Comparison of Detector Technologies for CAPS[9]

JANA L. STOCKUM
San Diego State University
San Diego, California

Introduction

In this paper, several different detectors are examined for use in a Comet/Asteroid Protection System (CAPS), a conceptual study for a possible future space-based system. Each detector will be examined for its future (25 years or more in the future) ability to find and track near-Earth Objects (NEOs) from a space-based detection platform.

Within the CAPS study are several teams of people who each focus on different aspects of the system concept. This study's focus is on detection devices. In particular, evaluations on the following devices have been made: charge-coupled devices (CCDs), charge-injected devices (CIDs), superconducting tunneling junctions (STJs), and transition edge sensors (TESs). These devices can be separated into two main categories; the first category includes detectors that are currently being widely utilized, such as CCDs and CIDs. The second category includes experimental detectors, such as STJs and TESs. After the discussion of the detectors themselves, there will be a section devoted to the explicit use of these detectors with CAPS.

Charge-Coupled Devices Background

Invented in the 1970s, charge-coupled devices (CCDs) and charge-injected devices (CIDs) have made a huge impact on astronomy. Previous observations were primarily made either directly by the human eye or by using photographic plates. Neither the eye nor the photographic plates have a linear response to exposure to light. However, CCDs and CIDs have a highly linear response. The linearity of the device allows scientists to better estimate integration times needed to make observations. As great as the leap of linearity was, these devices have not made such a large impact from this ability alone. CCDs and CIDs have more benefits, such as higher resolution, wider dynamic range, higher sensitivity, and digital capabilities specific to each.

CCDs have become the most widely sold detection devices to date, taking in a projected 79 percent of the market share of solid-state image sensors in the year 2000 (ref. 1). These devices have even made the transition from research tools to commercial use in everyday items, such as digital cameras and pharmaceutical lid detection (ref. 2).

There are several reasons for the large market share taken in by CCDs. These devices have reached a state of maturity allowing for nearly any configuration, and of nearly any size. The working temperature for astronomical uses is relatively easy to maintain. The vast capabilities of CCDs include operating as imagers, photon counters, and with spectrographs. Because of unique specifications, each function requires a different configuration (ref. 3).

One such general configuration used is that of an imager. Operating at nondiscrete wavelengths, the CCD potential wells collect the energy from the incident photons within their electron wells via the photoelectric effect. Once collected, the energy is read out well to well, row by row, and into a computer via charge transfer. The transfer of information from well to well is accomplished by applying a variable

[9]Chapter nomenclature available in chapter notes, p. 217.

voltage to neighboring potential wells. This transfer of charge is generally measured and referred to as the charge transfer efficiency (CTE). The CTE can slow the astronomer's ability to observe and therefore a lower CTE is a sign of a higher quality CCD. While the charge is being transferred, the CCD potential well makes no measurement of wavelength or exact photon timing. However, the energy can be used to produce an image of the object(s) being observed (ref. 3).

In order to view colors of the observed image, different pieces of equipment must be introduced to the configuration. A grating or prism is commonly used to separate the differing wavelengths from a source (ref. 3). However, the more commonly used grating (due to the difficulties of creating a perfect prism) works by bending the incoming signal. Once the signal is bent, it is weakened and the signal-to-noise (S/N) ratio drops. To regain a desired S/N ratio, a longer exposure time is required.

Another deficiency of CCDs, called "blooming," refers to the saturation of an electron well. Once an electron well has collected too many photons (the limit is set by CCD composition), incoming information will "spill" onto a neighboring well. The result may be an entire row or column of the array too full of energy to allow for much of an image. Only a streak of bright light across a row or column of pixels can be seen.

Charge-Injected Devices Background

CIDs are similar to CCDs in their general absorption of photons. However, CIDs have a specific configuration that allows for multiple benefits. Instead of reading the charge information via charge transfer, each potential well has the ability to be read individually. This characteristic allows for different modes of controlled operation and minimizes blooming.

The resistance to blooming enables the CID to perform many tasks that a CCD would have trouble completing. When a CID potential well is over-saturated, the energy does not "spill" over to a neighboring potential well, instead just that one, or at most a few, well is affected. For known bright sources, certain wells that would become oversaturated and rendered useless can be turned off. When collecting spectral information, this ability becomes vital for observing the weaker emissions that would otherwise be hidden by a stronger source.

The idea of effectively turning some collection wells off can also be extended into creating different modes of operation. For example, if the entire field of view offered by the device is not required, half the device can be turned off to allow for quicker recovery time. In the commercial world this is used for fast capturing needs, such as tracking. Another scanning method, a "progressive scan," is described by CID Technology on its website: "this readout enables real-time processing by eliminating the delay required to combine odd and even fields. Instead, lines are read sequentially (1, 2, 3, 4, etc.) allowing an image processor to analyze the latest row of video information while readout continues to the next line" (ref. 2). While these abilities are not crucial to near-Earth object (NEO) detection and tracking, they could be helpful in lowering the loss rate of objects.

Superconducting Tunneling Junctions

As valuable as CCDs and CIDs have been in the past, and promise to be in the near future, a new generation of detectors will likely have an even greater impact. Transition edge sensors (TESs) and superconducting tunneling junctions (STJs) have the ability to identify the time each incident photon arrives on the detector with varying time resolution of ≈5 μs (ref. 4). The wavelength of each photon, ranging from 1100 Å to 6 μs (ref. 5), and the location of incidence on the detection element are also immediately recorded by TESs and STJs. Armed with these capabilities, these devices have the potential to revolutionize astronomical observation as we know it today.

Currently, there are experimental data being taken by computer simulations (ref. 5) and with small STJ and TES devices on a handful of ground-based telescopes. The William Herschel Telescope is one of the main telescopes being used for such experiments (ref. 6).

The computer simulations of the STJ system performed at the California Institute of Technology demonstrate the enormous potential of these superconducting devices. In simulations described in detail in reference 5, the researchers compare the abilities of a CCD device attached to the Keck Telescope with the abilities of an STJ counterpart. The results include an estimation that, for the CCD arrangement to gain the same information as the STJ system, the observations would take five times as long, with the extra time owing for the need to use several observations with different filters to gain spectral information that was inherently gathered by the STJ. This study further adds that during a simulated galactic search using broadband techniques, the CCD apparatus attached to the simulated Keck telescope found 1018 of 8717 galaxies with redshifts of approximately 3 during a 4-hour observational time, while the same sized STJ device found 2045 galaxies with redshifts of 5 and with higher accuracy in only a 1-hour integration. In reference 5, Mazin and Brunner discuss the future of STJs and other cryogenic imaging spectrophotometers (CISs) as replacing CCDs as "the wide-field detectors of choice." As such, they speculate that if an STJ were used on a next-generation space telescope with "actively cooling detectors and passively cooled mirrors," this configuration would be able to observe as deep as the Hubble Space Telescope Wide-Field Planetary Camera 2 (WFPC2) instrument with higher spectral coverage and resolution, yet it would require only 2 percent of the observation time. With such resounding redictions, it is easy to see why scientists are excited about the possibilities for these cryogenic imaging spectrophotometers.

Several organizations have already made plans to include STJs as part of their future projects. The Boeing Company, for example, has proposed to install an STJ aboard its nonredundant linear array (NRLA) concept (ref. 7). Dr. Peacock, one of the founding scientists of the STJ concept, believes these detectors will soon be used in the microchip industry to identify contaminants in silicon. In fact, the STJ devices have many applications in "commercial and industrial fields, where fast measurements to capture phenomena in wavelength at very low light levels are required" (ref. 8).

Despite nearly limitless uses within the astronomical community and several commercial applications, the STJs and other CISs still need considerable support. The devices themselves need to be cooled to temperatures below 1 K. This refrigeration requirement must be met by some new cooling technology before a long-term space-based implementation can proceed.

Detector size is another hurdle that must be overcome. While research to increase the CIS detector size is currently progressing, much more needs to be done to equal the size of current CCDs. There is considerable optimism that the cooling technology and size limitation problems are solvable in the near future.

Transition Edge Sensors

TESs are among the newly created CISs. These devices appear to have great potential in revolutionizing astronomy and other imaging fields. TES devices are constructed from tungsten cells on a silicon substrate. The operating temperature is well below 100 mK. The sensor is held and monitored at a fixed voltage. Photons are detected when their incidences on the tungsten create a decrease in the current needed to maintain the fixed voltage. This decrease is related to the energy of the incident photon. The exact energy level is recorded as a pulse and sent to a direct current (DC) Superconducting Quantum Interference Detector (SQUID) array, which is one of the most sensitive devices for magnetic field detection (ref. 9). Within the SQUID, the pulse is amplified, digitized, and given a peak height. Then, the information is assigned a time from the Global Positioning System (GPS) receiver and recorded to a computer (ref. 10).

The inherent spectral range of the TES is quite large and may therefore be better suited for a Comet/Asteroid Protection System (CAPS) detection sensor. The sensitivity of the tungsten device begins near 372 nm and ranges to 18 600 nm (0.3 eV to 15 eV). However, the quantum efficiency (QE) in the optical, ≈50 percent, is not as high as in other CIS devices, such as STJs (ref. 10).

Detector Functionality: Classification Abilities

Of great importance to an NEO protection system is the determination of an asteroid's size and classification, or composition. These important characteristics cannot be accurately determined by visible observations alone because the amount of reflected sunlight from an object depends on the albedo and the size (ref. 11). Simultaneous measurements of the thermal flux and the visible brightness of an object are necessary to first classify it within the general asteroid compositional groups; then estimates of the size and albedo can be calculated. The hafnium-based STJ device is projected to gain a resolution of wavelength difference on the order of 5 nm over most wavelengths including the near infrared (2 μm on the ground and 6 μm on a space-based platform (ref. 5). According to A. Cellino, this is sufficient to detect the characteristic NEO identifier at 2 μm. However, these values are still insufficient to locate the reradiated peak located between 6 and 10 μm (ref. 12). Other asteroids may only be observable near 12 μm due to their extremely low albedos (ref. 13). A new base material would need to be used for the STJ to reach such wavelengths. TES devices actually have the capability of observing a larger wavelength range than STJs, including this needed range of 12 μm. However, this is at the cost of a 20-percent loss in QE over the optical range (refs. 14 and 15). Yet, even with the decrease in QE, the increased range of wavelength may make the TES detector more favorable. Regardless, the lack of sensitivity in the 8- to 12-μm range is a deficiency of the STJ that would need to be addressed by a CAPS infrared detection capability.

Time Tagging With Automation

Another feature of the STJ and TES that can greatly benefit CAPS would be the ability to time tag. It is possible that time tagging each photon incident to the detector could allow for a reference of movement across the detector's field of view, therefore permitting another (perhaps more accurate) method for a computer to recognize NEOs. To test this hypothesis, more research needs to be done, perhaps a full computer model testing this proposed method versus the streak identification process, or other methods in use today.

Comparison With Streak Method of Detection

Another comparison between the current methods for locating NEOs is presented mathematically. The limiting magnitudes for the systems are calculated using equations developed by Alan Harris. Therefore the larger the calculated number, the better sensitivity of the detection system. The presented mathematical model is taken from a previous comparison by Alan Harris (ref. 16). In his paper, Harris examines the benefits offered by CCDs over the then commonly used photometric plates. In this paper, a comparison of his data with values calculated by assuming an STJ with similar properties of a CCD, but with a more accurate QE, is provided. A description of the symbols used is provided in table 1. The results displayed in table 2 (in the bottom section) show that even when assuming the S/N ratio and limiting magnitudes are the same for the CCD and STJ, the enhanced QE allows an STJ system to find darker targets.

Table 1. Description of Symbols

Description	Symbol
Effective aperture, m	D
Effective focal length	f
Field of view	-
Quantum efficiency	Q
Number of pixels to contain image	N_p
Area of a point image, arcsec^2	A
Exposure time, s	t
Limiting magnitude	m_1

Table 2. Limiting Visual Magnitudes for Detector Technologies

	CCDs	STJs	Assumed for all systems	
S/N	6	6	A	2
Q	0.3	0.8	D	4
m_1	20.5	20.5	t	165
	Photographic limiting magnitudes	CCD limiting magnitudes	STJ limiting magnitudes	Description
Relatively stationary bodies	17.95	23.37	23.83	Object does not move in frame
Relatively short trailed objects	21.10	26.14	26.61	Object moves at rate > $\left[\sqrt{A}/t\right]$
Relatively long trailed objects	22.92	25.19	25.65	Object's trail spans over more than length of detector, here assume they are all the same length (5 cm): rate of movement>length of chip/t

Quantum Efficiency Comparison

It should be noted that the results depicted in table 2 assume conservative input values. To adequately reflect the performance of an STJ, the lack of readout noise needs to be considered when determining the value for the S/N ratio. Due to a lack of available estimates, CCD values were assumed to calculate a lower estimate. When complete STJ data sets become available, better comparisons can be formed. Based on the limited information available, a comparison of developed QEs is shown in figure 1. The higher the QE value, the better the detection device performs at any given wavelength.

Figure 1 is based on information gathered from reference 3 for CCD and eye, and reference 6 for STJs. As shown in the constructed graph, STJs do cover the wavelength range with higher average QE. While some of the wavelength coverage is not currently as efficient, many experts predict improvements with the STJ construction in the near future (next 10 years). Many articles note that hafnium-based STJs have shown improvements in QE (ref. 5). The data in figure 1 have also been limited by the atmospheric interference. One major beneficial change would be a space-based platform. Such improvements would then lead to the next graphical comparison, found in figure 2.

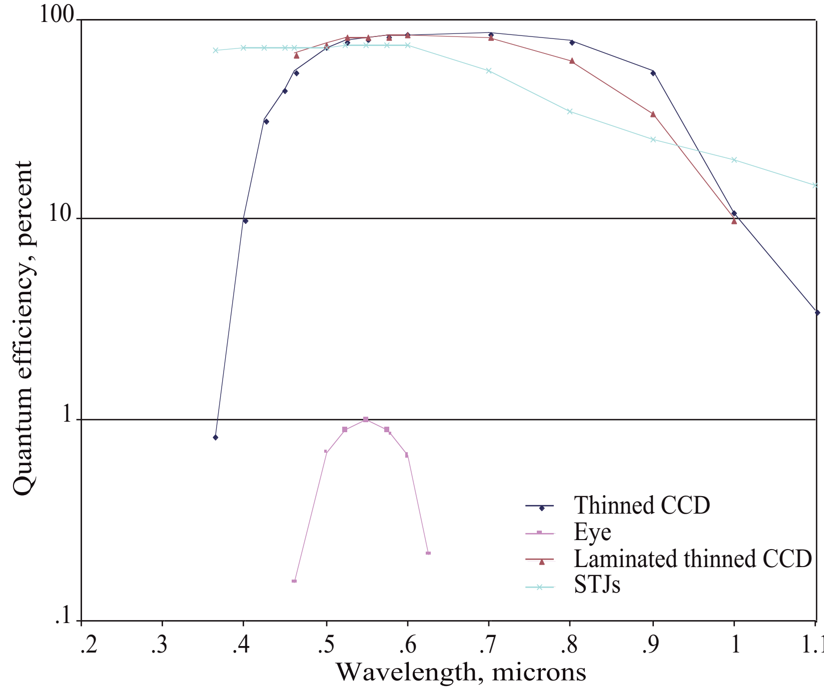

Figure 1. Quantum efficiencies for detector technologies.

Figure 2 is based on information gathered from reference 3 for CCD and eye, reference 6 for STJs, and projected hafnium abilities from personal communication with Mark Cropper (2002) and reference 5. Note that the QE for the projected hafnium-based device is a modest lower estimate. The actual device will have varying QE in relation with wavelength. Figure 2 depicts the projected abilities of the technologies according to Mark Cropper and Dr. Mazin as of the year 2002. When these technologies become available, it is clear to see (the orange line) that the STJ hafnium-based detector placed on a space-based platform will result in the best coverage. According to Dr. Cropper, the STJs will be able to achieve a QE of 90 percent for most of the observable wavelengths.

Near-Earth Object "Tagging"

The idea of assigning an identification description to an NEO apparition based on observable characteristics is theoretically possible. Several distinctions can be made between NEOs. Objects can be "tagged" at two instances: during and after observation.

Currently, "tagging" an object after observation is performed on a regular basis. The objects are separated by the rate at which they cross the frame. This method is performed by using the length of the trail and the time of exposure. In most cases, scientists can use the direction of observation to also infer direction of motion.

However, the trail identification method has some problems. One major concern for NEO tracking missions is the ability to reevaluate the orbit of the target. Many of today's NEO search programs lose objects before complete orbits can be calculated. One method to limit the number of lost targets would be to add more distinguishing characteristics to each description. As a result, any new observations of the previously identified object would be more readily confirmed. With more observations, the object's orbit becomes more accurately determined.

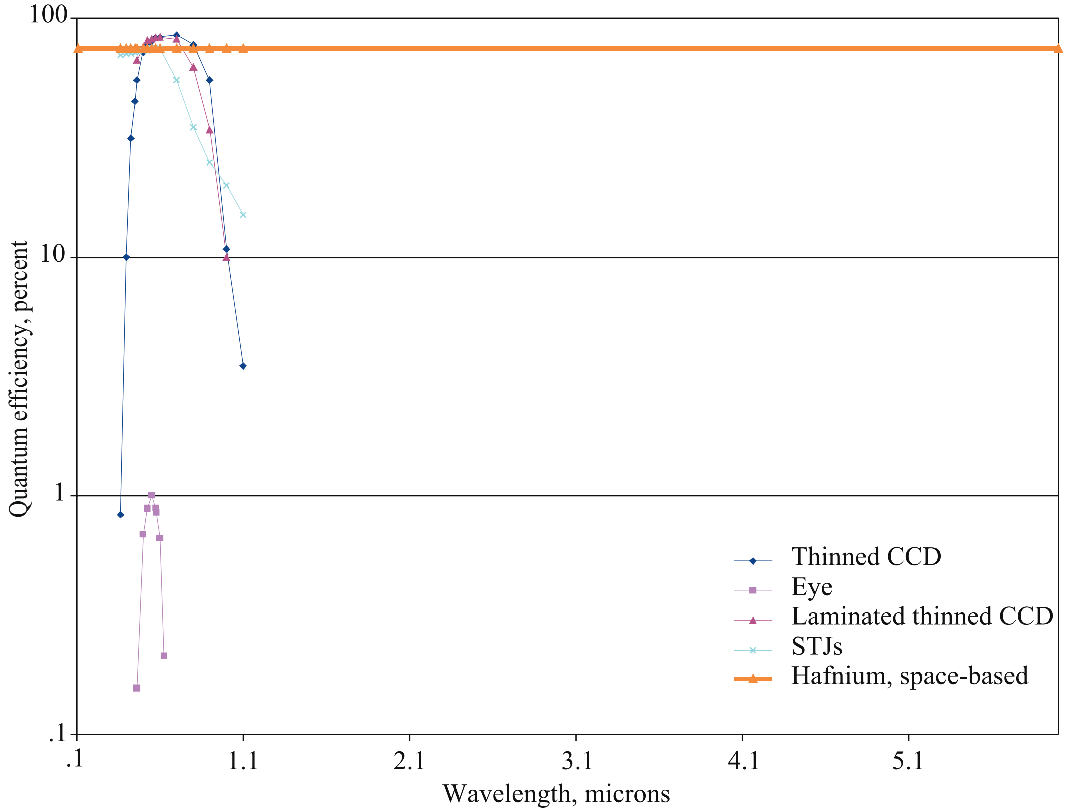

Figure 2. Quantum efficiency percentages of hafnium space-based STJs and other detector technologies.

There are three inherent characteristics of STJs and TESs that could aid in the reacquisition of NEO targets. One such characteristic is the spectral identification of each incident photon. While the objects may streak across the frame, most of the objects do not complete rotations on the scale of scanning observations. Therefore, each incident photon should be from the same side of the target. Ideally, these identified spectral features could allow for quick classification, especially if the aforementioned 2-µm wavelength is observed. Not only is the target less likely to be incorrectly identified as a new object, but also scientists could gain a general idea of the surface composition. Other devices can gain this spectral information as well, but only at the cost of signal detection because other detectors require filters to collect spectral data.

STJs and TESs also offer the same tracking abilities as the previously mentioned CIDs. The key to CID's various modes of operation were in their individualized connections to the computing hardware. STJs and TESs share that individual connecting construction and therefore it seems reasonable that they too could be used in various tracking modes. Being able to split the usage of the actual detection device could also minimize the number of lost targets.

There is one more attribute that the TESs and STJs have that may help tracking abilities: inherent time assignment to each incident photon. Another frame image that may become confusing for an automated computer detection system is that in which two or more objects have crossing trail patterns spanning over the entire detector. Trail patterns could become mixed or simply useless. However, with STJs and TESs, the computer can easily determine the direction of each object by time association. By comparing when each incident photon was detected, the computer can identify the "track" each object created.

The possible benefits of the new cryogenic devices are clear and numerous. While the more developed technologies do offer the same capabilities with the right extra equipment, the newer devices are much more efficient. Once the system has identified many of the NEO targets, research time on telescopes with the cryogenic devices will also be attractive to deep space astronomers. The devices are ideal for such subjects as pulsars or gamma ray bursts.

Array Sizes/Shapes

The possible size and shape of detection devices are also important factors in determining the best system. Currently, CCDs and CIDs are well-developed technologies and can be constructed in nearly any size or shape a reasonable project would require (personal communication with Dr. Bob Leach and Dr. Mark Cropper). Large (20000 × 20000 pixels) CCDs and CIDs are constructed as mosaics; however, this type of engineering cannot be directly applied to the newer cryogenic devices due to their complicated wiring/magnetic structures. Because STJs and TESs are only in the infancy of development, they are currently no bigger than a postage stamp. Yet, experts such as Dr. Cropper believe with proper funding, a multiplexing configuration or layering process could lead to competitively large arrays within 25 years.

Concluding Remarks

Considering all possible detectors mentioned herein, the benefits of transition edge sensor (TES) and superconducting tunneling junction (STJ) detectors are clear. Not only are the new devices more efficient, but they may offer benefits yet to be fully appreciated. Although they are experimental, assuming the cooling and engineering problems are resolved, usage of the TES/STJ detectors should be recommended. The sensitivity is slightly improved due to lack of readout noise, and the STJs and TESs offer other benefits, such as time tagging, inherent spectral capabilities, and versatility of operation. The largest problem facing the development of STJs and TESs is the cooling technology required to successfully operate the devices. The hafnium-based STJ needs to be kept at 0.01 K.

If a single advanced detector technology is not available or is limited, the solution for the Comet/Asteroid Protection System (CAPS) telescopes is to use multiple detector devices. This approach would use a combined cryotechnology and charge-coupled device (CCD) device, thus allowing for the visible and micrometer wavelength coverage. The refrigeration requirements are more reasonable (≈35 K for the system and 10 to 15 K for the devices) than those for STJs or TESs, and a computer model has already been developed. This type of approach has already been proposed for asteroid searches by Edward F. Tedesco and colleagues, and is described in reference 12.

The next step in the comprehensive study of revolutionary detector concepts is to add these described detectors to a working near-Earth object (NEO) detection computer program. After running the software with the various configurations, a general comparison can be made. Once the most effective system is determined, cost needs to be estimated. Finally, a cost/benefits comparison should then be preformed.

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