Soft X-Ray Detection System for the CATSAT Small Satellite

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ABSTRACT

We present an innovative approach to detecting low energy x-ray emissions from cosmic gamma-ray bursts. Our design employs an array of avalanche photodiodes (APDs) to measure x-rays from 500 eV to 10 keV over a wide field of view, approximately 2π steradians. These silicon devices are ideal in many ways for small satellite use.

This effort is driven by the scientific requirements of the CATSAT mission. Our objective is to meet the mission requirements within the time scale and cost constraints of the STEDI program. CATSAT is a joint effort between the University of New Hampshire, Weber State University and Leicester University in England.

1. INTRODUCTION

The Cooperative Astrophysics and Technology SATellite (CATSAT) is one of three projects selected for funding under the Student Explorer Demonstration Initiative (STEDI). The STEDI pilot program is intended to promote the advancement of small satellite technology in the area of space science, with student involvement being an integral part of the program. The primary scientific objective of CATSAT is the study of cosmic gamma-ray bursts, with specific interest in the distance to the source of these bursts. Astrophysicists have speculated for years on this phenomenon but no common theory is currently agreed upon. This is where CATSAT, as a small-satellite with an exploratory objective, can provide a important contribution to space science.

The lead team on the CATSAT project is the University of New Hampshire, which will be responsible for the construction of the gamma-ray and x-ray sensors. Two partners, Weber State University in Utah and the University of Leicester in England, are collaborating with UNH on the project. Weber State is responsible for the construction of the spacecraft frame and flight control; Leicester University is building the soft x-ray detector housing. The CATSAT group is currently working toward having several flight-ready subsystems built by December of 1995 for review by USRA. These subsystems include partial

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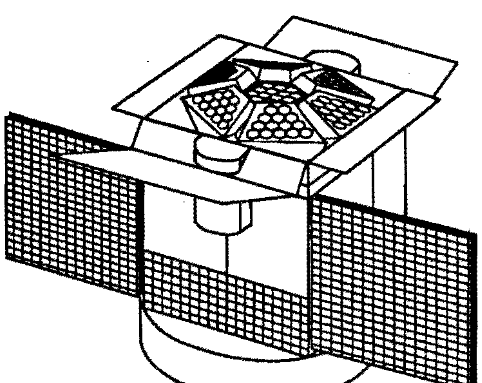
working models of the satellite's soft x-ray detectors. Certain portions of the satellite's digital electronics unit will also be ready by the December review.

This paper describes the design of the soft x-ray (SXR) detection system for CATSAT. The system, which includes x-ray sensors, low-noise signal amplifiers and analog to digital conversion circuitry, is innovative for two reasons. The APD, which has mainly been used for optical photon detection, will now be used for low energy x-ray detection. The second reason is the low cost of CATSAT's x-ray detector chain. The detector system will be implemented at a fraction of the cost of previous gamma-ray and x-ray detection experiments. These include Charged Coupled Devices, thin window flow proportional counters or photomultiplier scintillators. The SXR detection system demonstrates perfectly what the STEDI program was created for: student design of low cost small satellite technology.

Figure 1. CATSAT with SXR (top) protective doors open



2. SCIENTIFIC BACKGROUND

Gamma-ray bursts (GRBs) were first detected in the early nineteen seventies. Vela satellites accidentally discovered them as they were monitoring Soviet compliance with the Nuclear Test Ban treaty. [KLE, 73] Since that time astrophysicists have been unable to satisfactorily explain both the nature and the origin of GRBs. Current theories vary widely, from local origins to galactic and even extragalactic origins. It is generally accepted that the bursts are caused by extremely energetic events which may be some of the most spectacular in nature. Studies have been unsuccessful in trying to correlate the ~400 bursts reported per year with events at different wavelengths or other astronomical objects. It was hoped that counterparts to the GRBs would provide clues as to their origin using searches at radio, infra-red, optical and x-ray wavelengths. [OWE, 94]

CATSAT's innovative multi-observational approach will give scientists the first measurements of the distance to gamma-ray bursters, solving the most important problem in GRB studies. It will also provide high fidelity spectral measurements at energies from 500 eV to a few MeV and provide important new data on the polarization of burst emissions. In addition, CATSAT has various secondary scientific objectives. Among these will be the all-sky monitoring for transients such as soft gamma-ray repeaters, x-ray bursters, x-ray novae and continuous monitoring of solar flare activity.

3. CATSAT MISSION PROFILE

3.1 *Organization*

The CATSAT team is comprised of three universities, the University of New Hampshire, Weber State University in Utah and the University of Leicester in England. At UNH, the team leader, the Institute for the Study of Earth, Oceans and Space (EOS) is collaborating with the Electrical and Computer Engineering Department (ECE). This team will design the spacecraft's scientific instruments as well as the digital and analog electronics needed to interface with these instruments. Much of the design work is being carried out by undergraduate and graduate students. Experienced professionals from both departments are acting as mentors to the students. UNH has thirty years of experience in the design of gamma-ray instruments for spacecraft. Some projects include the Compton Gamma-Ray Observatory (GRO), the Solar Maximum Mission (SMM) as well as extensive experience in balloon programs. The instrument design group at UNH is working closely with Leicester University, where the housing for the SXR detectors will be built and tested.

The Center for Aerospace Technology (CAST) at Weber State University is handling the construction of the spacecraft frame. CAST will also be responsible for the electronics necessary for control of CATSAT once it is in orbit. WSU is the first university in the United States to have launched a satellite, NUSAT 1. Since 1985 WSU has designed and launched several more satellites in cooperation with both industrial partners and the US Air Force.

3.2 *Satellite Characteristics*

CATSAT will be launched into a sun synchronous, polar, dawn/dusk orbit at an altitude of 550 km. The satellite will have an operational lifetime of at least two years. The polar orbit keeps the SXR detector array pointing away from the sun and the solar panels facing toward the sun. This orbit also allows access to the two ground stations that will communicate with the satellite. The launch vehicle will be a Pegasus XL rocket.

The satellite's projected mass will be 120 kg, approximately 60% of which will be scientific instrumentation. The external dimensions, not including the solar panels, are 40" in height by a 30" depth and a 30" width. See Figure 1.

3.3 *Additional Characteristics*

Two solar panels will provide the satellite with 97 watts of power, stored in commercial grade Ni-Cad batteries. Of this, 48 watts will go to the scientific instruments and 36 watts to the spacecraft itself, this leaves 13 watts reserve. Satellite attitude control will be 3 axis stabilized with Momentum wheels and Magnatorquers with less than 5 degree real-time position control. Attitude determination will be within 2 to 3 degrees, using a GPS receiver and magnateometers.

WSU will communicate with CATSAT for housekeeping and attitude control using UHF transmission. Scientific data from the instrument memory will be downloaded to UNH via S-band transmission.

4. SOFT X-RAY DETECTION SYSTEM

4.1 *Resource Constraints*

Sensitivity to x-rays in the prescribed band, for a large field of view is essential to the CATSAT mission. An alternative solution to traditional detection methods that was relatively inexpensive and understandable was sought. Since CATSAT needs to be built in two years, mostly by students, simplicity is an important issue. Given the above constraints avalanche photodiodes (APDs) were chosen for the detection of soft x-rays.

APDs have a price range from a few hundred, to a couple of thousand dollars per device. APDs are based on relatively straight forward semiconductor physics,. Engineering students who have taken an electronics course can understand the principles of APD operation. This reverse biased p-n junction is the key to soft x-ray detection and thus to the CATSAT mission.

4.2 *Soft X-Ray Module*

The SXR module is located in a special housing on top of the spacecraft, shown in Figure 1. Protective doors will open once the satellite is in orbit to expose the module to the x-ray flux. The module is composed of seven fixed panels, six in a hexagonal structure with the seventh on top. Each panel has 16 APDs, giving a total of 112. Every APD has its own chain of electronics which amplifies and digitizes the detected signal for storage in memory.

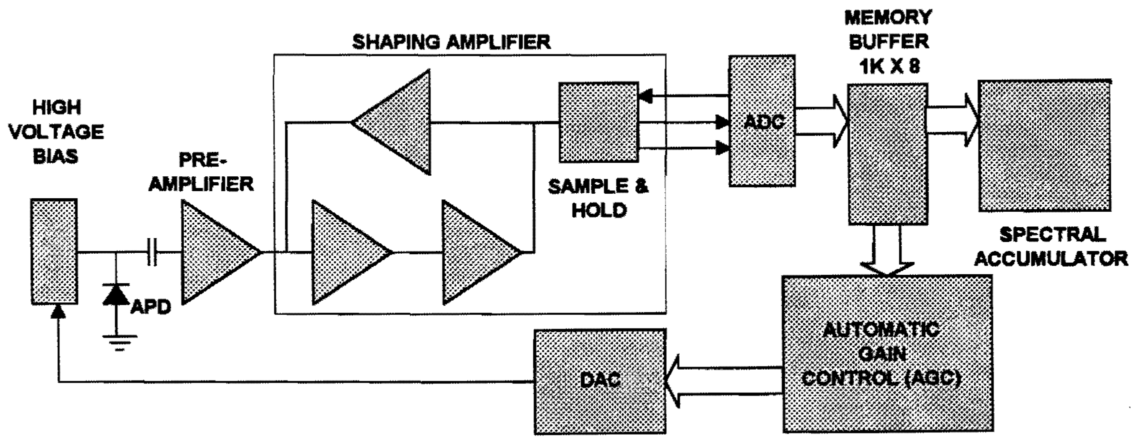
The satellite will be oriented so the top points away from the sun at all times. This will keep the SXR module at a temperature of -40 C, which is necessary for optimum performance of the APD and preamplifier. The remaining portion of the data paths will be in 7 electronics boxes in the midsection of the satellite. An ^{241}Am source and coincidence detectors will be mounted on the exterior of the SXR module for APD calibration and gain stabilization.

4.3 *Detection Path*

Figure 2 shows one of the APD signal paths from the APD detector through to the spectral accumulator (SA). The event path starts at the APD, goes through the charge sensitive preamplifier, through the shaping amplifier and through the ADC. The pulse is then checked for validity before being sent to the spectral accumulator. The SA sorts data for storage in memory.

The sequence described above is for a normal event, ie. a data x-ray being detected by the APD. There is another type of event, called a calibration event, which can be processed by the SXR data path. These events, described in section

Figure 2. Signal Path



4.4 are necessary for the continuous adjustment of the high voltage bias to the APD. The processing of a calibration event is similar to a normal events up until the memory buffer. At this point the digitized calibration pulse is read by the Automatic Gain Control (AGC) which will adjust the gain of the APD.

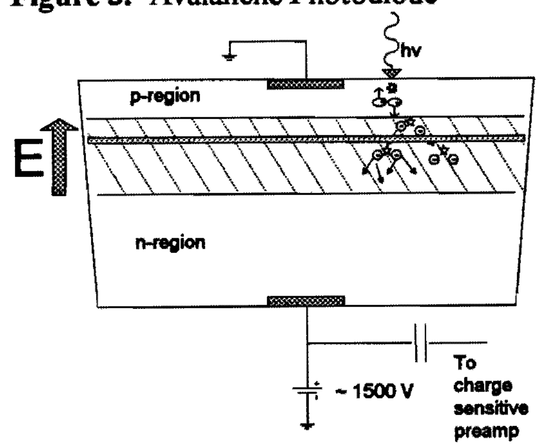
4.3.1 Avalanche Photodiode (APD)

The avalanche photodiode is ideal for small satellite x-ray detection. The compact, rugged, low power device has excellent energy resolution. The cost for these devices is very reasonable compared to the cost of other possible detector systems. The automatic gain control system to be used aboard CATSAT will calibrate and gain adjust each detector individually. This will ensure that when many detectors are put into an array, the array spectra will appear as though it is from one large detector.

Physical Description

The APD that will be used aboard CATSAT is a silicon device with a thickness of about 2 mm and a detector top surface area of 1.69 cm^2. The APD side view shown in Figure 3, displays the p diffusion region on top, the multiplication region in the middle and the n diffusion region on the bottom.

Figure 3. Avalanche Photodiode



X-Ray Detection

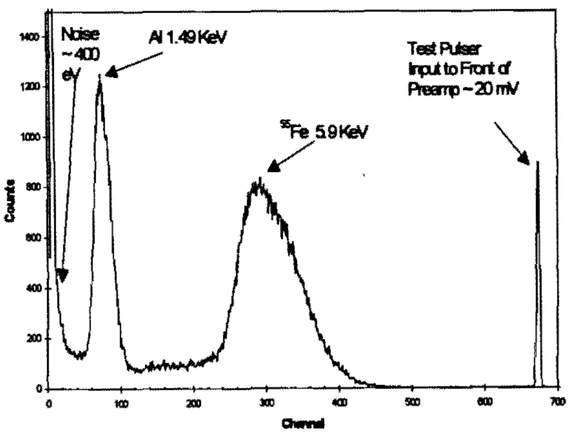
A positive voltage is applied to the cathode to reverse bias the APD. This voltage aids in depleting the PN junction of charge carriers, thus increasing the width of the depletion region. This region has high resistivity and drops the majority of the bias voltage. This voltage drop creates a very high E field of ~ 10^6 V/M.

The p region is exposed to an x-ray flux, a photon interacts with a silicon atom through photoelectric absorption or compton scattering and liberates one electron-hole pair for each 3.62 eV of photon energy [KNO, 89] The electrons migrate towards the positive cathode. The E field is large enough to accelerate the electrons to a velocity that is at or close to the saturation velocity of 10^7 cm/s [KNO, 89] This velocity gives the liberated electrons sufficient energy to free other electrons. This multiplication process takes place many times increasing the signal to a point where it can be seen above the noise. The APD used onboard CATSAT requires a high voltage bias of ~1500 V, creating a depletion region of ~ 150 μm which gives the device a gain of ~75. [FAR, 91]

Figure 4 shows an APD test spectrum taken at UNH's Small Satellite laboratory. This spectrum shows the noise threshold, an aluminum fluorescence line at 1.49 keV, a ^{55}Fe k α line at 5.9 keV, and a test pulser to the far right. The spectral width of the iron and aluminum lines is mostly due to the statistics of the decay. Some of the width is due to the APD multiplication process and very little is due to the noise.

Many test spectra have been taken to ensure that the optimum APD conditions are met. A combination of APD gain, temperature and shaping amplifier time constant have been found to minimize the noise and to obtain the best spectral resolution. Under certain conditions the spectral peaks have shown an asymmetrical feature. Although the cause of this is not completely understood, adjustments have been made to minimize this phenomenon. The adjustments have allowed maximum gain with minimum spectral distortion.

Figure 4.
Aluminum, ^{55}Fe X-Ray Spectrum
Large Surface Area APD
Gain ~ 100, T ~ -40 C



Noise

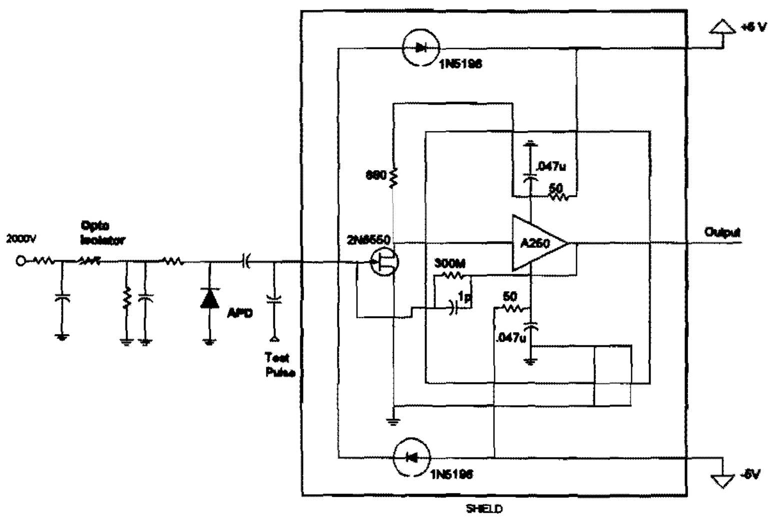
The noise is caused by numerous sources. The APD dark current, the FET thermal noise and the shot noise from the various resistive elements are the most significant contributors. The noise threshold can be seen in two ways on the spectra in Figure 4. The rising counts in the low energy channels are caused by noise, this feature masks signals from x-rays below 400 eV. The other way the noise can be seen is through broadening of the spectral peaks. This peak broadening can most easily be seen on the test pulser which would ideally have no spectral width if no noise was present.

The very low threshold of 400 eV is important from a scientific standpoint. In the spectra above this can be thought of as a couple of hundred micro volts on the gate of the preamplifier front end FET. An analysis of the noise sources is in progress, but it is quite clear that the total noise is strongly temperature dependent. The total noise is also dependent on the gain of the APD. This is most likely caused by the large capacitance of the detector at low gains.

4.3.2 Preamplifier

The preamplifier used with the APD is an Amptek A250 charge sensitive, low noise preamplifier, shown in Figure 5. This device is one of the few "high tech" items aboard CATSAT.

Figure 5. APD and Preamplifier



It utilizes an external FET, for impedance matching to the APD, and will be cooled by radiation along with the APD to - 40 C when CATSAT is in flight This cooling is achieved by placing the detector and preamplifier in the SXR module on the top of CATSAT's spaceframe, this also maximizes the distance between the noise sensitive components and the satellites operational controllers.

The A250 is rated at 19 mW typical power dissipation with the noise at room temperature approximately 100 electrons RMS. It is a highly reliable device particularly suited to aerospace applications. In this case a low noise device is extremely important due to the small signal coming from the APD. This signal can be significantly altered by relatively small amounts of noise. In an effort to minimize noise careful consideration is being give to match the preamplifier input impedance to the impedance of the APD/AGC circuitry.

To prevent damage to the FET two protective diodes are used . The diodes prevent the voltage at the gate of the FET from going above ~4.5 V and below ~-4.5 V. Also shown in the figure is a test pulse input, necessary for checking the integrity of the electronics chain. This is important for preflight checks as well as well as APD gain determination.

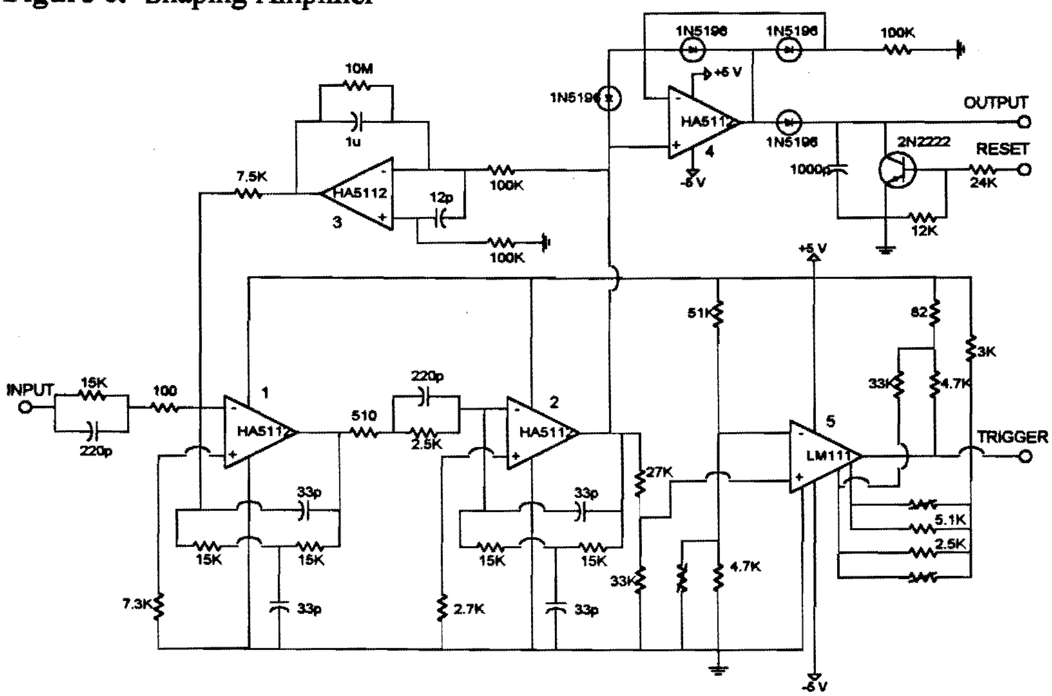
4.3.3 Shaping Amplifier

The circuit diagram for the shaping amplifier is shown in Figure 6. The amplifier is essentially two double integrators in series. The input to the amplifier is the output from the A250 preamplifier. The signal first goes through a "pole-zero," or a differentiator, which sharpens it into a narrow pulse before it enters the first double integrator. This differentiation/ integration process is repeated again through op-amp #2.

The integrators are built with low noise, high performance operational amplifiers. Both have identical RC time constants. Double integration is achieved using a bridged T-network as shown in the circuit diagram. To keep the DC voltage at the output zeroed a negative feedback loop is implemented using op-amp #3. Without this feedback pulse pileup could possibly saturate the amplifier.

is the output of the comparator. Trigger alerts the ADC circuitry that an x-ray event has been detected. The ADC can then read off the pulse height from the S/H and digitize it. Once the ADC has completed the conversion it issues a RESET which discharges the capacitor. At this point the circuit is ready to record another pulse.

Figure 6. Shaping Amplifier



Op-amp #4 is part of the sample and hold circuit for the amplifier. The additional circuitry (op-amp and diodes) has the effect of eliminating the diode drop that occurs in a conventional S/H. The typical diode drop is undesirable in this case, particularly when the pulse output from the amplifier has a magnitude significantly less than 5 V.

The usable output from the shaping amplifier is the voltage stored on the charged capacitor. The other output from the shaping amplifier, "TRIGGER,"

4.3.4 <u>ADC Circuitry</u>

The final design for the ADC has not been completed. Due to the large number of detection paths there are obvious constraints such as low power and high speed. The ADC circuit will have a conversion time of a couple of microseconds. This conversion time is the time from TRIGGER to RESET.

The basic function of the ADC is to digitize the output of the amplifier chain for two purposes, storage and calibration. The digital information will be stored in a buffer memory which can be accessed by both the CPU and the AGC. This will also speed up the ADCs since they will not have to hold the data until it can be retrieved.

4.3.5 Spectral Accumulator

The SA sorts data collected from all of CATSAT's sensors into corresponding energy spectra in memory. The data from the SXR module is divided into seven channels, each one corresponding to a panel of 16 APDs.

The SA has an 8 Kb buffer memory for storing spectra that is periodically transferred to the instrumentation's 24 Mb memory. This main memory is downloaded to a ground station at UNH twice per day.

4.4 *Instrument Calibration*

Calibration of the APDs will be continuously carried out while the satellite is in orbit. This will be implemented using an ^{241}Am source located above the surface of the SXR detector module. The ^{241}Am decay consists of an alpha (heavy charged) particle, as well as a spectra of x-ray lines. The alpha particle will be used for coincidence triggering.

The coincidence pulse will trigger the AGC and the SA so the calibration pulse does not go to main memory. The AGC will then read the digitized pulse and the address of the APD which generated the pulse. An algorithm will be run to compare the pulse to a reference ^{241}Am spectra. The output of the algorithm will either increment or decrement the high voltage bias to the APD.

5. CONCLUSION

APDs have kept the cost and complexity of the SXR detection system within the limits of a small satellite's monetary and personnel budget. The APD array, with its low noise threshold and wide field of view, will help astrophysicists determine the distance to the source of cosmic gamma-ray bursts.

The relative simplicity of the system has allowed the majority of design work to be carried out by engineering students. A combination of mentoring from experienced professionals and help from undergraduates is an important aspect of the STEDI program.

A partial proto-flight APD panel and associated electronics will be manufactured for the design review in December of 1995. Currently, the majority of theoretical design work has been completed and efforts will now be concentrated on design fabrication and testing.

6. ACKNOWLEDGMENTS

The authors wish to thank the University of New Hampshire Space Grant and the CATSAT project for graduate funding. In addition we would like to thank Dr. Tom Vestrand, Dr. Allen Drake, Dr. Andrzej Rucinski, Dr. David Forrest, Mr. Ken Levenson and Mr. Frank Hludik for their help and mentoring throughout the course of this work.

7. REFERENCES

[FAR, 91] Farrell, R., Vanderpuye, K., Entine, G. and Squillante, M.R. High Resolution, Low Energy Avalanche

Photodiode X-Ray Detectors. IEEE Transactions on Nuclear Science, Vol. 38, No. 2, April 1991. 144-147.

[KLE, 73] Klebasadel, R.W., Strong, I.B. & Olsen, R.A., Observations of Gamma-Ray Bursts of Cosmic Origin. "The Astrophysical Journal," 1973, 182, L85.

[KNO, 89] Knoll, Glenn F. Radiation Detection and Measurement. John Wiley & Sons, New York: 1989.

[OWE, 94] Owens, A., Schaefer, B. and Sembay, S. Deriving Gamma-Ray Burster Distances from Soft X-Ray Measurements. "The Astrophysical Journal," In-Press, 1995.