AN ALL-SKY OPTICAL SETI SURVEY

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ABSTRACT

We present plans for an all-sky search for pulsed optical SETI beacons at Agassiz station in Harvard, Massachusetts. We will use a 1.8 meter f/2.5 spherical “light bucket” (2-3 arcmin resolution) focused onto a multi-pixel camera consisting of sixteen 64-pixel photomultiplier tubes (with pixels measuring 1.5 arcmin on a side) in two matched focal planes. It will observe a $1^{\circ}\!.6 \times 0^{\circ}\!.2$ patch of the sky in transit mode, thereby covering the Northern sky ($-20^{\circ} < \delta < +60^{\circ}$) in 150 clear nights. Fast custom IC electronics will monitor corresponding pixels for coincident optical pulses of nanosecond timescale, triggering storage of a detailed digitized waveform of the light flash. Analysis will be similar to that from our ongoing targeted search.

Subject headings: interstellar communication; SETI

1. Introduction

Just two years after Cocconi and Morrison’s famous suggestion[1] that scientists look for signals from extraterrestrial civilizations at the 21 cm hydrogen line in the radio spectrum, Schwartz and Townes[13,15] proposed broadening SETI to include the optical spectrum. However, lacking the technology to construct sufficiently high-power optical transmitters, it was difficult for SETI researchers to justify building optical receivers; as such, optical SETI was primarily a theoretical exercise.[*] Spurred on by an annual Moore’s law doubling in optical laser power during the last 40 years, and the realization that we could build an optical transmitter capable of signaling across the galaxy today, optical SETI is coming of age.

One observing strategy in optical SETI is to look for narrow laser lines in the high resolution spectra of astrophysically interesting objects. Geoff Marcy and colleagues are “mining” their radial-velocity survey data for such lines[9]. Likewise, we have proposed that NASA’s Terrestrial Planet Finder (TPF) may serendipitously discover an extraterrestrial laser beacon intermingled with the chemical signatures of basic life in an extrasolar planet’s atmospheric spectrum[6]. An alternative observing strategy is to look for short optical pulses[11]. Optical SETI programs at Columbus[7], Berkeley[8], Harvard[5], and elsewhere now monitor individual nearby stars using this strategy in the 300-600 nm band. Note that with both observing strategies, one is looking for a signal with no natural astrophysical analog.

The primary attraction of optical SETI is the high gain of optical telescopes. With gains as high as 10^{16} (e.g., a Keck-class telescope at $\lambda = 330\,\mathrm{nm}$ – a factor nearly 10^{9} greater than the Arecibo observatory at $\lambda = 21\,\mathrm{cm}$), optical beams can be narrowly focused on planetary systems, and can compensate for the high energy cost of optical photons (relative to microwaves). Furthermore, temporal dispersion, which restricts galactic radio communication to relatively low data rates, is entirely negligible at optical wavelengths. As we have previously shown[5], using only “Earth 2000” technology – a transmitter capable of delivering nanosecond speed, megajoule optical pulses[14], at a 10 Hz repetition rate, attached to a Keck-class telescope – we could outshine our Sun, in the direction of the microradian beam, by a factor of more than 1000 in broadband visible light during the brief pulses; this signal could be easily detected by another Keck-class telescope at distances of up to

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[*] Of course, there are exceptions: notable early OSETI observers include Betz[2] and Schvartsman[12].

300 pc. The detector can also be much simpler than the computational workhorses used in radio SETI today, for example, a pair of photodetectors whose outputs feed multilevel discriminators corresponding to 1, 2, 4, 8, 16, etc. photoelectrons.[†] At nanosecond speeds, pileup of multiple photons from the host star is exponentially suppressed; the extraterrestrial's optical pulse manifests itself as many photons arriving at the detectors in an unresolved time interval, against a background patter of single, Poisson distributed photon arrivals from the host star.

2. Targeted Optical SETI at Harvard

In this section we will discuss the basic ideas of pulsed optical SETI by describing our ongoing targeted search for pulsed signals. As you will see in §3, the all-sky survey is a straightforward generalization of this experiment.

2.1. The Experiment

Our targeted search program runs piggyback on a stellar radial-velocity survey at the 1.5 m telescope at Agassiz Station in Harvard, Massachusetts. These experiments use an echelle spectrograph to measure the periodic Doppler shifts of stellar spectra indicating unseen companions. Our experiment takes about one third of the light from the relatively narrow field of view (a 15 arcsec circular patch) of the telescope, unused by the primary spectrograph, as shown in Fig. 1.

This light is re-imaged and passes through a beamsplitter into two hybrid avalanche photodiodes (Hamamatsu R7110U-07), whose outputs feed a pair of multi-level discriminators with levels corresponding to roughly 3, 6, 12, and 24 photoelectrons. By time stamping level crossings with a LeCroy MTD-135, we obtain approximate "waveforms" of incoming pulses.[‡] Coincident pulses seen in both channels trigger the microcontroller to record the waveform profiles and arrival times of both channels. A "hot event" veto filters out a class of large amplitude, bipolarity signals which appear to be produced by breakdown events in the photodetectors. Counters, and various controls and monitors allow us to test the apparatus and monitor its long term fitness. Fiber-coupled LEDs test the detectors and coincidence electronics before every observation.

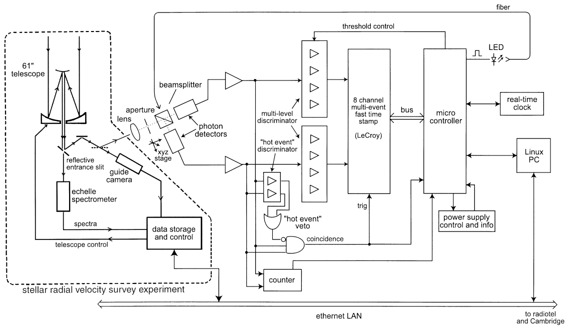

Fig. 1.— Block diagram of the targeted search.

The diagnostic data, along with coincident pulse data, are sent to a PC and recorded in a log file. After each night of observations, the log files are automatically transferred to computers at Harvard University where they are incorporated into a web-enabled database to facilitate analysis. We track the data through automated daily emails which summarize the previous night's observations. Additionally, the web-enabled database allows us to easily view the data in many forms: chronological summaries, ordered searches by various criteria, observational summaries for individual objects, diagnostic data for particular observations, etc.

Our target list is composed of objects being surveyed both for SETI and for other astrophysical interests. Dave Latham and colleagues have recently begun characterizing 11,000 F, G, and K dwarfs (800 completed thus far) for possible observations by next generation targeted SETI searches. Specifically, they're looking for evidence of stellar companions that would interfere with planets in the habitable zone. A sample of G dwarfs is being probed for close-in giant planetary companions to determine their galactic frequency and metallicity distribution. Various other programs observe a variety of other targets (A dwarfs,

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[†] The pair is wired in coincidence to reduce the background event rate due to occasional large pulses in individual detectors – a technique pioneered in optical SETI by Dan Werthimer at Berkeley.

[‡] Actually, the microcontroller records the *last* rise and fall times of a waveform through the four levels. This arrangement does not record detailed measurements of complex waveforms (double pulses, for example).

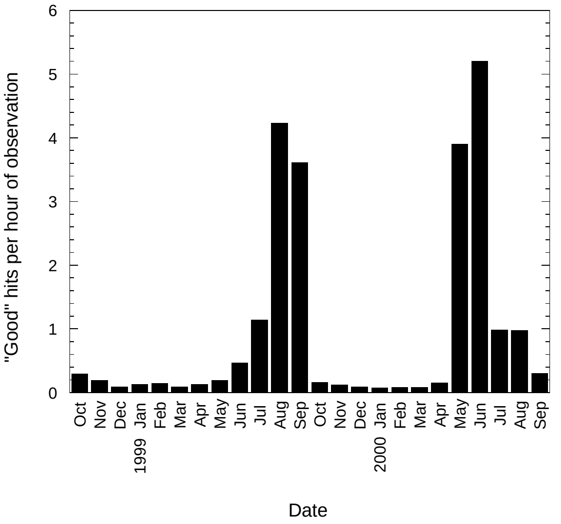

Fig. 2.— Here we show the humidity-induced seasonal trend in the "good" hit rate.

very young stars, very old stars in the Solar neighborhood, etc.).

2.2. Results

From October 1998 through September 2000, the targeted search has performed 15,000+ observations of 4,000+ stars, for a total of 80+ days of observation, as shown in Table 1. We do not have any evidence for pulsed optical beacons from extraterrestrial civilizations.

During this time, we have had over 4200 "hits." We define a hit to be an instance when the lowest thresholds are simultaneously exceeded in both channels. Although all hits are recorded, the "waveforms" are automatically passed through a filter which enforces certain sanity checks: the signals seen in each channel must be roughly the same amplitude (within one level of each other), and they must overlap in time (this is used to filter a class of hits in which one channel rises again after the other channel shows no signal). The subset of hits which pass this test are labeled "good hits"; to date, we have registered over 1400. We do not believe that this categorization scheme misses extraterrestrial beacons: the LED test flashes, which are done before every observation, have *never* failed this test.

There is a marked systematic seasonal trend in the rates of coincident hits; in particular, the detectors appear to be sensitive to ambient humidity. During the cold, dry months of fall, winter, and early spring (October-April), the data exhibits a good hit rate of 0.12 hits per hour of observation and a total hit rate of 0.51 hits per hour of observation. However, the hit rates are 30-40 times higher during the warmer and more humid summer months (May-September), as shown in Fig. 2. Furthermore, we see a memory effect: observations following wet weather exhibit hit rates many times higher than the summer average, but drop back after 1-2 nights of clear weather. Opening the camera (which is normally kept tightly closed and flushed with dry nitrogen) for maintenance work similarly raises hit rates, but with a longer decay time constant ($\sim$15 days). These hits tend to be clustered in time with, say, 10 hits in 3 minutes followed by many quiet 10's of minutes, a characteristic typical of corona discharge.

We believe that humidity promotes corona breakdown in one detector, which affects the other detector via electromagnetic (EMI) and optical coupling. The small hybrid avalanche photodiodes run at 7.5 kV (compared to photomultiplier tubes, which typically run at 1 kV), and are prone to corona breakdown. To combat this problem we have added gas lines to the optical and electrical compartments, to keep them under a slight positive pressure of dry nitrogen, and we installed a glass entrance window. We also installed bakeout heaters (250 W total) to the aluminum exterior of the experiment to purge absorbed moisture. Although most of these upgrades were completed only recently, the summer good hit rate appears to have gone down to 0.2-0.4 per hour of observation. We believe that we have largely mitigated the humidity problem, and that regular bakeouts can reduce it to levels such that no seasonal data needs to be excluded.

We have ruled out stellar photon pileup as a significant source of hits. At nanosecond time scales, photons arrive at our detector individually; multiphoton pileups are exponentially suppressed. For example, a solar luminosity delivers 10^6 photons per second into a one square meter aperture at 1000 light years, or one *milli*photon per nanosecond. As shown in Table 1, the hit rates appear to be independent of visual magnitude (which is an exponential function of stellar intensity).

TABLE 1
OBSERVATIONAL SUMMARY

Visual magnitude	Observations	Objects	"Good" hit rate	Hit Rate	Observation time
0	87	8	0.67	2.68	9.0
1	9	2	2.70	8.11	0.4
2	68	20	0.33	1.46	6.2
3	284	38	0.33	0.95	24.2
4	425	96	0.32	0.99	34.2
5	541	152	0.14	0.46	49.7
6	799	280	0.10	0.49	92.0
7	2314	647	0.11	0.50	307.5
8	3016	850	0.10	0.48	398.2
9	1476	362	0.10	0.45	240.3
10	612	185	0.11	0.45	148.0
11	102	25	0.00	0.19	26.5
12	1	1	0.00	0.00	0.3
Total:	9734	2666	0.12	0.51	1336.4

NOTE.—Here we summarize our observations to date (October 22, 1998-September 30, 2000), excluding the humid months (May 25-September 30, 1999 and May 1-September 30, 2000). Hit rates are given in hits per hour and observation time is in hours.

2.3. Simultaneous Observations with Princeton

Given our current background level of roughly one "good hit" per night of observation, a single optical pulse from an extraterrestrial civilization would likely be categorized as a background hit. To attract attention, the signal would have to be composed of successive pulses from a source candidate, perhaps exhibiting non-random arrival times. We recognize that this is a shortcoming of the experiment – we may miss a true beacon.

To address this problem, we are collaborating with Dave Wilkinson and colleagues at Princeton University to duplicate our experiment on their 0.9 m Cassegrain telescope in the Fitz-Randolph Observatory. This telescope will follow the Harvard telescope through its nightly observing programs, beginning in a matter of months. We plan to discipline the system clocks on the control computers at Harvard and Princeton to high accuracy; techniques have been demonstrated that can achieve computer synchronization accuracies of 20 microseconds or better using external GPS receivers.[10] Note that since Harvard and Princeton are separated by ∼300 miles ≈ 1.6 light milliseconds, the time travel delays are resolved at this temporal resolution. With good absolute time resolution, we can additionally verify that an observed time delay is consistent with the observing geometry. Figure 3 shows the angular uncertainty in the plane defined by the inter-site separation vector and the star's position vector as a function of elevation for three values of timing uncertainty between the Princeton and Harvard observatories.

Assuming that the background rate r_b of each experiment is 1 hit per hour, and if we require that each event be within a time window of, say, $\tau = 1$ millisecond, then the combined background rate is $r_b^2\tau = 3 \times 10^{-7}$ hits/hour, or 1 hit every 300 years. With such a low background rate, we would have to examine seriously the astrophysical and extraterrestrial significance of even a single coincidence at the two observatories.

3. Design of the All-Sky Survey

Despite these efforts, the targeted search has a significant shortcoming; after nearly two years of data collection, we have covered less than one millionth of the sky. With $\sim 10^6$ sun-like stars within 1000 ly, and the possibility that advanced life may exist in the voids between stars, a complementary observing strategy of targeted searches and sky

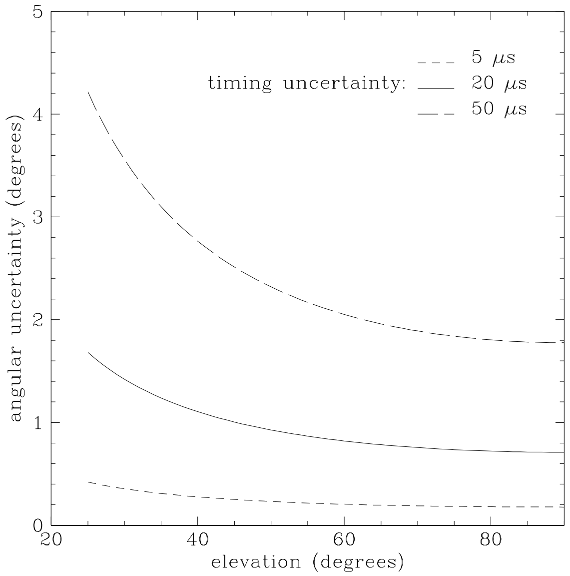

Fig. 3.— Plots of angular uncertainty (in the plane defined by the inter-site vector and the star's position vector) vs. elevation for three values of timing uncertainty between the Princeton and Harvard observatories. Modern computer synchronization techniques can achieve accuracies of 20 microseconds or better.

surveys represents the greatest chance for success in optical SETI.

We have begun construction of a wide-field telescope with a fast, pixelated photodetector whose sensitivity to pulsed optical beacons is complementary to our targeted search. The telescope will view a $1\overset{\circ}{.}6 \times 0\overset{\circ}{.}2$ field with a pair of 512-pixel photodetectors operating in meridian transit mode with adjustable declination and fixed hour angle: each pixel will cover 2.3 square arcmin. It will scan the sky in 1200 hours – roughly 150 clear nights. Each point on the sky will be viewed for a minimum of 48 seconds with this experiment; polar regions are viewed for longer periods of time.

As mentioned above, the all-sky survey will look for pulsed optical beacons with a strategy complementary to the targeted approach. In the latter experiment, we are able to choose stars that we believe are likely to harbor life (as well as the targets in the radial-velocity surveys), and observe them for many tens of minutes. The all-sky survey will observe these stars, and millions more, but for shorter periods of time. Freeman Dyson has pointed out that the SETI community's bias towards observing stars may even be misplaced; extraterrestrials may live in, and transmit from, the *voids* between the stars[4]. The all-sky survey will observe these areas too. Although low duty cycle optical beacons may be missed in the all-sky survey, they are guaranteed to be on the target list (assuming that they're visible from the northern hemisphere). As with SETI at all wavelengths, we believe that a balanced strategy of careful observations of candidate stars coupled with broad surveys of the entire cosmos represents the best chance for contact.

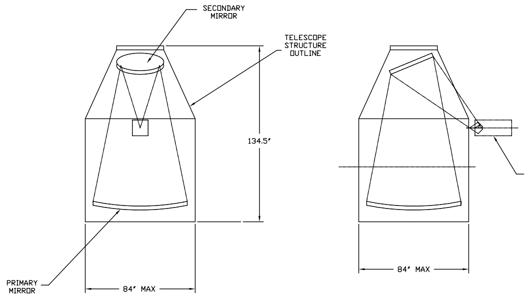

Fig. 4.— Two views of the "pseudo-Newtonian" telescope to be used in the all-sky survey. The steel support structure surrounds and holds the primary and secondary mirrors, as well as the detector package.

4. Telescope and Physical Infrastructure

The 1.8 m telescope for the all-sky survey will be fabricated by fusing a thin glass slab over a spherical form, then figuring and polishing. Including the effects of spherical aberration, the primary mirror's star images will exhibit 2-3 arcmin of blur.[§] As shown in Fig. 4, the telescope (perhaps better described as a "light bucket" given its limited optical quality) is a "pseudo-Newtonian" with a 0.9 m flat secondary mirror at 22.5° with respect to the optical axis. The detector optics, shown in Fig. 5, consists of a large beam splitter

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[§] A parabolic primary mirror has severe off-axis coma for the wide field and small f-number that our experiment requires. A fast parabola without additional correctors is worse than a sphere, and harder to make.

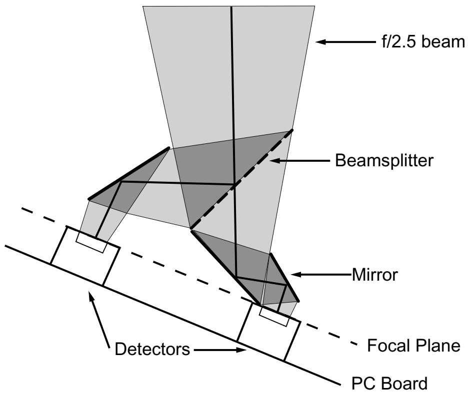

Fig. 5.— After reflecting off of the flat secondary mirror (in Fig. 3), the converging f/2.5 beam passes through a beamsplitter. The reflected and transmitted halves fold once and twice, respectively, on smaller mirrors so that two identical images appear on their respective detectors in the same focal plane.

and three folding mirrors to image the beams onto two rows of detectors attached to a single printed circuit board. We determined that this imaging configuration was much easier than using a beamsplitter with no folding mirrors, because in the latter case the two beams are imaged on to two separate PC boards in a dihedral arrangement with all of the high-speed data from one board flowing to the other.

The building that will house the all-sky survey measures 9 m (N-S) × 5 m (E-W), and is shown in Fig. 6. The telescope will sit on an isolated concrete pier in the southern part of the building while the northern part is comprised of a covered control room for electronics, computers, motors and other equipment. A rolling roof sits on rails that span the length of the building and extend another 7 m to the North on a steel support structure. This roof will be parked to the North during observations; it can also extend slightly over the South wall so that heavy equipment can be lifted into the building using a steel beam in the roof truss structure. A section of the South wall will roll down for viewing on the southern horizon.

5. Detectors, Electronics, and Software

The detector package will house the beam splitting and folding optics, photodetectors, full-custom chips and other electronics. It is the brains of the all-sky survey. We discuss several parts of this package below.

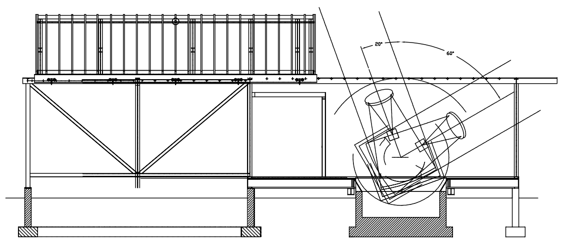

Fig. 6.— Here we show the all-sky survey telescope in its building with the rolling roof extended to the North.

5.1. Multi-pixel Photomultiplier Tubes

Without the recent advances in the photodetection industry, it would be difficult to pursue this all-sky optical survey. Hamamatsu, among others, recently introduced multi-pixel photomultiplier tubes, which have the radiant sensitivity (quantum efficiency of ∼10-20% for 300-550 nm), gain ($\sim 10^6$), and the speed (rise time of ∼1 ns and FWHM of ∼3 ns) of traditional, single-pixel photomultiplier tubes in each of 64 independent pixels. The tradeoff for adding pixels is anode nonuniformity, which varied by a factor of three in a sample tube we used.[¶] These tubes, like all photomultipliers, also show poor pulse height resolution owing to the statistics of cascaded, low gain stages; individual photoelectrons are incompletely discriminated from unresolved pulses of, say, five photoelectrons, but are easily separated from ten photoelectron pulses.

The tube has an active area of 18.1 mm on a side, with each of 64 square pixels measuring 2 mm on a side with 0.3 mm gaps between pixels. Because packaging overhangs the active area by another 6 mm on a side, we will stagger 16 of these tubes into a pair of one by eight declination stripes.

A pair of pixels – one from each declination stripe – observing the same $1'.5 \times 1'.5$ patch of the sky will function like the single-pixel experiment described in §2. Each pixel pair produces a pair of nanosecond speed analog electrical signals that

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[¶] This appears to be an engineering and manufacturing problem and should not be a long term feature of multi-pixel photomultipliers.

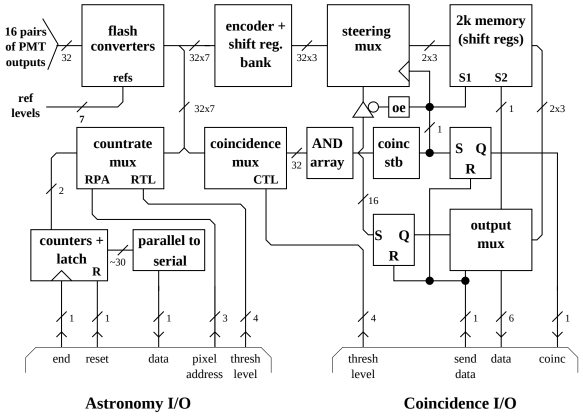

Fig. 7.— Block diagram of an OSETI signal processor chip.

must be constantly monitored. With 512 such pairs, the electronics to detect large amplitude coincident pulses becomes complex.

5.2. OSETI Signal Processor

Analog data from these 512 pairs of pixels will be analyzed on thirty-two, identical full-custom chips – the signals from two detectors are handled by four chips. These chips are presently being designed in-house, and will be fabricated on TSMC's 0.25 μm process. Their primary purpose is to monitor pixel pairs for large amplitude pulses; additionally, the chips will give a crude image by measuring the single photon count rates for each pixel.

The chip's block diagram is shown in Fig. 7. Sixteen pairs of corresponding channels from two photodetectors are fed into each signal processor, as shown on the left. The signals enter a flash converter bank with seven externally set, logarithmically spaced reference levels. Each flash converter is composed of seven gate-isolated clocked sense amps[3]. Every 2 ns, the analog PMT signals are digitized into thermometer code (7 bits per pixel, where a given bit is high if the corresponding level was exceeded by the input). The lowest level corresponds to $\approx$15 mV, still well within the single photoelectron energy spectrum; the highest level will be $\sim$1 V, or roughly 100 photoelectrons. The outputs of the comparator bank feed both the coincidence and astronomy circuitry.

The coincidence circuitry starts with a multiplexer (mux) that passes the externally set threshold bit from every channel. A coincidence is detected by ANDing corresponding pairs of these bits together.[‖] The output of this block, the one-of-sixteen address of a coincident pixel, is latched and fed to a steering mux. Meanwhile, the output of the comparator bank is also fed into an encoder bank which compresses each channel from 7-bit thermometer code to 3-bit Gray code. This signal is also delayed for $\sim$10 clocks in a shift register bank while the coincidence circuitry has time to act. The steering mux then diverts 2048 clock cycles of the coincident channels to the memory bank of shift registers. While all of this is happening, the coincidence strobe (simply the latched OR of the coincidence address) notifies an external microcontroller that a coincidence was registered. The microcontroller then acknowledges this, and the 4 ms (total duration at 2 ns resolution) encoded waveforms of the coincident channels, as well as the address of the coincident pixels, are passed to the outside world. The chip then resets itself and waits for the next coincidence.

The astronomy section of this signal processor operates in parallel with the coincidence detection section. A mux passes only two of the 32×7 of the same comparator bank outputs – those corresponding to a particular pixel pair (both channels) and a particular level (which is, in general, different from the coincidence threshold level). A pair of counters then measure how many times the level is exceeded in that pixel pair during a programmable length of time. This countrate, which is a measure of the light intensity on the pixel pair, is latched and passed to the outside world.[**] By cycling through the various pixels, the microcontroller can obtain a crude image.

5.3. Other Electronics

All thirty-two signal processing chips, along with the 16 photomultipliers will reside on a single PC board. A microcontroller will orchestrate the flow of data between the signal processors and a serial port connection to an external computer.

[‖] If the hit rate becomes too high, we can reduce it by using a higher threshold bit. This of course comes at the expense of weak signal sensitivity.

[**] Note that the countrate is only proportional to the intensity for the single-photon level. In general, a count rate for n-photons is proportional to the intensity to the nth power.

It will also monitor pixel countrates and perform various diagnostic functions. The challenging details of this board have yet to be worked out; in theory, it will be a parallelized version of the targeted search's electronics.

5.4. Software

The signal processing chips will reduce the data flow to a manageable rate.[††] Still, we can expect substantially more data than with the targeted search since we are viewing a much larger portion of the sky.

The software, like the chips, will have two primary functions: astronomy and coincidence detection/archiving. It will monitor the pixel countrates to obtain a sky image which will be used to accurately determine where the telescope is pointed. This will allow it to tag the locations and times of coincidences. Additional software will distill the real time data to a searchable archival form, perhaps in a database. These details will be worked out after the electronics have been built and tested.

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[††] With 1024 7-bit flash converters operating at 500 MHz, the pre-filtered data rate is truly enormous – 3.5 *tera*bits per second. That's the contents of all books in print, every second!