Omega Prime: The Wide-Field Near-Infrared Camera for the 3.5 m telescope of the Calar Alto Observatory.

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ABSTRACT

Omega Prime is a wide-field near-infrared camera for the prime focus of the Calar Alto 3.5 m telescope in Spain. The detector is a 1024 x 1024 pixel HAWAII array made by Rockwell. The image scale is 0.4 arcsec/pixel, giving a field of view of 6.8 x 6.8 arcmin. In order to maximize the throughput, the optics were designed as a prime focus corrector with only three lenses. This simple design without a cold pupil provides an excellent image quality over the entire field of view. To reduce thermal background at wavelengths longer than 2.2 μm, Omega Prime has a series of cold internal baffles and an additional toroidal mirror outside the dewar. This annular reflector causes detector pixels to "see" mostly the cold interior of the camera. The camera has been in operation since May 1996 and has been used for a variety of scientific programs, including a very deep K' survey covering 1000 square arcmin to a 5 σ limit for point-sources of 20.5 magnitude.

Keywords: HAWAII array, near infrared, wide field camera,

1. INTRODUCTION

The numerous upcoming 8m class telescopes call for new scientific goals for the 4m class telescopes. Wide field surveys are a useful task for these telescopes if appropriate instruments are available. Wide field cameras are common for the visible wavelength region, but are presently rare for the near infrared wavelengths on large telescopes.

The availability of 1024 x 1024 pixel infrared arrays was the primary driving force behind the idea for a high efficiency wide field IR camera designed for the 3.5m telescope at the German-Spanish Calar Alto Observatory in Spain. The nature of the site and the scientific requirements favored the 1-2.5 μm wavelength range, hence the instrument was designed around the HgCdTe HAWAII array from the Rockwell International Science Center. This selection also simplified the technical requirements, allowing for simple liquid nitrogen cooling. Another goal was to develop the camera on a fast timescale, going from concept to commissioning in about one year. Our camera, which we have named Omega Prime, was commissioned in May 1996, and was one of the first cameras operating a 1024 x 1024 pixel IR Focal Plane Array (FPA). The continuing heavy demand for this instrument, as well as the projects already completed with Omega Prime over the last two years, attest to its success.

2. OPTICS, FILTERS, AND BAFFLING

The optical designs of most IR imaging cameras are based on a re-imaging system, producing a real image of the entrance pupil between the collimator and camera. Here, a cold Lyot stop is placed at the pupil to reduce the background light by blocking emission from the telescope structure surrounding the primary mirror. Such an optical design also provides for greater flexibility, allowing for spectroscopy or polarimetry with the addition of the appropriate optical elements (e.g., slits, masks, grisms, polarizers). However, it proved to be a non-trivial task to realize a reimaging optical design for the f/10 focus of the 3.5m telescope yielding 0.4 arcsec per pixel over the full 1024 x 1024 pixel FPA, requiring many surfaces and materials to correct all of the aberrations. This was made particularly difficult by the small pixel size (18.5 μm x 18.5 μm) of the HAWAII array[4)5)].

Prime focus correctors are commonly used for wide field imaging at visible wavelengths. Here, the optics are located in front of the telescope focus, simplifying the optical design for wide field imaging. Unfortunately, this configuration provides no real pupil image for baffling, and the higher background becomes a limiting consideration at IR wavelengths[2].

Nevertheless, our calculations showed that the disadvantages of the higher background caused by working without a cold stop at prime focus were compensated by the much wider field of view (assuming 0.4 arcsec/pixel versus the 0.3 arcsec/pixel of a feasible optical design that included re-imaging) and higher throughput (of only 1 mirror and 3 lenses), as long as the additional background does not exceed a certain level. This condition can be reached even in the K band by using other forms of baffling than a conventional design with a traditional Lyot stop.

2.1 OPTICS

The Omega Prime optics were designed by Eric Mentzel of Perseus Consulting, USA. The corrector triplet (Figure 1) has some power, compressing the telescope's f/3.3 beam to a final focal ratio of f/2.75, which corresponds to the 0.4 arcsec / pixel scale at the 3.5m telescope. Two different materials, CaF_2 and Fused Silica, are used to minimize chromatic aberrations. Because wide-field surveys are often done by combining multiple, shifted images into final mosaics, we required excellent image quality over the entire field.

The calculated spots, even at the corners of the array, are less than 2 pixels, with 80% of the enclosed energy within one pixel (Figure 2). It is also crucial to control image distortion for applications involving wide-area mosaics. The distortion in Omega Prime is less than 0.25% from center to corner, i.e. less than 2 pixels. Omega Prime is not equipped to image simultaneously at two or more wavelengths, so the optical design was optimized for each of the three bands separately and therefore the telescope must be refocused when the wavelength of interest changes from one band to another (Figure 3, left panel). The design is fairly telecentric, where a change in focus (a change of filters) does not change the image scale.

The optics were optimized for operation at 77 Kelvin (liquid nitrogen). The empirical results achieved during actual observations agree very well with the original design goals. All of the lenses are broadband antireflection coated. The transmission for a single lens (2 surfaces!) is more than 98% over the whole spectral region, and more than 99% in the K band.

2.2 FILTERS

Omega Prime use standard astronomical filters from Barr Associates, fabricated in 2 inch diameter pieces. The filters are located between the last lens of the corrector and the detector, in the converging beam. Three motorized wheels can hold a total of 15 filters (6 slots per wheel, 1 empty slot per wheel). Interference filters shift slightly towards a shorter central wavelength and the FWHM broadens slightly when used in a converging beam. Calculations[6] show that this effect is still acceptable, particularly if the tolerances of the filters given by the manufacturers are taken in account, even though the peak transmission is slightly reduced. We therefore opted to use the available standard narrow band filters. For broadband filters the effect is negligible. The transmission of the filters is a main factor in the total efficiency of the camera. Typical numbers for peak transmission of the Omega Prime filters are >75% for broad band filters (e.g. peak transmission of K'=95%) and >80% for the narrow band filters. These relatively high values contribute to the very high total efficiency of the camera (see Section 6).

2.3 BAFFLING

Every detector element in Omega Prime "sees" the radiation emitted or reflected within 2π steradians. Only a small fraction of this is covered by the primary mirror. The rest is composed of the cold dewar shield, the warm telescope, and ist surroundings (mirror cell, floor, dome walls). To reduce the excess thermal background seen by the detector, it would be best to extend the length of the cold baffles as long as possible. The detector in Omega Prime therefore sits 45 cm behind the dewar entrance window. In fact, the limiting factor for the depth of the array in the dewar is the diameter of the dewar entrance window.
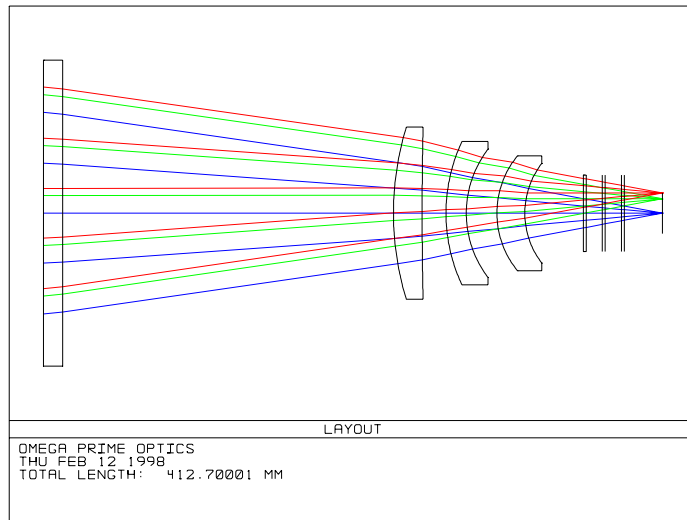
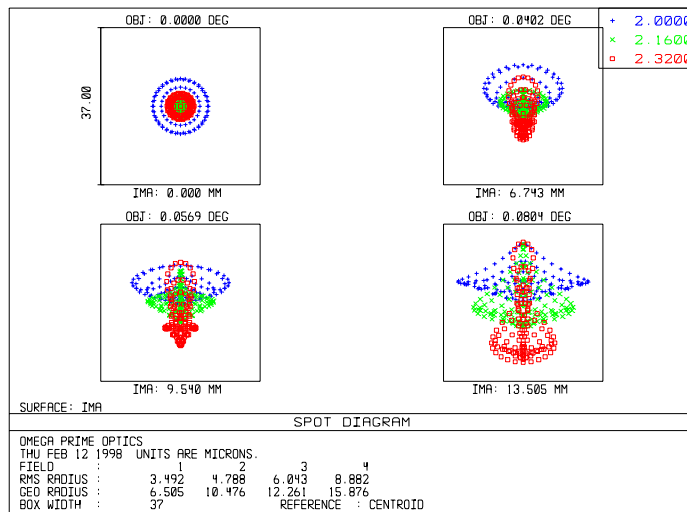**Figure 1:** Optical layout consisting of entrance window, lens triplet and filters

Figure 2: Calculated spots for the K band. Box size corresponds to 2 x 2 pixel on the detector.
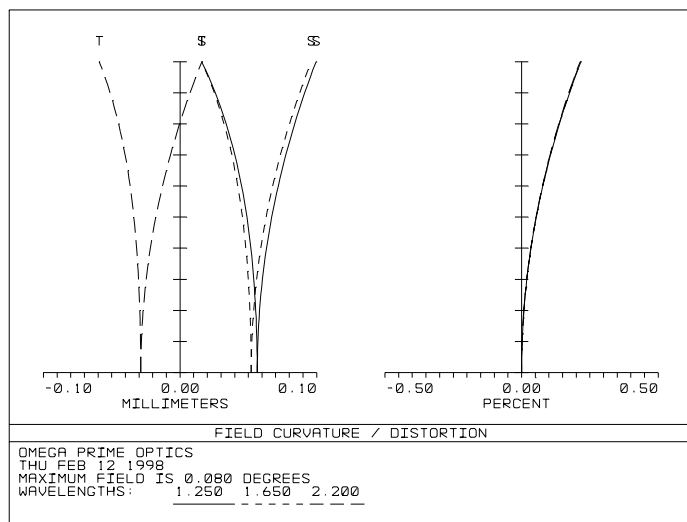

Figure 3: Refocusing is required for the different wavelength bands. Distortion is very low.

The window material is CaF$_2$, 8 inches in diameter, a compromise between reduction of the background and cost and feasibility of producing the window. The diameter of available CaF$_2$ crystals is limited, and the price increases nonlinearly with diameter. The danger of crystal defects increases, and the polishing becomes more difficult as well.

For further reduction of the background, an additional warm mirror baffle was added about 30 cm outside of the dewar window. This highly reflective annulus makes the detector elements 'look back' into the cold dewar. In cross-section the shape of the mirror is an oblate ellipsoid with the two focal points placed at the edge of the first internal cold baffle. This shape is such that all rays coming out of opening in the first cold baffle are reflected back into the dewar. The position and diameter of the ring baffle is defined by the central obscuration (hole) of the primary mirror if no additional obscuration is desired. The baffle was machined out of aluminum using a in house CNC mill.

3. MECHANICAL DESIGN

Omega Prime is built into a standard HD-10 dewar from Infrared Laboratories in Tucson, Arizona. It is equipped with two nested tanks for liquid nitrogen to ensure a stable temperature of 77 Kelvin for the detector and the inner parts of the camera. Both of the tanks hold 10 liters of LN$_2$. The hold time is more than 24 hours, even with the extra heat load through the big window direct on the inner shields.

The detector, optics and baffles are mounted off center in the dewar to maximize the size (and therefore capacity) of the filter wheels. The three filter wheels can hold 2 inch diameter filters, and are driven by external motors which are mechanically coupled via vacuum tight ferrofluidic feedthroughs. The dewar and the ring baffle are mounted together with a space frame on an xy stage which is mounted on the front ring of the telescope. The front ring can also be tilted around two axes, so an exact alignment of the camera with the telescope optical axis can be achieved. Omega Prime's dewar can be easily refilled with liquid nitrogen while on the telescope at the prime focus service position.
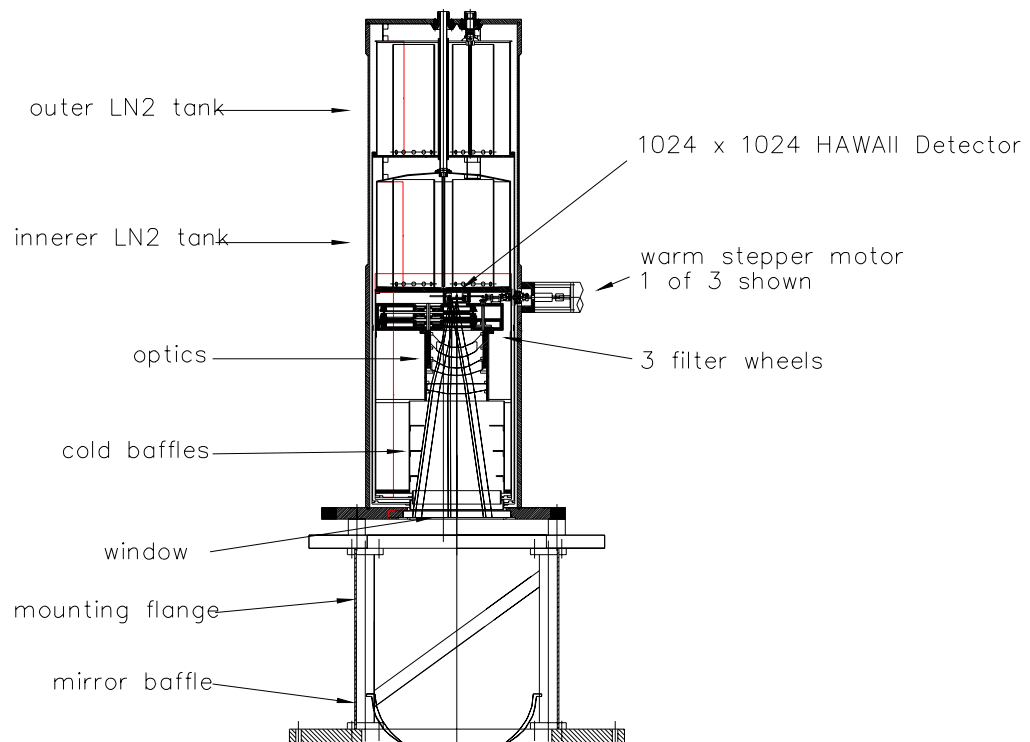

Figure 4: Schematic of the dewar and the baffle system.

4. DETECTOR AND ELECTRONICS

The detector used in Omega Prime is a 1024 x 1024 pixel HAWAII FPA made by Rockwell International Science Center[4][5]. The array has an intrinsic read noise of ~16 electrons when operated with the on-chip amplifiers. Including all electronics we achieve a read noise of ~25 electrons for a double correlated read. The recommended clock speed of 3 μsec per pixel defines the 0.8 sec minimum integration time for the whole array. A full well capacity of ~200,000 electrons is achieved with an applied 1 V reset voltage. A dark current of less than 0.1 electrons per second per pixel is well below the level which would affect the background-limited observations for which Omega Prime was built. Since the HAWAII array is a commercially available product, more information about the array can be found in the WWW.

The complete set of electronics was purchased from Infrared Laboratories in Tucson, Arizona. The MCE-3 readout electronics[3] are mounted in a standard VME crate. Four 1 MHz A/D converters are used to digitize the data. The electronics are equipped with a hardware co-adder, providing the possibility to subtract the two reads of a double correlated readout scheme in the camera hardware, before reaching the control workstation. This reduces the data rate to the computer by a factor of two. A fast fiberlink transfers the data from the MCE-3 electronics, mounted on the front ring of the telescope, to a frame buffer in the observing room. The buffered data is then transferred as a parallel data stream via direct memory access over an EDT SCD40 board to a SPARC20 workstation. The firmware on the MCE-3 currently supports two readout techniques: single correlated and double correlated reads. Other techniques commonly used to reduce read noise (e.g. sample up the ramp or multiple end points) are not necessary in Omega Prime as it can be used under background limited conditions in all filters. Even the narrow band filters are background limited in a few seconds of integration time (see Section 6).

5. SOFTWARE AND DATA HANDLING

The camera software was designed to control all of the infrared instruments operated by the Max Planck Institut für Astronomie (MPIA), independent of the detector type and specific camera hardware. In addition, the software can be used to control most of the major functions of the telescope where these instruments are used (three telescopes at Calar Alto and UKIRT). All software is written in C, and runs on SUN SPARC workstations under the Solaris operating system.

The basic process of the generic software is a command shell. Input to this shell can be made by typing commands with the keyboard, using a Graphical User Interface (GUI), or starting a pre-recorded macro file. The initiated actions start individual processes which can run parallel in background. The processing activities are synchronized by information from a database kept in shared memory for fast access. For image acquisition, the data are transferred from the fast I/O interface with DMA into shared memory. The shared memory is organized with two sets of buffers for the raw image data to enable simultaneous reading and processing of data, which increases the efficiency of data acquisition. Status information is continuously updated in the database to allow other running processes e.g. statistics, immediate access to the data. The image display process needs the data prepared according to the selected readout modes, filtering and scaling options. This happens on time, calculated from the raw data in memory. Some of the data processing options only affect the displayed data (e.g. scaling and filtering), while other options may also apply to the data saved to disk (e.g. integration of many exposures into a single disk image). There is no automatic data reduction offered by the software although both IRAF and MIDAS are available for immediate reduction and analysis.

The GUI and the macro option are essential parts of the software for convenient and efficient observing. Besides the camera, telescope control and data display for basic operation, the GUI also supports further capabilities such as user supplied object lists, standard star catalogs, and air mass display. This allows for intuitive handling of observing tasks and a visualization of the current activities. Macro files offer the most efficient usage of the instrument, telescope, and data handling. Coordination and synchronization of the various processes optimize the ratio of on-source integration time versus the system overheads.
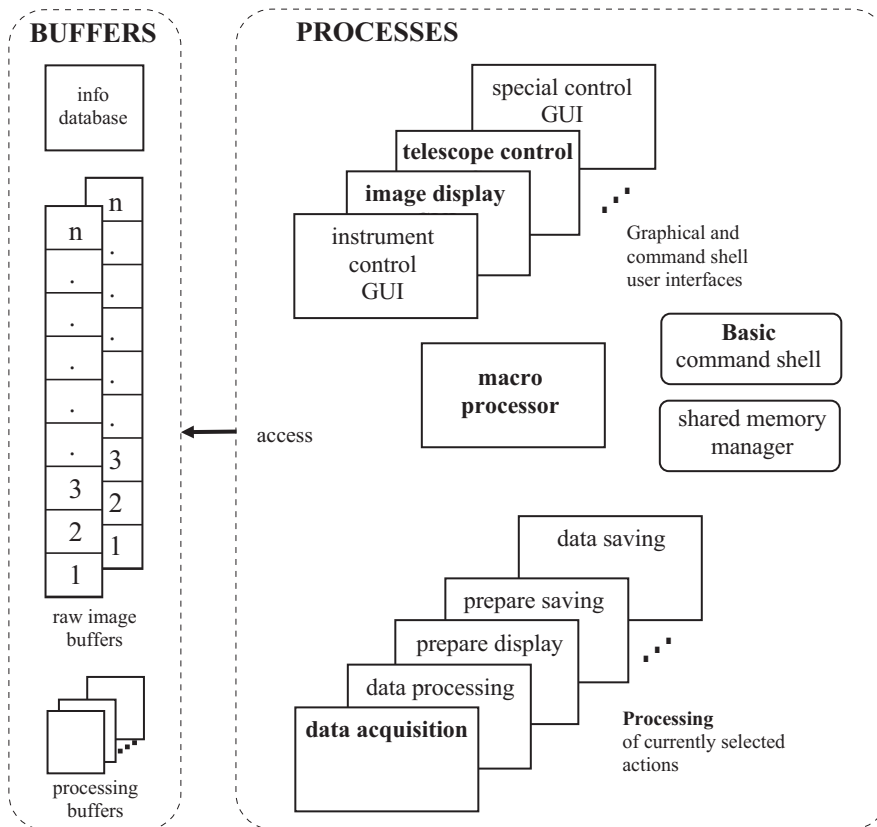
Figure 5: Software design

6. SYSTEM PERFORMANCE

The number for the throughput, given in the following, is determined from standard star measurements on the telescope. The very high number is in agreement with a rough calculation based on the throughputs of the individual elements, i.e. atmosphere 0.95, Primary 0.96, window+lenses 0.99*4 (measured), K' filter 0.93 (measured), detector 0.65 $\Rightarrow$ 0.53 total.

Bad Pixel Fraction	less than 1 %
Read Noise	~ 25 electrons for a double correlated read
Dark Current	< 0.1 electrons / second / pixel
Pixel Scale	0.396 arcsec / pixel
Sensitivity For point sources to the 5 sigma level (peak pixel equals 5 times the noise) with 2 minutes integration time and a seeing of 1 arcsec FWHM.	K' = 17.5 mag H = 18.1 mag J = 19.2 mag
Throughput Including atmosphere, telescope, optics, filter and detector	~ 53 % in the K' band

The camera has been used in a variety of studies which require a wide field of view, from surveys of galactic star-forming regions for molecular outflows to imaging of galaxy clusters. Shown here (Figure 6) is a portion of the deepest K' image taken so far with Omega Prime, obtained as part of the CADIS survey. The full image covers an area of 160 square arcmin, to a limit of $20^m.5$ (5σ detection of point sources). This single image, constructed from 1209 individual 30-second exposures taken in a 2x2 mosaic, covers 18 times the area surveyed in the Hawaii Deep Survey to similar depth! Some early results from analysis of this image are a good brown dwarf candidate, and a number of galaxies with unusually red colors.

The second image (Figure 7) demonstrates the full field of view of Omega Prime. It shows the Ring Nebula in the constellation Lyra. The image was taken at a wavelength of 2.122 µm. It also shows the maximum field of view of Omega Cass[7] on the same telescope.

7. REFERENCES

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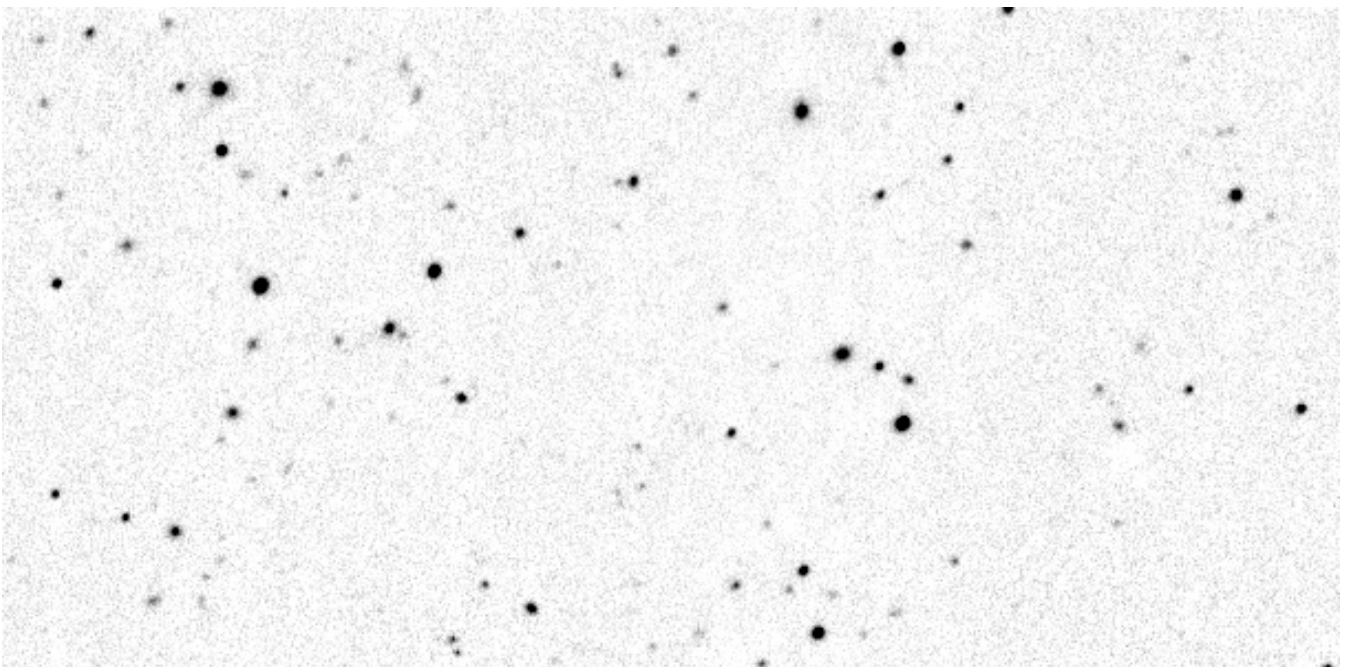
Figure 6: A 2 x 4 arcminute square subimage from one of the CADIS survey fields. The image is constructed from 1209 individual 30 second exposures showing objects to a limit of $20.^m5$.
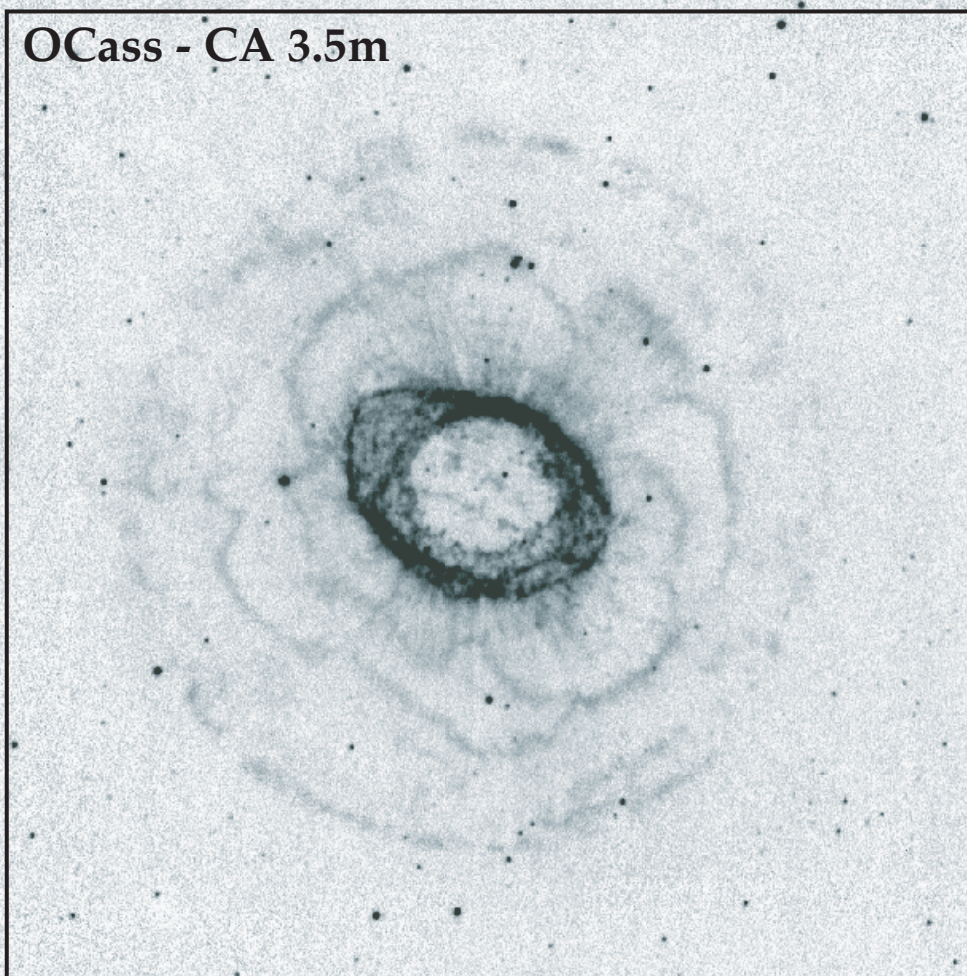
Figure 7: M57 taken at the wavelength of molecular hydrogen (2.122 μm). The size of the image is 6.8 x 6.8 arcmin square and demonstrates the full field of view of Omega Prime.