Designing a Low-cost LED Sun Photometer

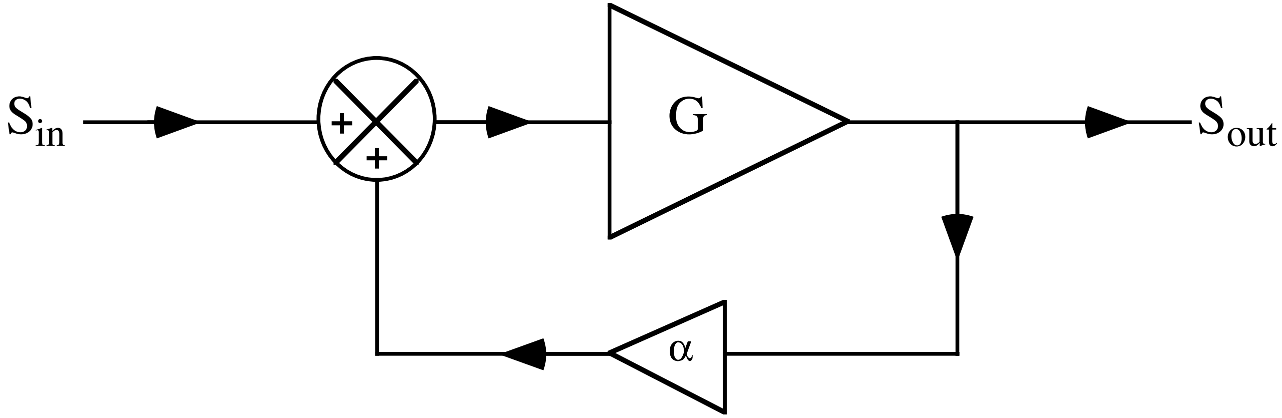
Edoardo Milotti, Department of Physics, University of Trieste

The Abdus Salam International Centre for Theoretical Physics

UNIVERSITÀ DEGLI STUDI DI TRIESTE

A little analog electronics: negative feedback and OP-AMPs

Basic feedback scheme



$$S_{out} = G \cdot \left(S_{in} + \alpha S_{out} \right)$$

$$\Rightarrow \quad S_{out} = \frac{G}{1 - \alpha G} S_{in} \quad \Rightarrow \quad G' = \frac{G}{1 - \alpha G}$$

$$G' = \frac{G}{1 - \alpha G}$$

1. $1-\alpha G > 1$ (i.e., $\alpha G < 0$) then *negative feedback*
2. $1-\alpha G < 1$ (i.e., $\alpha G > 0$) then *positive feedback*
3. $1-\alpha G = 0$ *self oscillation*

Negative feedback enhances stability

$$G = G(p)$$ gain may depend on one or more parameters

but ...

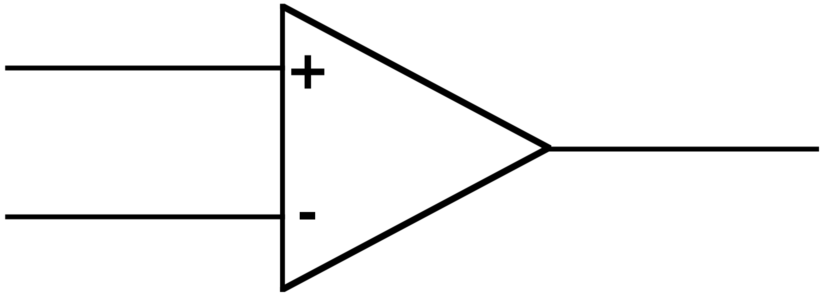
$$\frac{\partial G'}{\partial p} = \frac{\partial}{\partial p}\left(\frac{G}{1-\alpha G}\right) = \frac{\partial G}{\partial p}\cdot\frac{1}{1-\alpha G} + \frac{\partial G}{\partial p}\cdot\frac{\alpha G}{(1-\alpha G)^2} =$$

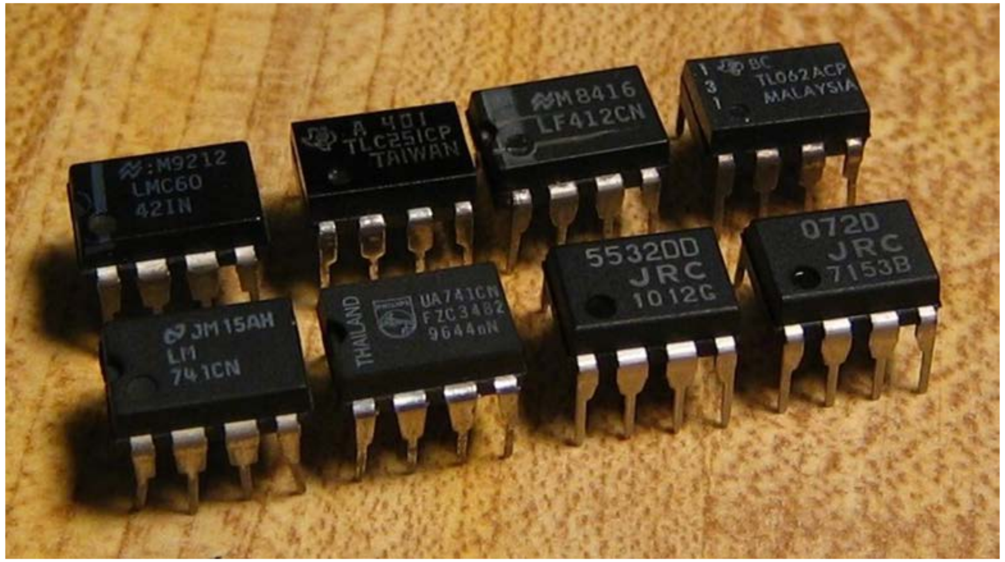
$$= \frac{\partial G}{\partial p}\cdot\frac{1}{(1-\alpha G)^2}$$

$$\Rightarrow \quad \frac{1}{G'}\frac{\partial G'}{\partial p} = \frac{1}{(1-\alpha G)}\left(\frac{1}{G}\frac{\partial G}{\partial p}\right)$$

Negative feedback reduces fractional gain change, i.e., it enhances stability.

Enter the Operational Amplifiers

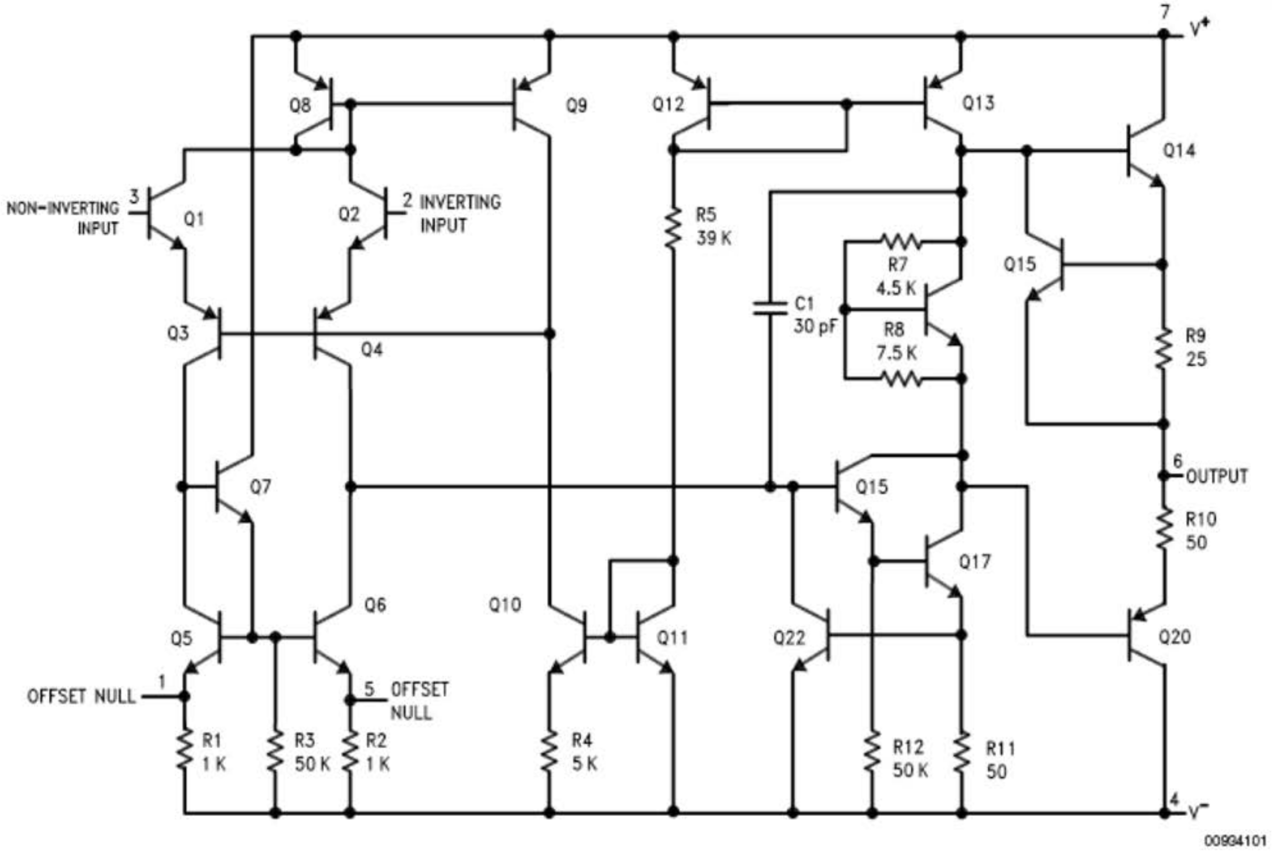


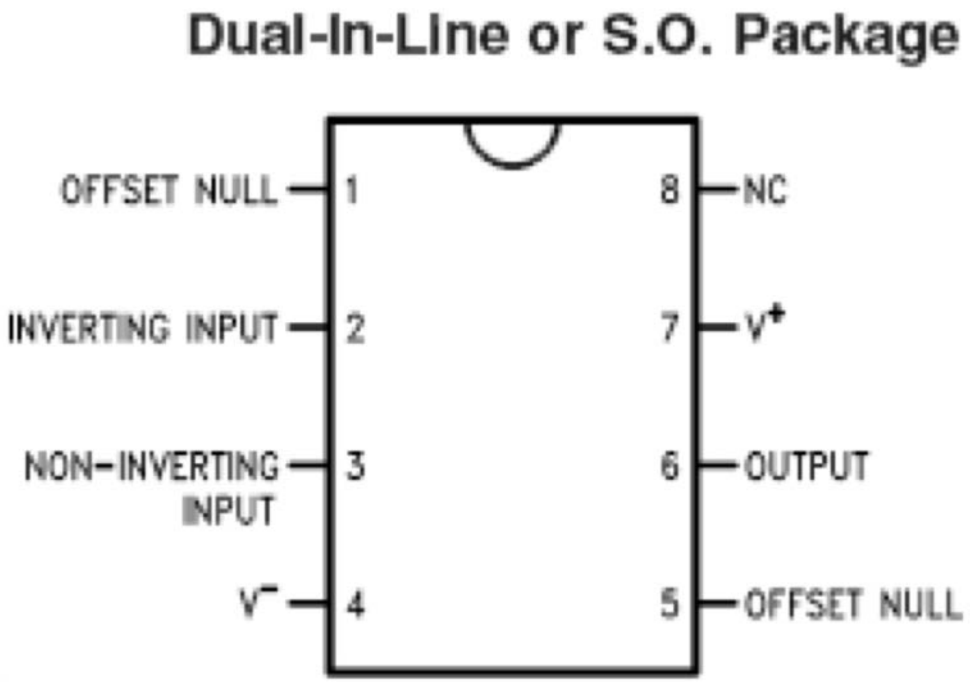


The Operational Amplifiers (OP-AMPs) are differential amplifiers with a huge input impedance (greater than 1 MΩ, often as large as 1 GΩ).

A differential amplifier outputs a voltage that is proportional to the (signed) voltage difference between the inputs.

The first highly-successful OP-AMP : the µA741 (Bob Widlar: 1968)





20 transistors in a small, optimized design, in a simple-to-use packaging

The OP-AMPs are normally used in a negative feedback configuration, and since they have a very high open-loop gain

$$G' = \frac{G}{1-\alpha G} \to -\frac{1}{\alpha}$$

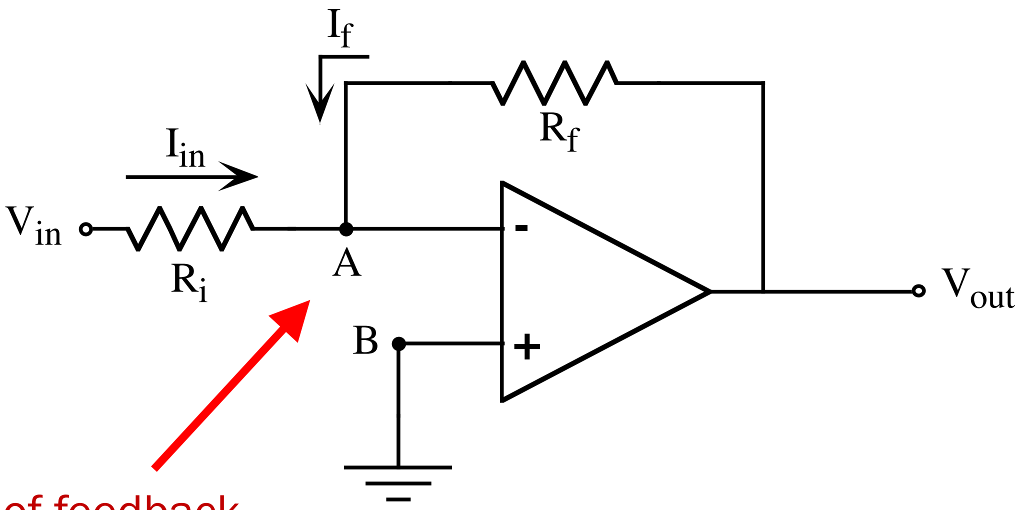
Then, the input signal becomes "negligible" (this means that the voltage difference between inputs is very close to 0 V)

$$S_{in} + \alpha S_{out} \approx S_{in} + \alpha\left(-\frac{1}{\alpha}\right)S_{in} = 0$$

This takes us to the two basic (approximate) "golden rules":

1. An OP-AMP draws very little current (0.2 nA for the LF411, very high input impedance)
2. The voltage difference between the inputs is negligible (feedback)

A very basic circuit: the inverting amplifier



because of feedback,
A is a *virtual ground*

$$I_{in} = V_{in}/R_i \qquad I_f = V_{out}/R_f$$

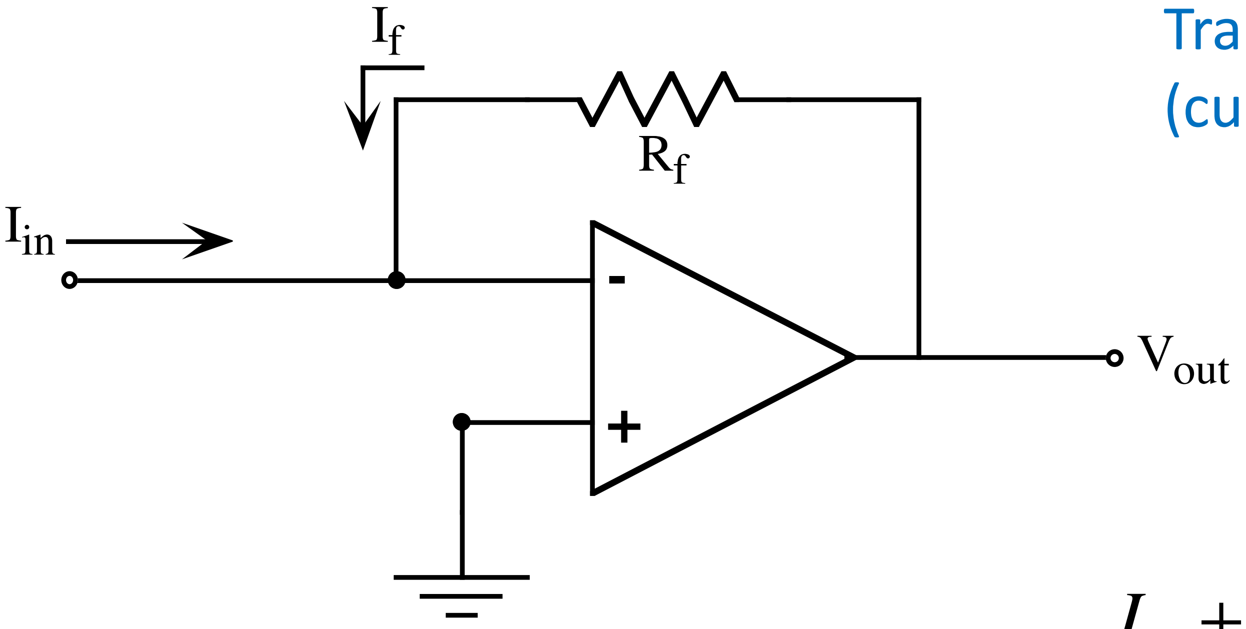
$$I_{in} + I_f = 0$$ (very large input impedance)

$$V_{in}/R_i + V_{out}/R_f = 0$$

$$V_{out} = -\frac{R_f}{R_i} V_{in}$$

output voltage depends only on the feedback network

Transimpedance amplifier (current-to-voltage converter)



$$I_{in} + I_f = 0$$

$$I_{in} + V_{out}/R_f = 0$$

$$\Rightarrow \quad V_{out} = -R_f I_{in}$$

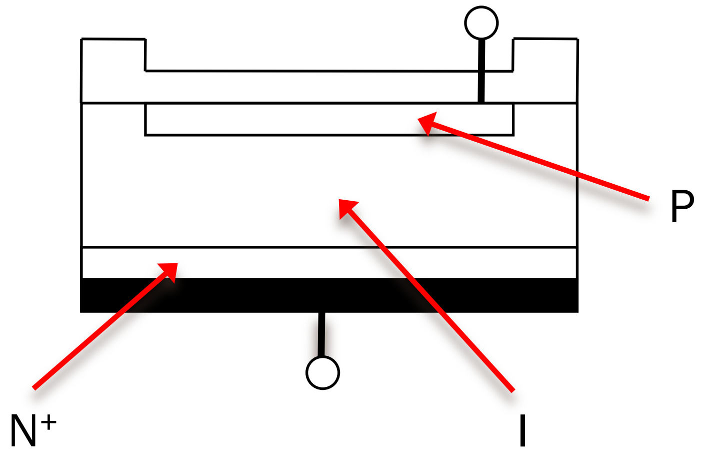
Using a 10MΩ feedback resistor the amplifier converts a 1 μA into a 10 V voltage.

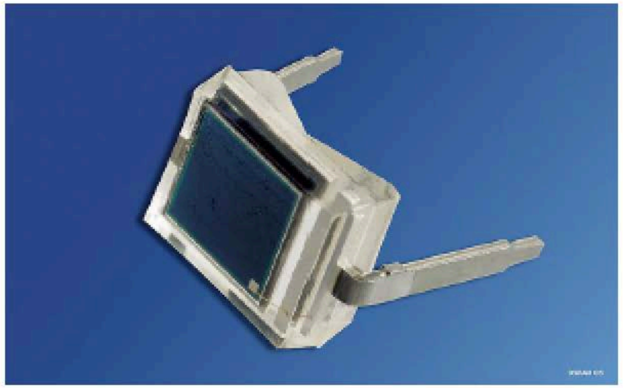
THIS IS THE BASIC TEMPLATE FOR MANY PREAMPLIFIERS.

The transimpedance amplifier configuration is used with photodiodes and other detectors that behave like current generators.

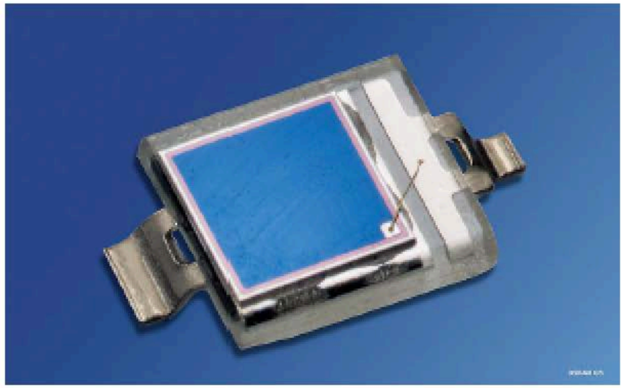
The BPW34 is a common and accurate photodiode.

fotodiodi BPW34





BPW 34 B



BPW 34 BS

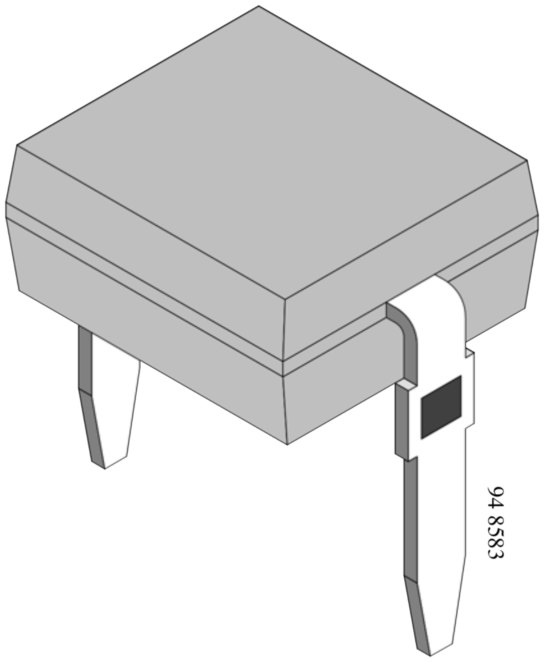
TEMIC
Semiconductors

BPW34

Silicon PIN Photodiode

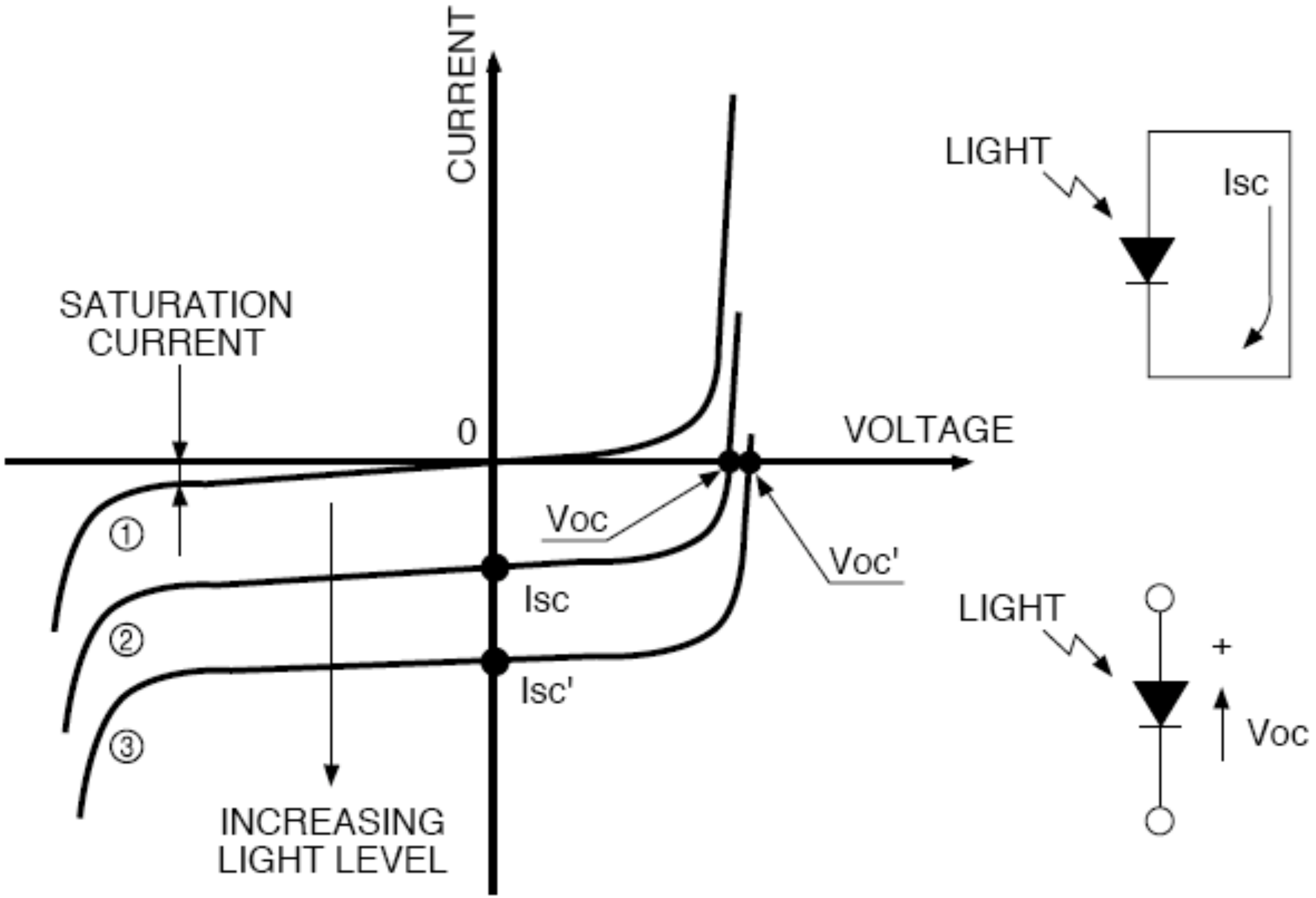
Description

The BPW34 is a high speed and high sensitive PIN photodiode in a miniature flat plastic package. Its top view construction makes it ideal as a low cost replacement of TO–5 devices in many applications.
Due to its waterclear epoxy the device is sensitive to visible and infrared radiation. The large active area combined with a flat case gives a high sensitivity at a wide viewing angle.

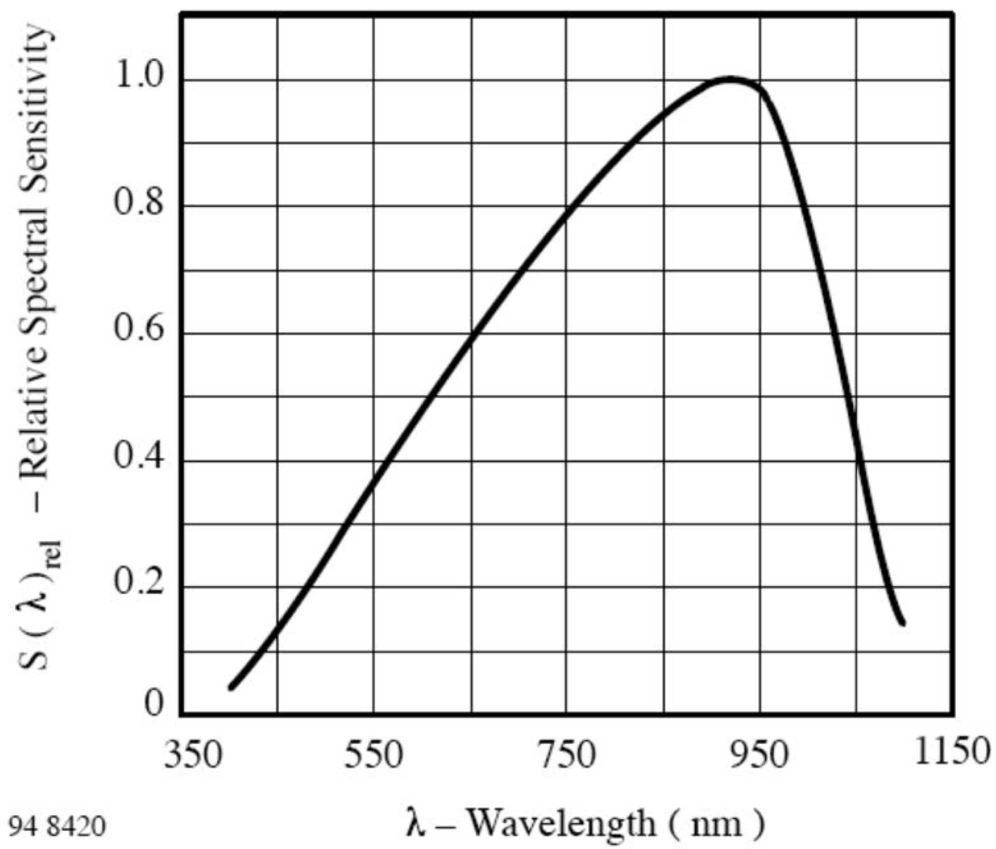


Features

- Large radiant sensitive area ($A=7.5\ mm^2$)
- Wide angle of half sensitivity $\varphi = \pm 65^\circ$
- High photo sensitivity
- Fast response times
- Small junction capacitance
- Suitable for visible and near infrared radiation


CURRENT
SATURATION
CURRENT
0
VOLTAGE
Voc
Voc'
Isc
Isc'
①
②
③
INCREASING
LIGHT LEVEL
LIGHT
Isc
LIGHT
+
Voc

Spectral sensitivity of BPW-34



Spectral sensitivity of BPW-34B

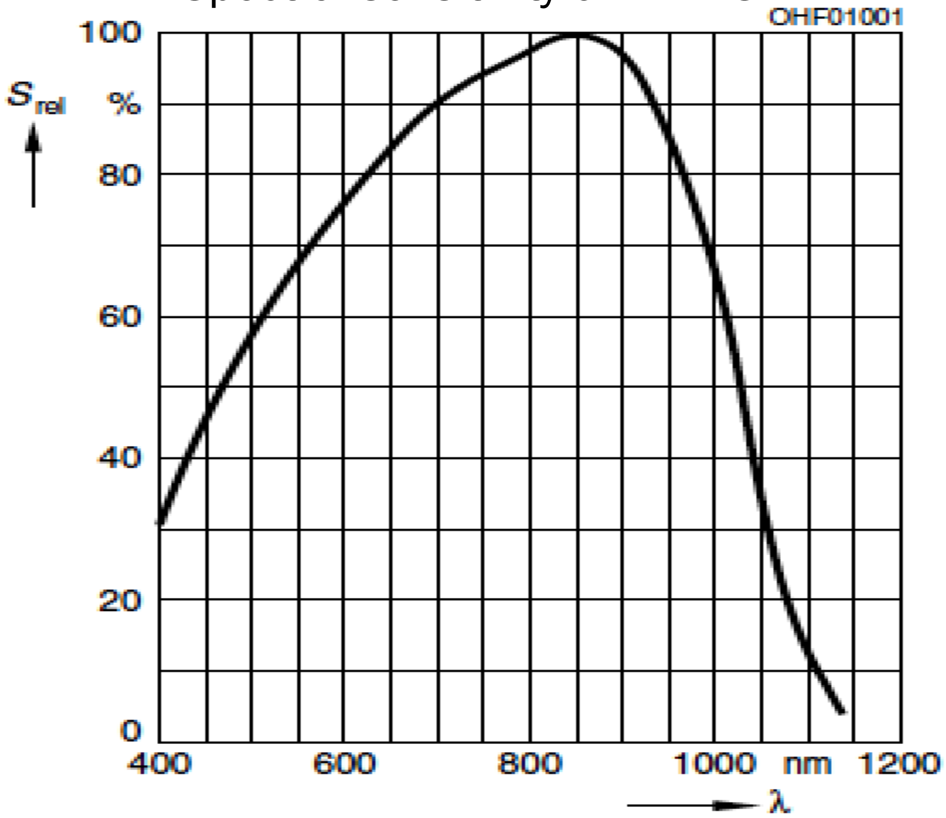
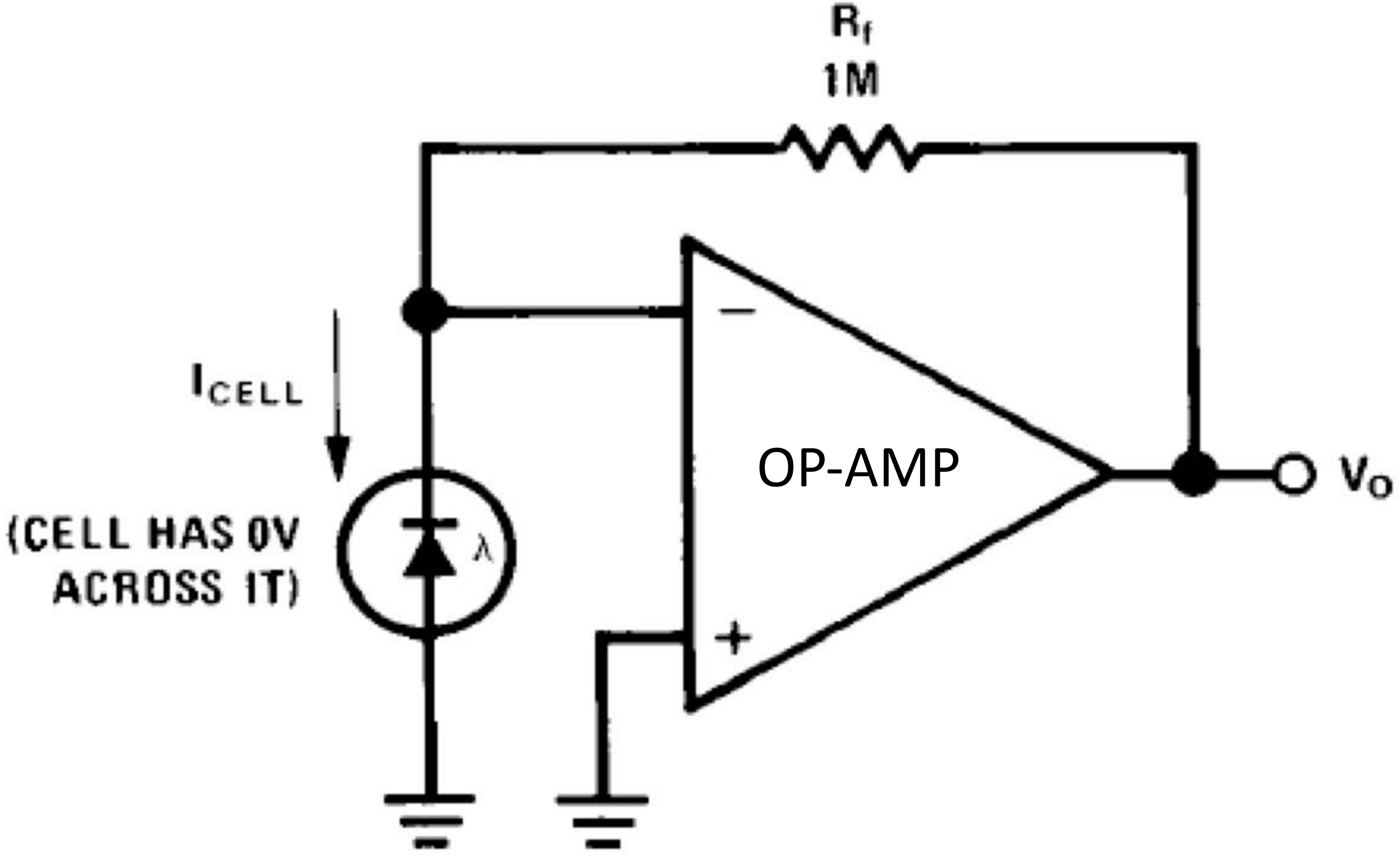


Photo Voltaic-Cell Amplifier



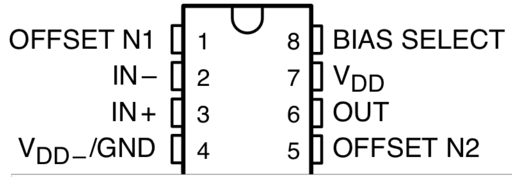
Schematics of a simple TLC251C based photometer

TLC251, TLC251A, TLC251B, TLC251Y
LinCMOS™ PROGRAMMABLE
LOW-POWER OPERATIONAL AMPLIFIERS

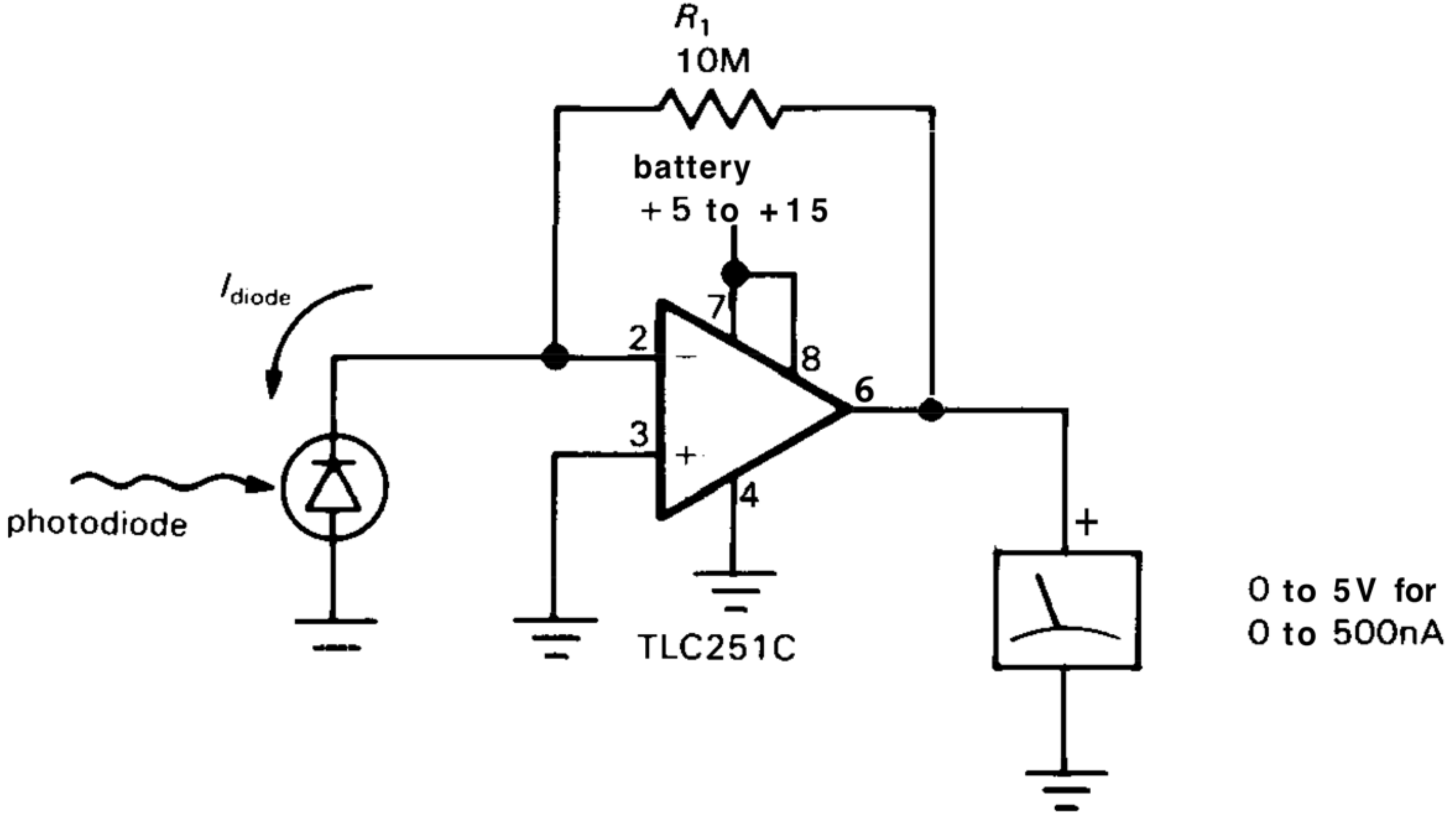
SLOS001F – JULY 1983 – REVISED MARCH 2001

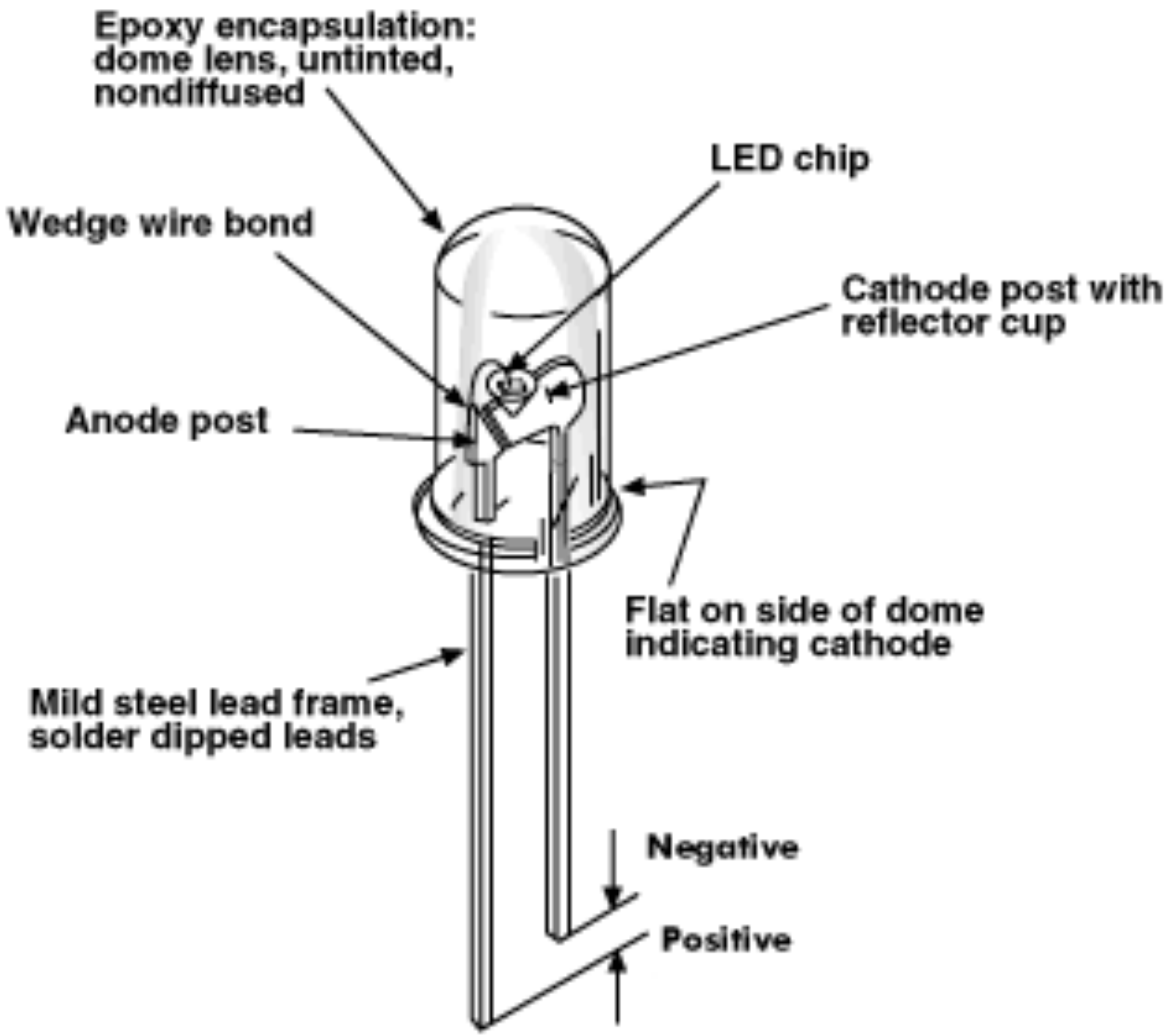
- **Wide Range of Supply Voltages**
  1.4-V to 16-V
- **True Single-Supply Operation**
- **Common-Mode Input Voltage Range Includes the Negative Rail**
- **Low Noise . . . 30 nV/√Hz Typ at 1-kHz (High Bias)**
- **ESD Protection Exceeds 2000 V Per MIL-STD-833C, Method 3015.1**

D OR P PACKAGE
(TOP VIEW)



symbo





...

At about 2¢ each in large quantities, LEDs cost about five times as much as diodes, but they are much more sensitive as photocells. With the sun falling directly on it, the photocurrent of a red 5-mm LED (1000 mCd @ 20 mA) is over 20 μA; in the sunny tropics this might keep a clock battery charged. They're not well-suited for power generation, but LEDs are convenient photodetectors at about 10% of the price of purpose-made ones.

...

from J.Bryant, Analog Dialog, 108 (Aug. 2014)

http://www.analog.com/en/analog-dialogue/raqs/raq-issue-108.html

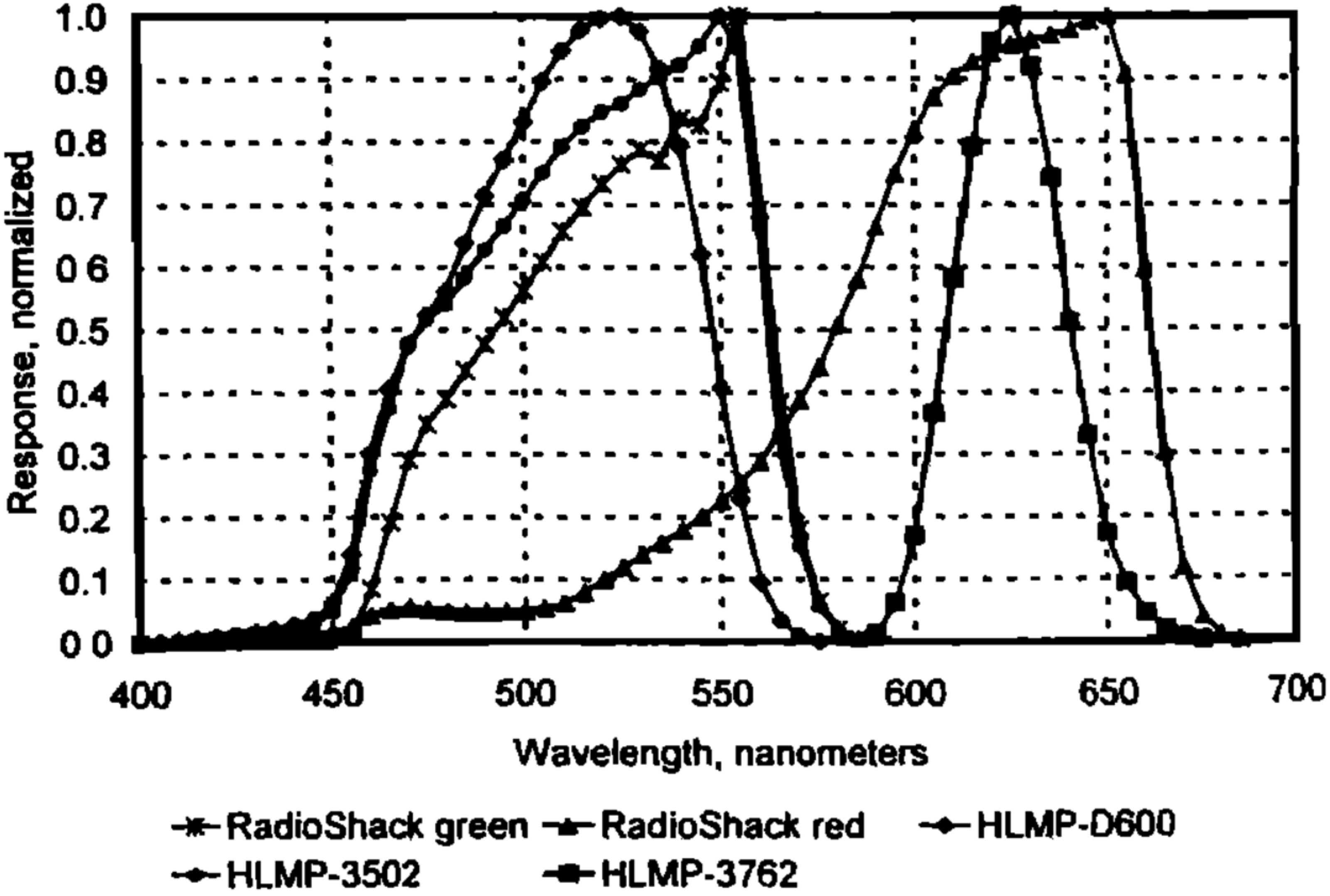
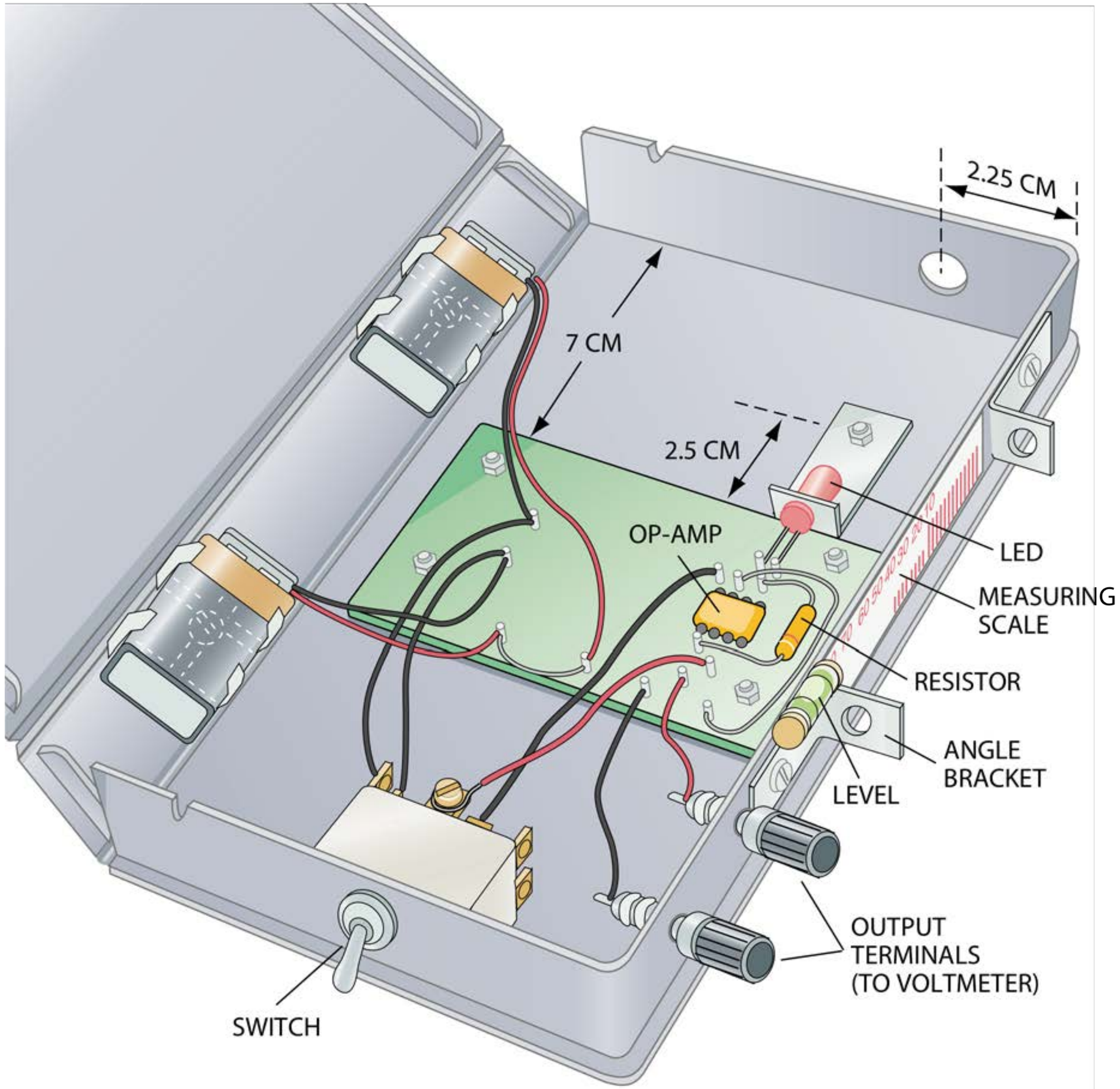


Figure 2. Spectral response of selected LEDs.

from Brooks & Mims, J. Geophys. Res. **106** 4733 (2001)

The sun photometer

(scheme from Carlson, Sci. Am., May 1997, 107)



HAZE SENSOR
fits neatly into a videocassette case. Angle brackets align the case to the sun. They can also be used with the level to calculate the sun angle.

The Langley plot

$$I_\lambda(m) = I_0(\lambda)\exp(-\alpha_\lambda m)$$

Irradiance at the photometer position, at wavelength λ, with an airmass *m*

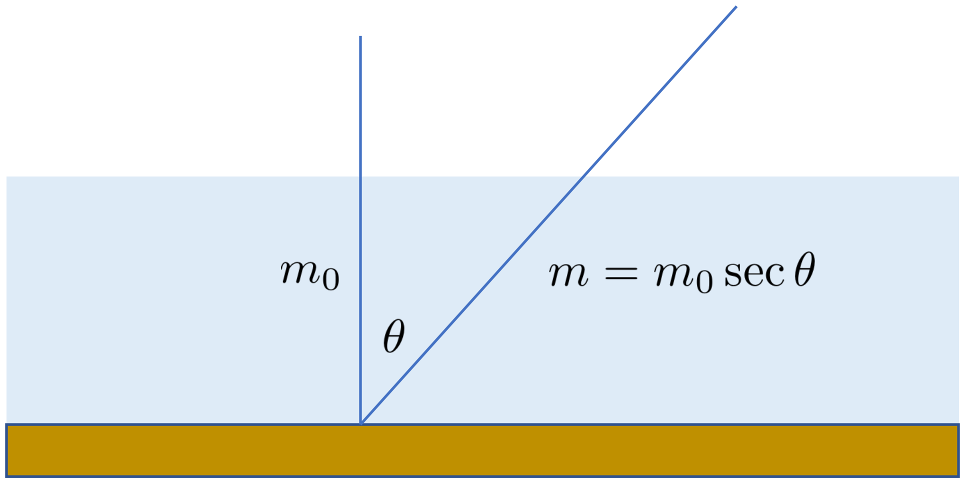
Solar irradiance above the atmosphere at wavelength λ

Attenuation coefficient at wavelength λ

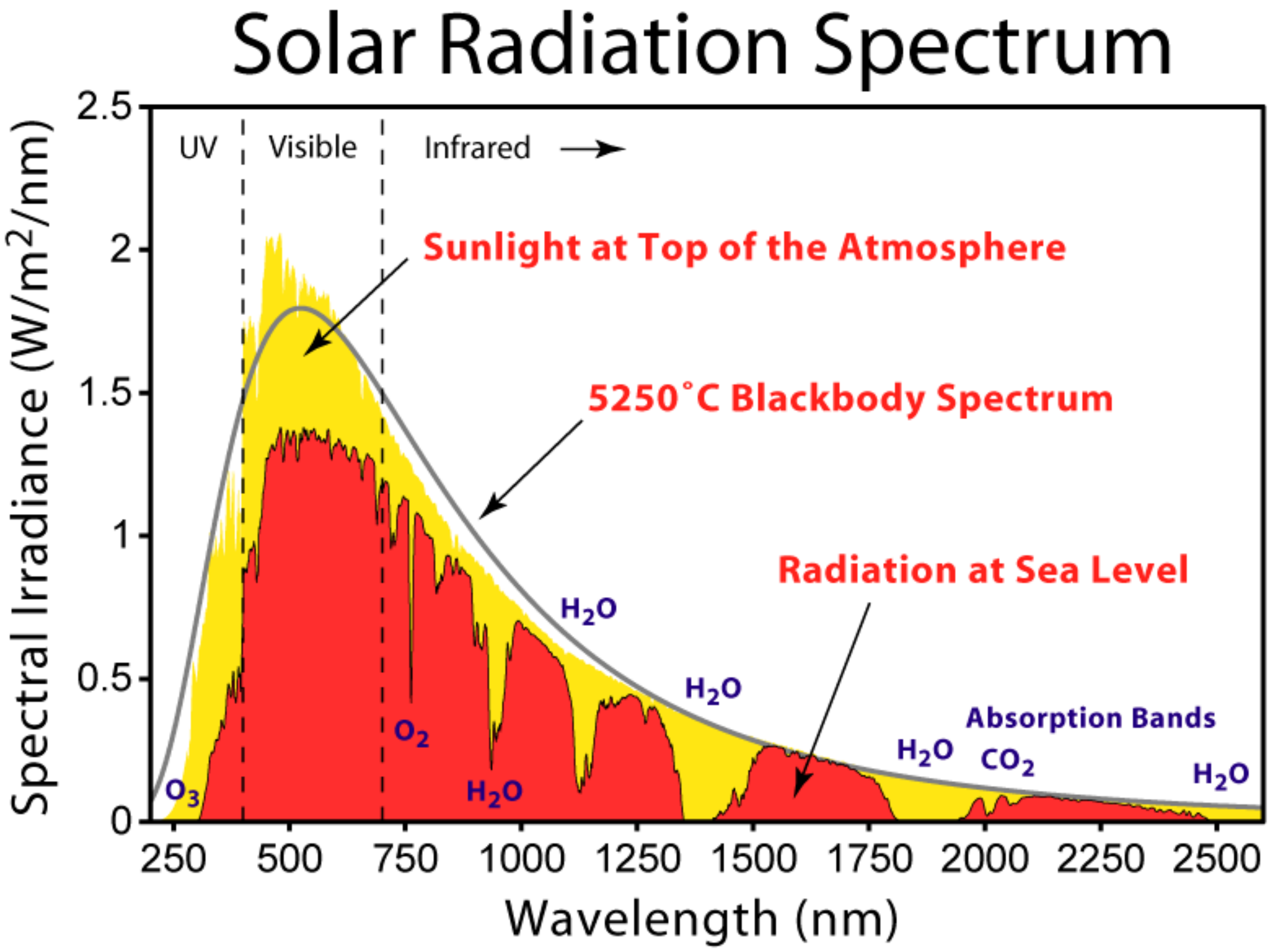
Airmass

Langley plot

$$\ln I_\lambda(m) = \ln I_0(\lambda) - \alpha_\lambda m$$



The solar spectrum is widely variable, and it is advisable to define the wavelength with a narrowband filter (a LED detector is a reasonable approximation)



https://physics.stackexchange.com/questions/152963/solar-spectrum-units

Langley plot

$$\ln I_\lambda(m) = \ln I_0(\lambda) - \alpha_\lambda m \approx \ln I_0(\lambda) - (\alpha_\lambda m_0)\sec\theta$$

The absorption coeffecient can be split in two parts: one that depend on the haze and the other that depends on Rayleigh scattering (which is pressure-dependent)

$$\alpha_\lambda = \alpha_H + \alpha_R \frac{P}{P_0}$$

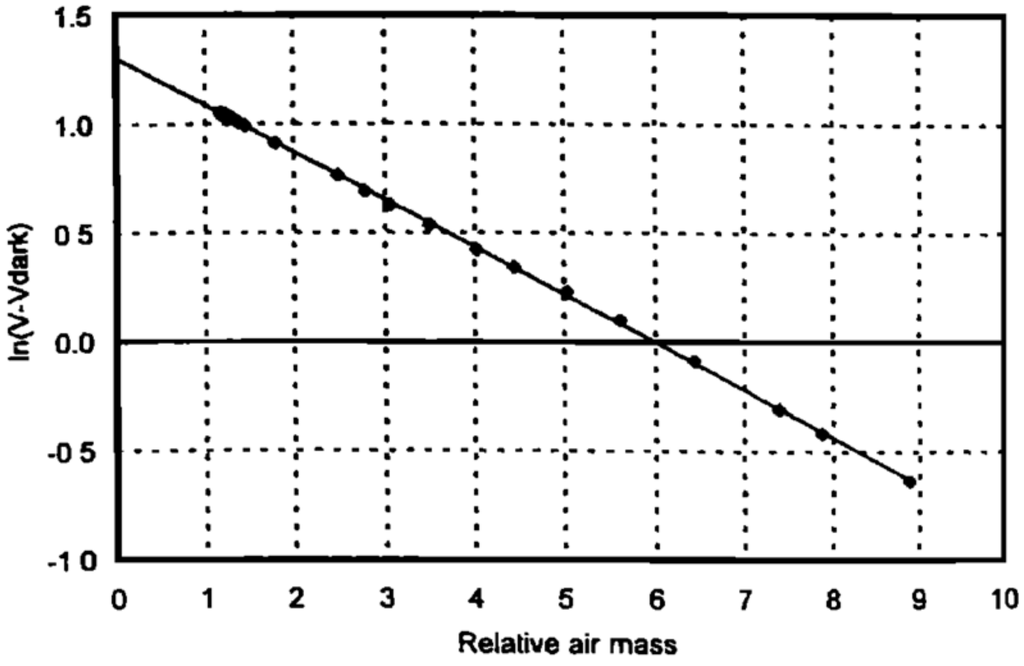


Figure 1. Langley plot calibration for a light-emitting diode (LED) based Sun photometer, from Seguin, Texas, March 9, 1999 (unpublished data from Mims).

from Brooks & Mims, J. Geophys. Res. **106** 4733 (2001)

Langley's plot *after* amplification

$$V_\lambda(\theta) = V_0(\lambda) \exp\left[-\left(\alpha_H + \alpha_R \frac{P}{P_0} \right) m_0 \sec\theta \right] + V_D$$

a "solar constant"

"dark" voltage

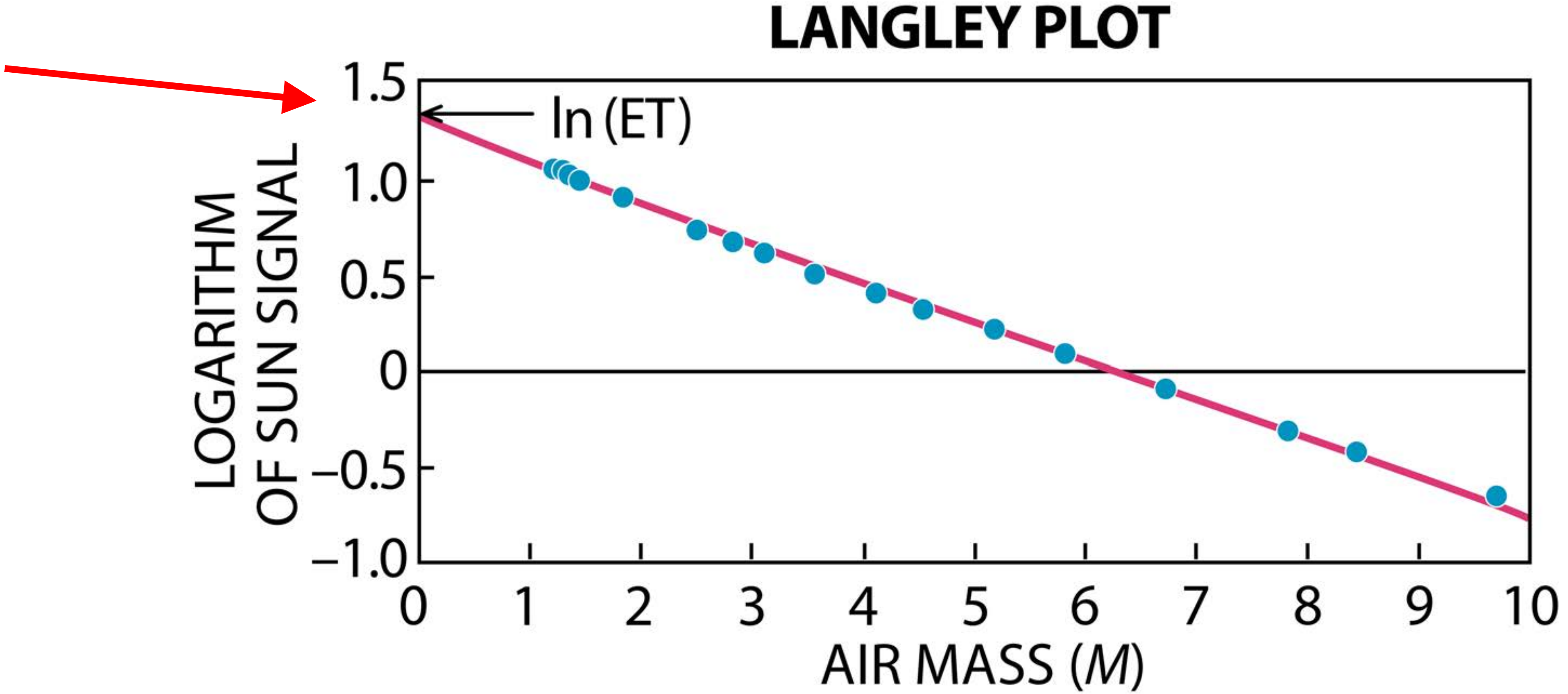
$$\ln\left(V_\lambda(\theta) - V_D\right) = \ln V_0(\lambda) - \left(\alpha_H + \alpha_R \frac{P}{P_0} \right) m_0 \sec\theta$$

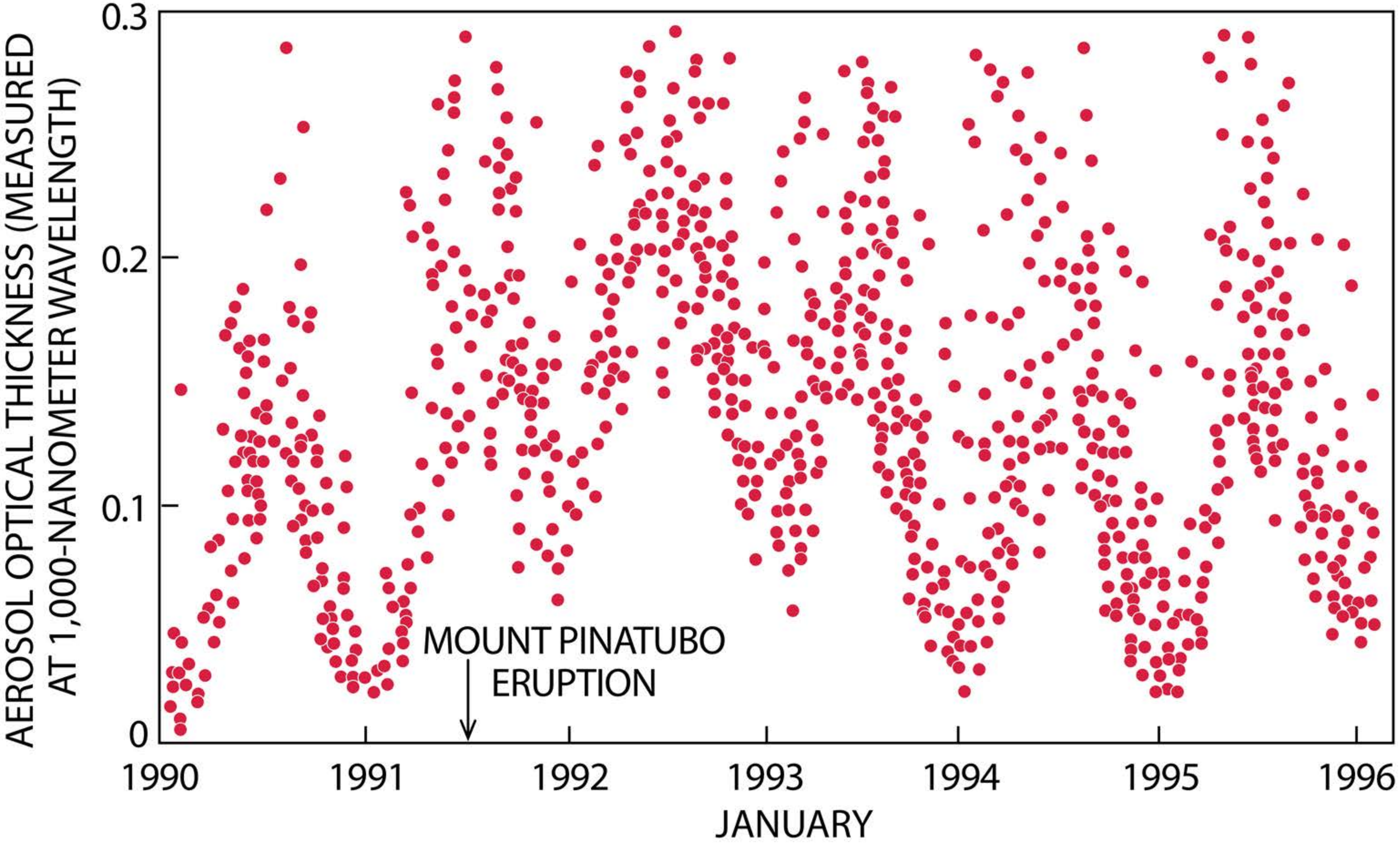
$$\mathrm{AOT} = \alpha_H = \frac{\ln V_0(\lambda) - \ln(V_\lambda(\theta) - V_D) - \alpha_R (P/P_0) m_0 \sec\theta}{m_0 \sec\theta}$$

AOT = Aerosol Optical Thickness

$$\text{AOT} = \alpha_H = \frac{\ln V_0(\lambda) - \ln(V_\lambda(\theta) - V_D) - \alpha_R(P/P_0)m_0 \sec\theta}{m_0 \sec\theta}$$

ET = ExtraTerrestrial constant, the signal that would be measured just outside the atmosphere.





from Carlson, Sci. Am., May 1997, 107

More details (and a few misprints ...) in this paper

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D5, PAGES 4733–4740, MARCH 16, 2001

Development of an inexpensive handheld LED-based Sun photometer for the GLOBE program

David R. Brooks
Department of Mathematics and Computer Science, Drexel University, Philadelphia, Pennsylvania

Forrest M. Mims III
Sun Photometer Atmospheric Network, Seguin, Texas

See also https://www.globe.gov

The Global Learning and Observations to Benefit the Environment (GLOBE) Program is an international science and education program that provides students and the public worldwide with the opportunity to participate in data collection and the scientific process, and contribute meaningfully to our understanding of the Earth system and global environment. Announced by the U.S. Government on Earth Day in 1994, GLOBE launched its worldwide implementation in 1995.

Now we are ready to build and use a sun photometer !

Lower resistance (3.9 MΩ) resistor suggested