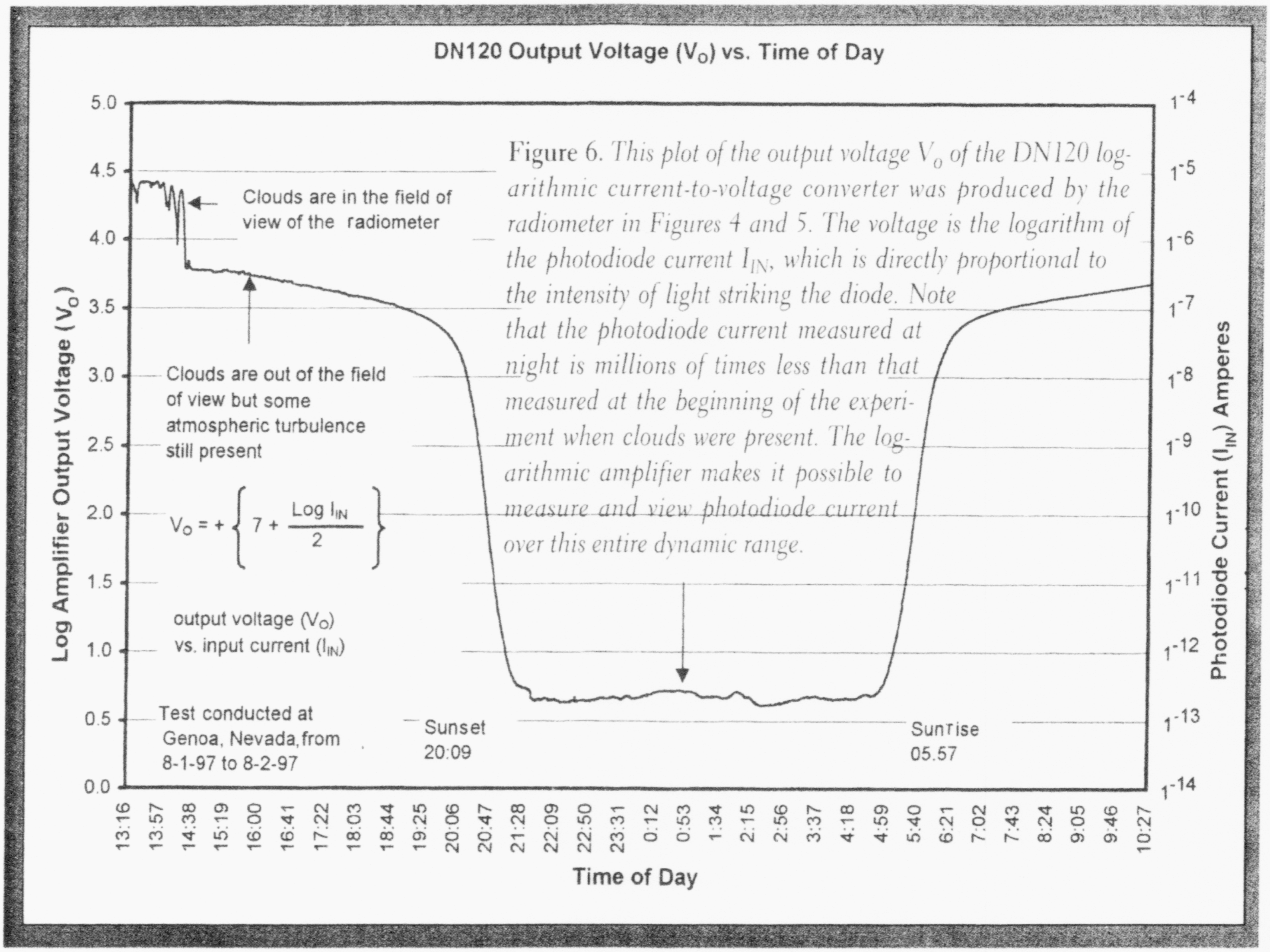

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