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The history and technical capabilities of Argus

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Abstract

Over the past 25 years, optical remote sensing has been developed into a very useful tool for sampling the nearshore environment, principally through the use of Argus Stations. However, the capabilities of such systems as scientific tools depend on an understanding of the physics of the camera as an optical sensor (including a detailed knowledge of accuracies and resolution) and of the relationship of optical signals to the geophysical signals they represent. This paper describes the components of Argus Stations with an emphasis on quantitative characterization of the accuracies and resolution of system components. Algorithms for estimation of a range of important nearshore measurements are discussed and their accuracies and ground-truth test results referenced. References to a number of key examples of Argus-based contributions to the scientific literature are cited. Since Argus technology serves as the basis for the CoastView Program, the technical capabilities described below are part of the foundation of CoastView sampling.

1. Introduction

The basic tool of the CoastView Program has been the Argus Station, developed by the Coastal Imaging Lab (CIL) at Oregon State University (OSU; http://cil-www.coas.oregonstate.edu:8080). An Argus Station enables the controlled acquisition and return of optical remote sensing data from land-based computers observing coastal sites of interest. Physically, an Argus Station consists of a number of video cameras attached to a host computer that serves as both system control and communication link between the cameras and central data archives (Fig. 1).

The objective of the CoastView Program was to develop tools to exploit the low-cost, long-term optical measurements available from Argus to solve a range of Coastal Zone Management problems, as exemplified by the management issues that arise at the four CoastView field sites and are discussed in this volume. The two primary challenges were a) to develop methods by which scientific measurements can be organized and synthesized to address different management problems (through Coastal State Indicators), and b) to make accessible a robust set of technical Argus capabilities, originally developed in a research environment, to allow non-research users to make those measurements.

The objective of this manuscript is to lay the foundations for later papers describing CoastView applications by reviewing the technical capabilities and history of Argus Stations and the overall Argus Program under which they were developed. This paper will start by discussing the general requirements for idealized sampling of the nearshore domain and the limitations of traditional in situ approaches. The paper will then consider the range of optical signatures available in the nearshore that can be exploited to make the desired measurements. This will be followed in Section 2 by discussion of the sampling strategies adopted by the Argus Program. In Section 3, we discuss the technical issues of optical sampling, particularly temporal and spatial resolution and accuracy, followed by discussion of user issues related to Argus in Section 4. Section 5 outlines some of the main Argus-based contributions to different aspects of the nearshore literature and is followed by a final section that discusses the directions of future development. Some of the key history in the development of Argus is outlined in Appendix A, while the nature of the current Argus research program hosted by the CIL is described in Appendix B.

1.1. Sampling requirements in the nearshore

Much of the societal and CZM focus for understanding the nearshore is on understanding the morphodynamics of the nearshore system, which is the response of nearshore bathymetry and sediments to the presence of overlying waves

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Fig. 1. Camera configuration for the Noordwijk Argus Station in The Netherlands. Argus Stations consist of a suite of cameras rigidly mounted on a roof or tower, and a computer with communications link to the world for control and data return, plus a timing module to synchronize collections between the cameras. Sites also require survey Ground Control Points in the field of view of each camera to allow estimation of the geometry of each view.

and currents. Risks of erosion, overtopping and inundation, and the associated hazards to safety or infrastructure are all associated with characteristics of the fluid domain and the evolving bathymetry. Thus, the desired sampling of the nearshore zone includes sampling of nearshore bathymetry/topography and of the fluid motions that occur over (and are considerably modified by) that sloping bathymetry.

Design of an adequate sampling strategy is complicated by the wide range of scales of spatial and temporal variability that are typical of the nearshore and the inadequacy of a sparse in situ array for proper characterization of this variability. In the spatial domain, the nearshore is a region of strong inhomogeneity in which wave characteristics typically change substantially over several hundred meters as the waves shoal, break, dissipate across a surf zone and finally reflect from the shore in the swash zone. Longshore and rip currents are usually contained in the first 100 m from shore and can have strong longshore variations. Ocean waves must be spatially sampled at fractions of their 10–100 m typical wavelengths. Bathymetry (excluding shorter scale bedforms, neglected in this paper) varies considerably on scale of tens to hundreds of meters, with sand bars often taking very complex forms (Lippmann and Holman, 1990).

Time scales of variability similarly span many orders of magnitude. Wind waves and swell have typical periods of 10 s and require sampling at several Hertz. Lower frequency motions such as infragravity and far infragravity (shear) waves are common, can be energetic and dynamically important, and have periods that can reach hundreds of seconds (Oltman-Shay et al., 1989; Howd et al., 1991). Tidal variations on a barred beach cause strong modulations of surf zone characteristics with 12-hour periods (Thornton and Kim, 1993), while storms, seasonal wave climate changes and interannual variations cause lower frequency variability. Bathymetry changes at the shoreline can occur in hours (Holland and Holman, 1997), while sand bars can respond to storms as quickly as in 1 day (Sallenger et al., 1985), but generally evolve more slowly and can also exhibit regular cycles that span up to 15 years (Wijnberg and Terwindt, 1995).

This wide range of scales of variability poses severe challenges to traditional in situ sampling schemes, and attempts at long-term monitoring with fixed instruments have been expensive and spatially sparse. Instead, the requirements to sample frequently but over extended periods and with high spatial resolution but over large areas suggest the potential of a remote sensing approach. In the Argus Program, the focus has been on the remote sensing of optical signals.

1.2. Optical signatures in the nearshore

Fortunately, the nearshore is replete with optical signatures that can be exploited. Ocean waves are visible to the eye due to variations in the reflection coefficient of water with sea surface slope (steep front faces are dark; Walker, 1994). Thus, the period, wavelength and direction of ocean waves can easily be seen. Wave breaking, a key aspect of nearshore wave and current dynamics, is very obvious to the camera. Fluctuations in breaking that might cause infragravity forcing (Symonds and Bowen, 1984; Lippmann et al., 1997) are clearly visible. Foam left by breakers can be seen to drift along the beach with longshore currents, indicating the strength of the currents (Chickadel et al., 2003). Since waves break in shallow water, locations of concentrated breaking indicate positions of submerged sand bars (Lippmann and Holman, 1989). All these signals can be exploited for making nearshore measurements.

There are also several possible limitations to optical remote sensing. First, for beaches with a clear water column, optical signals will be dominated by bottom reflection (distorted by refraction through the time-varying sea surface) and will provide little usable information about the sea surface and waves. Fortunately, most beaches have turbid water and surface signatures dominate. Second, for turbid waters, only a thin surface layer is sampled. However, because nearshore dynamics are generally depth-uniform (with the main exception of undertow), surface signatures are a good representation of the overall water column. Finally, for standard, non-intensified cameras, optical signals are not usable at night or during inclement weather (fog, heavy rain, etc.). Nevertheless, optical signatures have the potential for providing an enormous source of data at low-cost and with a temporal and spatial dynamic range appropriate to our sampling needs.

The program objectives of CoastView require measurements that generally overlap the measurement needs of the Argus Program. It is for this reason that CoastView was primarily based on Argus technology.

2. Argus sampling methods

Video cameras are very rich sources of data, typically providing 30 images frames per second, each of which contains approximately 768 kB of data (based on Scorpion SCOR-14SOC cameras, the type being used in the current generation of Argus Station). Even with significant JPEG compression, each camera would collect 18 GB per camera per day to record 12 hourly runs of 17-minute duration. For the 48 cameras of the Argus Program, the volume would be 881 GB per day or 321 TB per year! The logistics of storing and analyzing such large data volumes are daunting, but are dwarfed by the near impossibility of automated return of data from remote sites, particularly over dial-up modem connections.

As a consequence, Argus sampling methods have been designed to sharply reduce the volumes of returned data. This is done in two ways: a) the production of single-image products that represent the bulk statistics of the intensity variations among images collected over an entire sampling period, and b) the return of full time series data from the sampling period, but from only the selected small subset of pixels that are required to allow estimation of a desired geophysical quantity.

2.1. Image products

While long-term collection and return of continuous video streams of data is impossible for remote sites, return of a few images or image products is not challenging. Argus Stations routinely collect three types of image products each hour: a single snapshot, a 10-minute time-exposure and a 10-minute variance image.

A single snapshot image is usually collected at the beginning of each hour for each camera to record the conditions and provide a picture of the site that can be used to interpret other collected data (Fig. 2, upper panel). At the time of writing, snapshots were not being used for routine quantitative analysis, but rather for qualitative visual assessment.

The second standard image product, time-exposure (or timex) images (e.g., Fig. 2, lower panel) are the primary and most popular product of Argus Stations. Collected hourly, each image represents the mathematical time-mean of all of the frames collected at 2 Hz over a 10-minute period of sampling. Non-moving objects onshore are rendered as they appear in a snapshot. However, moving features such as waves are averaged out and only their mean brightness returned. The principle feature of time-exposure images is delineation of areas of preferred wave breaking in the surf zone as white bands. It has been shown that, since submerged sand bars cause preferential breaking over the bar crest, these images can be used to find the locations and morphology of submerged nearshore sand bars and rip channels (Lippmann and Holman, 1989). Since that time, further research has found small discrepancies in this link that are associated with tide elevation and variations in wave height, but that can be corrected with improved models (van Enckevort and Ruessink, 2001) or with a neural network system (Kingston et al., 2000).

Time-exposure images paint a picture of beach morphology over a swath of beach (the surf zone) that shifts cross-shore position with the tide. To assemble these glimpses into a composite picture and to remove tidal dependencies, “daytimex” images were created by averaging each day’s timex images. Long time series of timex and daytimex images have provided excellent, low-cost datasets of morphodynamic variability over time scales from days to decades (Section 5).

The third standard image product is the variance image. While time-exposure images are found as the time mean of image intensities from all of the frames collected over 10 min, variance images are found from the variance of image intensities from the same set of image samples. (Variance images are actually stored and presented in terms of standard deviations rather than variance, the square of standard deviation, but the shorter name is retained for convenience.) Variance images are bright not where image intensities are bright, but where they vary strongly. Thus, a bright sandy beach will appear dark in a variance image while the surf zone will appear very bright, due to the breaking waves. Variance images are primarily used to delineate the surf zone and regions of wave breaking.

Time-exposure and variance images represent two simple and robust syntheses of pixel intensities over the 10-minute period of sampling. Others are possible and have been the subject of experimentation. For example, brightest and darkest images can be found from the extremes of intensity variations during the sampling period. The darkest image has some capability to view through the water column in regions of intermittent breaking (Clarke and Werner, 2003 discuss a sophisticated version of this sampling approach).

With JPEG compression, a standard collection of three image products per hour typically generates only 1.8 MB per day per camera, a manageable amount to return and archive.

2.2. Pixel time series products

Much of the value of video imaging comes from the availability of time-domain information that can be used to measure waves and currents. For example, the period of ocean waves can be found by sampling intensity variations at 2 Hz over a number of wave periods. This measurement does not

Fig. 2. Example snapshot (upper) and time-exposure (lower) image pair. While hourly collection of these images is now routine, this time-exposure image happens to be the first used for nearshore studies and was taken photographically in 1982 at Short Sands Beach, Oregon. The objective was to find longshore nodes of runup associated with standing edge waves, trapped in this 800 m long pocket beach. While unsuccessful, the accidental discovery of a white band offshore associated with (and indicative of) preferential breaking over a submerged sand bar formed the basis for the eventual development of Argus Stations. The white arrow in the upper image indicates two people conveniently walking along the beach to provide scale.

require sampling and storage of the entire image at 2 Hz, just the intensities at one or more locations of interest. Such data collections of intensity variations with time at individual pixel locations are called pixel time series and form a key method of reducing the data flow required to make a number of optical measurements in the nearshore.

The power of pixel time series comes not so much from the individual pixel time series, but from the coherent analysis from an array of pixels whose number and locations are appropriate for a desired type of measurement. Such arrays, often based on designs developed for in situ sensors, are called pixel instruments, and represent a considerable reduction in required data volume. For example, even for an intense field experiment like the recent NCEX experiment in Southern California (Long and Özkan-Haller, 2004), the use of only 1% of the available pixels was sufficient to provide a very good statistical description of the important variables over a very large area.

Pixel instruments have now been developed to measure a range of nearshore variables. Table 1 lists the commonly used pixel instruments, the number of pixels needed for each, and publications supporting the validity of each approach. In several cases the collection and analysis of particular instruments is still in the research domain, although all listed instruments have already been fairly well tested. Other, more exploratory techniques are omitted from this discussion.

The simplest pixel instrument consists of a single, isolated pixel collecting a time series of optical intensity. The spectrum of this signal is related to the in situ wave signal through the Modulation Transfer Function (MTF), a spectral representation of the physics by which we see waves (Walker, 1994). While the

Table 1
Pixel instruments that are commonly used in research, and supporting publications

Pixel instrument	Variable of interest	Number of pixels	Publications in support
Single pixel	Wave period	1	(Lippmann and Holman, 1991; Stockdon and Holman, 2000), some continuing research for complex 2D bathymetries
Alpha array	Wave angle, wave directional spectrum	17	(Lippmann and Holman, 1991; Herbers and Guza, 1990), evolving research topic
Tess array	Wave angle field, field of wave directional spectra	O(1000), sampling area dependent	Evolving research topic
Bathy array	Bathymetry	O(100) for single transect	(Stockdon and Holman, 2000; Piotrowski and Dugan, 2002), evolving research effort
Runup array	Wave runup	O(100)	(Holman and Guza, 1984; Holland and Holman, 1991)
Vbar	Longshore current	O(100)	(Chickadel et al., 2003)

MTF is still the subject of much research, optical signals outside the surf zone generally depend on sea surface slope, so the MTF is strongly frequency-dependent and optical signals will be dominated by high frequency waves if no correction is applied. Nevertheless, for non-complex ocean wave spectra, optical spectral will usually have a spectral peak that corresponds well to the incident wave peak frequency. Within the surf zone, the physics by which waves are seen is quite different from the offshore specular reflection mechanism, but optical spectra will, again, allow identification of a dominant spectral peak.

Alpha arrays (Fig. 3 inset) are small 2D groups of pixels designed to allow estimation of peak wave direction or, preferably, full directional wave spectra (alpha is the Greek symbol commonly used to represent wave direction). Analysis is based on pair-wise cross-spectral moments among a suite of sensors whose locations are chosen to yield a large range of 2D horizontal lags. The theory of optimal spectral estimation from such an array has been well established by (among others) Herbers and Guza (1990). Because pixels are cheaper to deploy than in situ instruments, optical alpha arrays can easily be created that yield excellent directional resolution and estimates of peak direction for non-complex cases. The role of MTF in more complex cases of mixed seas is currently under investigation.

Tess arrays were developed to allow measurement of wave direction at not just one or a few locations, but as a dense spatial field of estimates (Fig. 3). A tess array is simply a method of constructing and organizing a compact tiling of alpha arrays (the term tess comes from tessellation, referring to the repeating pattern of alpha arrays). As such, a tess array has the same capabilities and limitations as alpha arrays. Directional estimates can be derived from anywhere in a tess array.

The estimation of bathymetry from wave propagation characteristics has been a long-held and important goal of optical remote sensing in the nearshore. Most techniques seek to exploit the properties of the dispersion relationship, relating

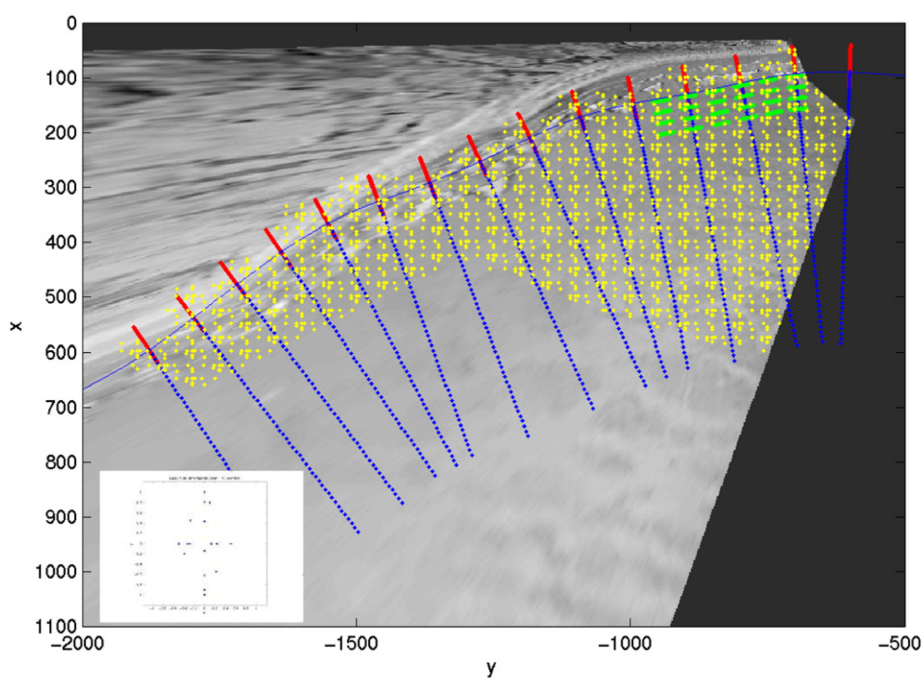

Fig. 3. Pixel instrument design for the NCEX field experiment carried out at Black's Beach, California, in the fall of 2003. Dot colors indicate pixels associated with various arrays, including: yellow, tess array; blue, bathy arrays; red, runup arrays; and green, Vbar arrays. The inset shows the lag array of pixels used in alpha arrays. The longshore (cross-shore) physical scales of the array are chosen to be two (one) times the wavelength of a typical ocean wave.

wave period, wavelength and depth. By measuring period and wavelength optically, depth can be found. The idea has been demonstrated a number of times (e.g., Stockdon and Holman, 2000; Piotrowski and Dugan, 2002) and yields reasonable (O (10%)) errors for non-complex seas away from currents such as rip currents. Finite amplitude corrections to the dispersion relation must be applied in the surf zone. Due to the importance of bathymetry, new approaches and algorithms for this measurement continue to be studied. Fig. 3 illustrates a simplified linear version of a bathymetry, or bathy, array appropriate for near normally incident waves.

Runup arrays are simply cross-shore transects of contiguous pixels that span the swash zone (Fig. 3). The resulting time space dataset (called a timestack) is digitized using a semi-automated algorithm with user supervision. The correspondence between optical and in situ runup has been well documented (Holman and Guza, 1984; Holland and Holman, 1991). Ideally runup transects lie on a known (surveyed) beach profile. The absence of such information can limit the accuracy of the runup magnitudes but will not usually have a major impact on the spectral shape.

Vbar arrays, used to measure longshore currents (usually denoted $\bar{V}$, hence the instrument name), are based on contiguous arrays of pixels, much like runup, but the arrays are located in the surf zone and are oriented in the longshore direction (Fig. 3). Analysis is based on the drift of foam patches along the array (y direction) with time, and uses spectral techniques to yield robust estimates with confidence limits. Accuracies are typically ±10 cm/s (Chickadel et al., 2003).

3. Technical issues

The early history of the Argus Program was based around time exposure imagery that placed few technical challenges on the system. However, with time and more sophistication in sampling strategies, it was realized that optical sampling had considerable untapped potential that depended on a firm technical understanding, and that Argus Stations should be thought of as scientific instruments whose sampling capabilities must be understood properly. Thus, there developed a clear need to understand the resolution and accuracy of Argus data in both the time and space domains.

3.1. Temporal resolution and accuracy

The current generation of Argus technology is used for many purposes, each of which has different accuracy requirements for temporal sampling rate and drift. In order of increasing demands on temporal accuracy, broad sampling categories are: a) hourly image products, b) stand alone pixel time series data, and c) pixel time series data that must be coherently merged with instruments logged on a separate sampling system.

Hourly images such as time exposures could be reasonably created with a set of images collected at random times over a roughly 10-minute span. The resulting data is robust to variations in the sampling rate and in the absolute accuracy of system timing.

For stand alone pixel time series used to characterize the nearshore fluid domain, absolute time accuracy is less important than accuracy in sampling rate. Sampling of ocean waves with typical periods of 10 s can be handled at 2 Hz, usually for a run length of 1024 s (17.06 min). Some techniques such as the Optical Current Meter (OCM; Chickadel et al., 2003) rely on tracking small patches of foam and benefit from 4 Hz sampling. Sampling for the current generation of Argus (Argus III; see Appendix A) is based on a triggered pulse from an oscillator that is accurate to 1 part in 10^4, so frequency data will have equal precision. However, absolute (world) time is tracked by computer system clocks and can drift up to 1 min per day if there is no external correction. Most derived variables such as wave direction are insensitive to this drift since these estimates are usually averages over a 17-minute data run and the variables evolve only slowly. Nevertheless, regular clock updates are used for all sites.

The most stringent timing accuracy is required when Argus is used in conjunction with in situ sensors and analysis requires phase comparison between the sampling systems for ocean waves or similar phenomena. For an ocean wave of 5-s period, a 10° phase difference is equivalent to a time lag of 0.14 s. Maintenance of this accuracy requires resynchronization of the oscillator every 0.39 h. Argus has been designed with this need in mind, but regular online connection is required. For an online station, absolute time control for Argus is handled through standard Unix network time servers using NTP protocol that yields an ongoing time accuracy of a few milliseconds. Modem connected stations achieve this accuracy through regular updates as needed.

3.2. Spatial resolution and accuracy

The geometry of digital images is usually modeled by light rays passing through an idealized pinhole lens and projecting an inverted image of the world onto a sensor that is spaced f millimeters behind the pinhole (f is the focal length of the lens; see Hartley and Zisserman, 2003 for a good discussion of image projections). The geometry is identical but more convenient if the sensor is thought of as being placed f millimeters in front of the lens, producing a positive (non inverted) image. Since an Argus III digital image is composed of an array of roughly square pixels, spatial resolution of each pixel is determined by the projection from the pinhole through the pixel onto its ground footprint. In the camera coordinate system, this resolution is defined as having components in both the range (the direction radially away from the camera) and cross-range (azimuthal) directions.

Argus III digital images are composed of a rectangular array of [NU×NV]=[1024×768] pixels. These span a horizontal angular field of viewδ, that depends on the focal length of the lens, f, and the sensor chip size in millimeters, L_s, as $\delta=2\arctan(L_s/2f)$. Thus, the angle subtended by a pixel is roughly δ/NU and the cross-range size of the pixel footprint, Δ_c, is closely approximately by

$$\Delta_c = R\delta/\mathrm{NU} = (2R/\mathrm{NU})\arctan(L_s/2f) \quad (1)$$

where R is the slant range distance from the camera. For the approximately square pixels of Argus Stations, the size of the pixel footprint on a horizontal surface (such the mean ocean surface) in the range direction can be shown to be

$$\begin{aligned}\Delta_{\mathrm{r}} &= \Delta_{\mathrm{c}}R/z_{\mathrm{c}} = (R^2/z_{\mathrm{c}})(\delta/\mathrm{NU}) \\ &= (2R^2/(z_{\mathrm{c}}\mathrm{NU}))\arctan(L_{\mathrm{s}}/2f)\end{aligned} \tag{2}$$

where z_{c} is the height of the camera above the surface of interest. For example, for a camera situated 40 m above sea level with a wide angle lens having a 40° field of view, the pixel resolution at 1 km range would be $[\Delta_{\mathrm{c}}, \Delta_{\mathrm{r}}]=[0.68, 17.0]$ m.

Most applications of Argus data are based on a local Argus x–y coordinate system that is aligned across (x) and along (y) the local shoreline direction, not with the camera. Conversion from range/cross-range resolution to x–y resolution, $[\Delta_x, \Delta_y]$ is computed as

$$\begin{aligned}\Delta_x &= \max(|\Delta_{\mathrm{c}}\cos\alpha|, |\Delta_{\mathrm{r}}\sin\alpha|) \\ \Delta_y &= \max(|\Delta_{\mathrm{r}}\cos\alpha|, |\Delta_{\mathrm{c}}\sin\alpha|)\end{aligned} \tag{3}$$

where α is the azimuth of the direction of view, defined in a compass sense from the y-axis. Note that the resolution along each axis can be dominated by either the range or cross-range resolution, depending on the look direction of the camera. While R is strictly defined as slant range distance, for most applications tilts are roughly horizontal and the slant range can be reasonably replaced by the horizontal range. An example map of cross-shore and along-shore pixel resolutions from Egmond, The Netherlands, is shown in Fig. 4 (from Aarninkhof, 2003).

Two important points arise from the above discussion. First, while the cross-range resolution degrades linearly with range, the range resolution degrades as R^2. So the principle loss of resolution with distance from the camera is the worsening of range resolution as pixel footprints stretch out. Fortunately, for most applications, distant views look along-shore, a direction with much smaller spatial gradients than in the cross-shore. Second, the principal method to improve range resolution is to use the maximum possible camera height. There is no substitute for high vantage points.

An equally important issue is the accuracy with which the pointing angles of the camera can be known. Holland et al. (1995) describe the photogrammetric relationships that allow conversion between image and world coordinates and the calibration procedures used to find intrinsic parameters of any camera (details about the sensor, the camera field of view and the distortion parameters of the lens). The extrinsic calibration parameters of an installed camera include the camera position (which is surveyed), and the pointing angles of camera tilt, azimuth and roll (which must be determined during and after camera installation). Determination of the latter three angles is known as "solving for the image geometry".

To retain accuracy in photogrammetric transformations of Argus images, image geometry solutions must be of an accuracy that is commensurate with pixel resolution, typically of order 7×10^{-4} rad, or 0.04°. This is well beyond our capability to make direction measurements of the pointing angles of an installed camera, so these angles are instead found by locating in the image a set of Ground Control Points (GCPs) whose world locations are well known. Transformation equations between image and world coordinates can then be inverted to solve for the camera pointing angles (Holland and Holman, 1997). At least two GCPs are required, but more allow a least squares solution that is usually accurate to within 1 pixel.

It was initially anticipated that good accuracy could be achieved by solving the image geometry at the time of installation and at any subsequent time when the camera view is seen to shift. However, it has subsequently been found that viewing angles regularly shift slightly for a variety of reasons including thermal and wind effects, especially on tall towers. Fig. 5 shows the results for hourly solutions for camera tilt for one camera mounted on a 43 m high tower at Duck, NC.

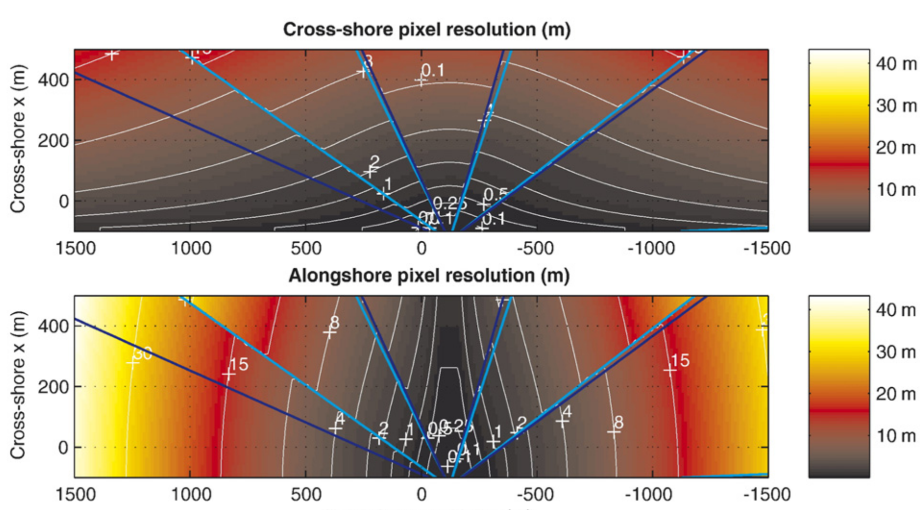

Fig. 4. Cross-shore (upper) and along-shore (lower) pixel resolution maps for the "Jan van Speyk" Argus Station at Egmond, The Netherlands (from Aarninkhof, 2003). The changing resolutions of each of the five cameras at this site are apparent and result from the different lenses.

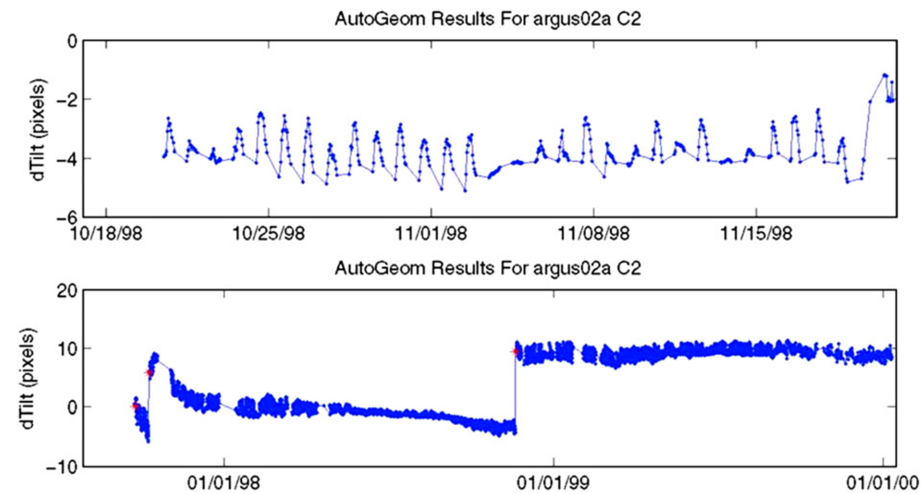

Fig. 5. Automated geometry solution results for the tilt of one camera at Duck, North Carolina, expressed as a deviation from an initial tilt and represented in terms of the equivalent pixel shift rather than as an angle shift. The upper panel shows an example of 4 weeks of hourly data (dots) while the lower panels show variations over 2 1/4 years. Daily fluctuations in the upper panel are due to solar heating (occur on sunny days only) while the jumps in the lower panel correspond to slight resets of camera aim.

Solutions were found using a template matching method wherein small, high-contrast regions (templates) from an original base image are matched against corresponding locations in subsequent images and the tilt and azimuth angles for the best fit determined. Since the solutions are not direct tilt and azimuth measures, but are instead deviations of tilt and azimuth from the original base image, the data are recorded as deviations and are expressed as an equivalent pixel shift. The automatic solution methods demonstrated here are part of a research capability and are not yet a routine part of the CoastView Program. However, these results illustrate the behavior of Argus cameras and the capability of detecting and addressing fine variations in camera movement.

The upper panel of Fig. 5 shows 4 weeks of hourly estimates of tilt deviations. The confidence limit on each solution is no worse than 0.25 pixels. A diurnal signal of about 2-pixel range is apparent on most days. Comparison of points in Fig. 5 with their corresponding images showed that days with little or no diurnal variation (e.g., November 3, 4, 13 and 14) corresponded to cloudy days and we conclude that the primary signal is a thermal response either in differential heating of the tower on which the cameras are mounted or of the box in which the cameras are mounted. The lower panel of Fig. 5 shows 27 months of tilt solutions for the same camera. Variability can either be in the form of jumps (e.g., Dec. 98) or drift (Dec. 97) and can be up to 10 pixels in magnitude.

Jumps and trends in pointing angles can be accounted for by occasional updates to the basic geometry solution (red asterisks in Fig. 5 lower panel). However, hourly and daily variations require an automated technique and, for some installations, will remain uncorrected. While it is hard to generalize results from one installation, a reasonable estimate of the final accuracy of a wide-angle camera in a well-managed system is ±2 pixels for manual geometry solutions and ±0.5 pixels for automated solutions. Table 2 summarizes the accuracy and resolution characteristics of Argus III.

Table 2
Accuracy and resolution characteristics of Argus III

Temporal domain		
Pixel sampling rate accuracy	• 1 part in 10^4	
95% absolute time accuracy	• 2 ms with online NTP server • better than 1 min per day free-running (correctable as often as needed)	
Spatial domain		
Pixel resolution	Cross-range	Range
	$\delta R/NU$	$\delta R^2/(NUz_c)$
	Cross-shore	Along-shore
	$\Delta_x=\max(\lvert\Delta_c \cos\alpha\rvert, \lvert\Delta_r \sin\alpha\rvert)$	$\Delta_y=\max(\lvert\Delta_r \cos\alpha\rvert, \lvert\Delta_c \sin\alpha\rvert)$
95% pointing accuracy	• typically ±2 pixels for manual geometry solutions • ±0.5 pixels for automated geometries	

Variables are defined in the text.

4. User issues

The algorithms and technology of Argus has evolved over two decades and include many complications. To allow users to deal with the considerable complexity of the system and to reduce the potential for user errors, a range of support tools and standards have been introduced.

4.1. Database and data control issues

Digital video is a medium that appears easy to deal with, but exploitation requires knowledge of a surprising number of details and bookkeeping of very large volumes of data. A typical Argus Station contains 5 cameras, each of which returns roughly 3 images per hour for an average of 12 h per day for a total of 180 images per day per site. Many sites routinely run pixel instrument collections (Section 2) that commonly involve sampling 10^4 pixels per camera for twelve 17-minute runs per day. The CoastView Program operated four such sites, while the Argus Program run at OSU has maintained 11 Argus sites for time spans of up to two decades (Appendix B).

To deal with this volume of data and to organize the wide range of information required for Argus to operate successfully, a number of routines, databases and conventions have been developed. Image names are purposely verbose, for example, "1077166800.Thu.Feb.19_05_00_00.GMT.2004.palmetto.c1.snap.jpg," and are key to a number of automated routines to find the images and their support data. For example, the leading 10-digit number in the name is a unique time stamp for each image at a station and represents the Unix epoch time (seconds since midnight, January 1, 1970, GMT) of the start of the collection. All files are named according to GMT time zone to overcome confusion regarding time zone and daylight savings time problems.

The enormous range of support data required for image analysis is stored in a set of four database structures which describe the configuration of any particular location (site, station, image processor and camera, having 16, 9, 13 and 26 subfields, respectively, some of which are themselves structures). Geometry solutions are contained in four additional database structures: manual geometry solutions, automated geometry solutions, GCP details and details of which GCPs were used in any geometry solution. Other database structures deal with pixel instrument collections.

Development of the Argus database schema and strict adherence to conventions have been key to the successful operation and expansion of the Argus Program and are essential to data retrieval and analysis. It is unlikely that any program with the data volumes like the Argus Program could be run without a sophisticated database foundation.

4.2. Design and analysis of pixel instruments

Many steps are involved in the design, creation and tasking of pixel instruments, and also for retrieval and analysis of the resulting data. Designs for the number and configuration of pixel instruments are usually based on a signal processing literature that has developed over many years. For example, the choice of the number of pixels and their lag spacing for alpha arrays is based on a known lag space analysis, with only the physical scale of the final array dependent on the anticipated ocean wavelengths to be detected.

The steps in designing and implementing a set of pixel tools are complicated and (as experience has shown) prone to error if done manually. To facilitate this work, a number of tools and toolboxes have been created for dealing with pixel instruments. Pixel instruments are designed in world coordinates for simplicity. The processes of conversion of a user measurement goal at a particular world location to a set of pixel locations, allocation to appropriate cameras, elimination of redundancies and tasking of actual data collections is carried out automatically in MATLAB Toolbox routines. In some cases, sampling is required at specific world locations rather than at the nearest pixel, and optical intensities must be interpolated from the surrounding four pixels. Alternately, the closest pixel may be sufficient but the precise location of the pixel center is needed for the analysis (e.g., alpha arrays). Extraction of organized pixel instrument data from the returned data file involves similarly arduous bookkeeping.

Analysis of the returned data similarly usually involves sophisticated signal processing that has already been designed and tested, with algorithms available from the literature. An important criterion for any analysis routine is the return of a confidence interval for each estimate to allow automatic distinction of significant results from those for which the optical signals were not sufficiently strong (for example, on a foggy day). These analysis routines also become part of the Argus toolboxes as they are developed and approved.

5. Scientific contributions from Argus

The role of Argus Stations is to provide a low-cost, accessible system for long-term sampling of the important hydrodynamic forcing and bathymetric response variables in this range of nearshore environments. This role is similar to that played by satellites in understanding the dynamics of the world's oceans. Both yield long time series over large regions, but through signals whose relationship to traditional in situ measurements is not always clear. Thus, like the satellite literature, Argus-based contributions to the literature can be divided into technique development and demonstration, and science through Argus data exploitation.

5.1. Measurement methods based on Argus

Papers describing methods and accuracies for Argus-based fluid measurements were introduced in discussions of pixel instruments, Section 2.2 and Table 1. Methods for measuring bathymetry and morphology are noted below.

Lippmann and Holman (1989) were the first to demonstrate and model the relationship between the bands of white in time-exposure images and the crest position of underlying sand bars. Discrepancies associated with the tide elevation and varying wave height could be as large as 30 m, but could be corrected with improved models (van Enckevort and Ruessink, 2001) or with a neural network system (Kingston et al., 2000).

The above methods yield maps of morphology, but not actual bathymetry. A number of techniques have also been developed to measure bathymetry or aspects of sub-aerial topography. In some cases, these methods rely on tricks to retrieve three-dimensional information from 2D images. For example, Holman et al. (1991) showed that shadows falling across a beach could be used to measure sub-aerial beach topography. In addition, Holland and Holman (1997) demonstrated how stereo imagery of moving swash taken by three cameras could be analyzed to yield accurate two-dimensional topography over a small foreshore region. Shorelines mark an approximate elevation contour on a beach and can be found automatically in ways that depend on detection of a bright band associated with the shore break or a color change between wet and dry sand (Plant and Holman, 1997; Aarninkhof et al., 2003; Alexander and Holman, 2004; Plant et al., in review). Changes in cross-shore position of these detected shorelines with tide elevation can be used to determine the foreshore beach profile (Plant and Holman, 1997; Madsen and Plant, 2001).

Finally, bathymetry can be estimated from more fundamental physics properties of waves propagating over a sloping bathymetry. Aarninkhof et al. (2003) showed that the patterns of wave dissipation observed in time-exposure images could be analyzed to reveal the beach profile that was required to produce that dissipation pattern. Several authors have exploited the celerity of ocean waves, a quantity that is observable in optical images and is readily related to the underlying depth through the dispersion relationship (Stockdon and Holman, 2000; Piotrowski and Dugan, 2002). This method requires time-domain sampling through pixel instruments (in the simplest case, implemented with bathy arrays).

5.2. Scientific exploitation of Argus

A key element of nearshore system dynamics and variability is feedback between the two major components of the system, the fluids and the bathymetry. The hydrodynamics of the wave-driven nearshore region depend strongly on the bottom profile, yet the profile of the sandy bottom is just a function of the overlying fluid motions. Such coupled systems often exhibit complexity and the nearshore is no exception. Argus is an ideal tool for sampling such a large, complex system and for carrying out such sampling over the extended durations needed to see a full range of behavior. It can be seen from Table B1 that Argus data collections span almost 20 years, with the OSU Argus research program containing 106 site-years of daily data at the time of writing, perhaps the most extensive archive of nearshore data in the world. These long time series from different sites have been central to a great deal of science, including the following examples.

Lippmann and Holman (1990) used the first 2 years of time-exposure image data from Duck, NC, to describe the statistics of the inner bar configuration and its response to wave forcing. Contrary to expectations, bar morphologies were rarely straight, were complex more frequently than rhythmic, and went through a ordered set of transitions between states during calm conditions but jumped to high energy states during storms. A follow-on study after 5 years of sampling (Lippmann et al., 1993) showed the first Argus observation of interannual

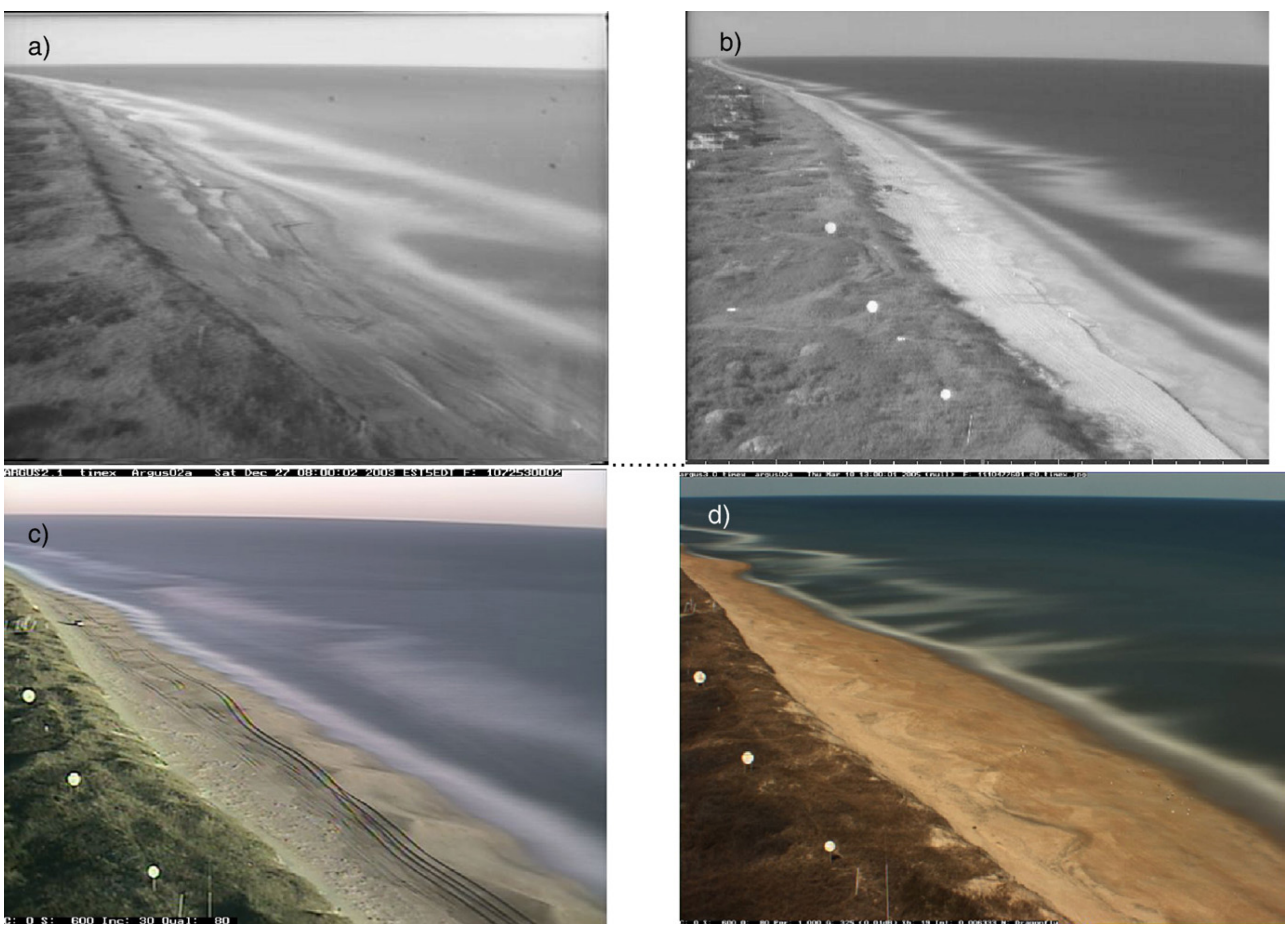

Fig. 6. Example time-exposure images from camera c0 at Duck, NC, from each of the four generations of Argus: a) Argus 0, October 7, 1986; b) Argus I, October 8, 1997; c) Argus II, December 27, 2003; d) Argus III, March 10, 2005. Camera views have shifted over the 18 years of data collection. Dark cuts through the bars in Figures b) and c) correspond to rip currents.

variability, a phenomenon that had previously been seen in survey data in The Netherlands (Wijnberg and Terwindt, 1995) and at Duck (Birkemeier, 1985). Argus imagery was used on the Dutch coast to examine this interannual variability (Wijnberg and Holman, 1997) and to study the along-shore-uniform (van Enckevort and Ruessink, 2003) and along-shore-variable (van Enckevort and Ruessink, 2003) components of sand bar variability. Alexander and Holman (2004) used Argus data to compare the bulk statistics of shoreline and bar variability at four, dynamically distinct Argus sites.

Sand bars are often incised by cross-shore rip channels that are apparent in time-exposure images as dark cuts through the sand bar (Fig. 6b, c). Ranasinghe et al. (1999, 2004) demonstrated this technique and used Argus data from Palm Beach, Australia, to characterize and model beach states that featured rip currents. Holman et al. (2006) used 4 years of daily Argus images from Palm Beach to characterize the occurrence and spacing statistics of rip currents at the site. Rips were found to have long lifetimes, to be very mobile and to typically have highly variable spacing, in contrast to predictions of many existing models. Rip formation from along-shore-uniform conditions, the assumed initial state for most models, was very rare.

Fundamental studies of hydrodynamics from Argus are not common, primarily due to the fact that pixel tools are only a recent development. However, a number of video-based studies have been published including description of the statistics of swash maxima (Holland and Holman, 1993; Stockdon et al., 2006), the near-bed kinematics of swash on a low-sloping beach (Holland et al., 1995), and the wavenumber–frequency partitioning of infragravity swash (Holland and Holman, 1999). Swash motions on an evolving field of beach cusps were carefully examined for the presence of subharmonic edge waves (Guza and Inman, 1975), but no evidence to support this popular model was found (Holland and Holman, 1996). Finally, Chickadel and Holman (in review) used 14 months of daily data from Vbar pixel instruments at Duck, NC, to examine the extent to which the longshore current system there can be modeled with longshore uniform dynamics. In contrast to earlier studies, they found that 62% of the data runs failed criteria for longshore uniformity and would require 2D modeling. This has consequences to both the complexity of nearshore observatories and operational nearshore models under which they would run, as well as for the data requirements for feeding these models.

6. Future development

Argus has developed over almost 25 years and continues to evolve as good ideas and increasing technical power align. While it is not easy to predict the future, several trends are apparent.

Work on algorithm development is always ongoing and has yielded excellent products. At a fundamental level, understanding of the optical MTF underlies all imaging in the nearshore and will continue to be a high priority. Similarly, improved use of color information and potentially optical polarimetry, coupled with increased understanding of the physics of these basic imaging processes, could have large payoffs in measurement capabilities. At a more specific level, further exploitation of stereo and of shadows cast across the beach (to estimate sub-aerial topography) are actively being pursued.

Small commercial cameras and their hardware and software infrastructure continue to improve, largely driven by the machine vision market. This steady improvement in sensors, available bandwidth, disk storage volumes and processing power all make approaches possible that were not envisaged even 5 years ago.

Finally, there is an increasing assimilation of Argus data products into composite nearshore prediction tools. Optical sampling can be combined with radar to their mutual benefit. Optical data can also be used as input data or output validation for numerical models (Holland et al., 2002; Long and Özkan-Haller, 2004). The development of Coastal State Indicators (CSIs) under the CoastView Program is a prime example of this type of work.

7. Summary

The nearshore is replete with visible signatures that can be imaged by cameras and analyzed to make important measurements. While “beach cams” provide a monitoring capability, quantitative estimation of geophysical variables requires an understanding of the camera as an optical sensor (including a detailed knowledge of accuracies and resolution) and of the relationship of optical signals to the geophysical signals they represent. This paper describes the elements of Argus Stations, optical systems developed for nearshore sampling over 20+ years and the basis for the CoastView Program. Accuracies and resolutions of the system are characterized, including accuracies of algorithms to find the pointing angles of installed cameras. A suite of sampling and analysis tools (pixel instruments) is described along with studies that have determined their accuracy and practicality. Examples of Argus-based contributions to the science literature illustrate the power of long-term, quantitative sampling.

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Appendix A. Historical development of Argus

The move to optical remote sensing and the development of the Coastal Imaging Lab at Oregon State University was a response to some very practical problems of studying infragravity wave dynamics under stormy conditions on the Oregon Coast. With wave heights often exceeding 5 m and surf zone widths reaching 1 km, sampling with traditional in situ sensors was viewed as impractical, if not life-threatening.

The first roots of our optical approaches came from the use of time-lapse photography to capture runup time series of infragravity swash over a longshore span of beach. Data were played back one frame at a time and the swash location manually digitized using a variety of pointer devices ranging from a toy train to the track of a drawer slide. Frequency–wavenumber spectra of the resulting data were used to detect and study very large-scale edge wave motions (e.g., Holman and Bowen, 1984).

The time-exposure images that have become the primary Argus product were discovered by accident, as part of a study to detect longshore-standing edge wave motions on a pocket beach. To supplement swash data being collected optically along the length of the beach, it was decided to take 10-minute time-exposure images of the beach and nearshore using a 35-mm camera with a 13-stop neutral density filter. The hope was that dominant standing wave patterns would be directly revealed by a visible nodal pattern in the swash zone. While the time-average swash results turned out to be uninformative, the time-exposure image did reveal a surprising offshore band of strong wave breaking that was felt to be related to an offshore sand bar (Fig. 2). This result rapidly became the focus of investigation until the link between sand bar location and its time-exposure signature was specifically demonstrated in ground-truth tests at Duck (Lippmann and Holman, 1989). Further investigations have refined this relationship (e.g., Aarninkhof et al., 1997, 2003; van Enckevort and Ruessink, 2001).

The beginning of regular, long-term sampling of sand bar variability via time-exposure images also began fortuitously at the end of the SuperDuck field experiment at Duck, North Carolina, in 1986 (Crowson et al., 1988). In closing down experiment sampling, it was decided to leave one of our video cameras on the newly constructed observation tower (built due to the tireless efforts of Col. Grumm, USACE). A VCR was programmed to collect daily 15-minute recordings of surf zone waves. Tapes were subsequently sent to OSU for post-processing to create daily digital, 512 × 480 pixel, time exposures (Fig. 6a) using a recently acquired digital image processing system. It rapidly became apparent that our preconceptions of the nature and time scale of sand bar variability at Duck were completely naive (Lippmann and Holman, 1990). The value of and need for long-term, low-cost measurements of sand bar variability became obvious. Argus was created to fill this need. The data collection effort at Duck from 1986 to 1993 is sometimes retrospectively called Argus 0, the pre-cursor to subsequent automated systems.

A.1. Argus I

The value of regular timex sampling was obvious but the tedious processes of videotape collection, shipping and post-processing motivated automation of timex creation. The first automated Argus Station in 1992 was based on a Dipix image processing board hosted in a DOS computer, deployed at Yaquina Head, Oregon, and connected by modem back to OSU. Analog black-and-white video signals from two cameras were digitized at 3.3 Hz and averaged into digital timex images of 640 × 480 pixels each (Fig. 6b). Collections were scheduled hourly, with data transmission to OSU programmed to occur nightly.

Automation of data collection and return enormously simplified the sampling process and allowed continual (daylight) monitoring of sites of scientific interest without intervention. This continuous monitoring capability lead Paul O'Neil, an engineer responsible for early development, to give these computer stations the name Argus Stations after the hundred-eyed dog that constantly watched over Io in Greek mythology.

Because time-exposure images paint a picture of beach morphology over only a swath of beach (the surf zone) that shifts cross-shore position with the tide, the idea was developed to compute daytimex images to average over tidal shifts. Variance images were also introduced at this time as a method to isolate breaking waves in the surf zone from bright but unchanging regions such as the sandy beach. The time-exposure and variance image products have considerably changed the way we think about sand bar dynamics and Large Scale Coastal Behavior (LSCB).

At around this same time, we began to explore the use of time series data from individual image pixels to extract information about the wave field that forced observed sand bar changes (Lippmann and Holman, 1991). Sampled at 2 Hz, data could be collected from arrays of pixels in what eventually evolved into the current pixel instruments. However, the technology of the early DOS Argus computers could not keep up with the increasing sampling demands of pixel time series and a new generation of Argus Stations was needed.

A.2. Argus II

Argus II was designed around a computer host, the SGI O2 Unix workstation that had both a robust and flexible computing environment and a native ability to digitize video data. Argus II was based on color cameras whose frames were digitized into 640 × 480 pixel images that were of considerably better quality than those from Argus I (Fig. 6c). Moreover, pixel time series

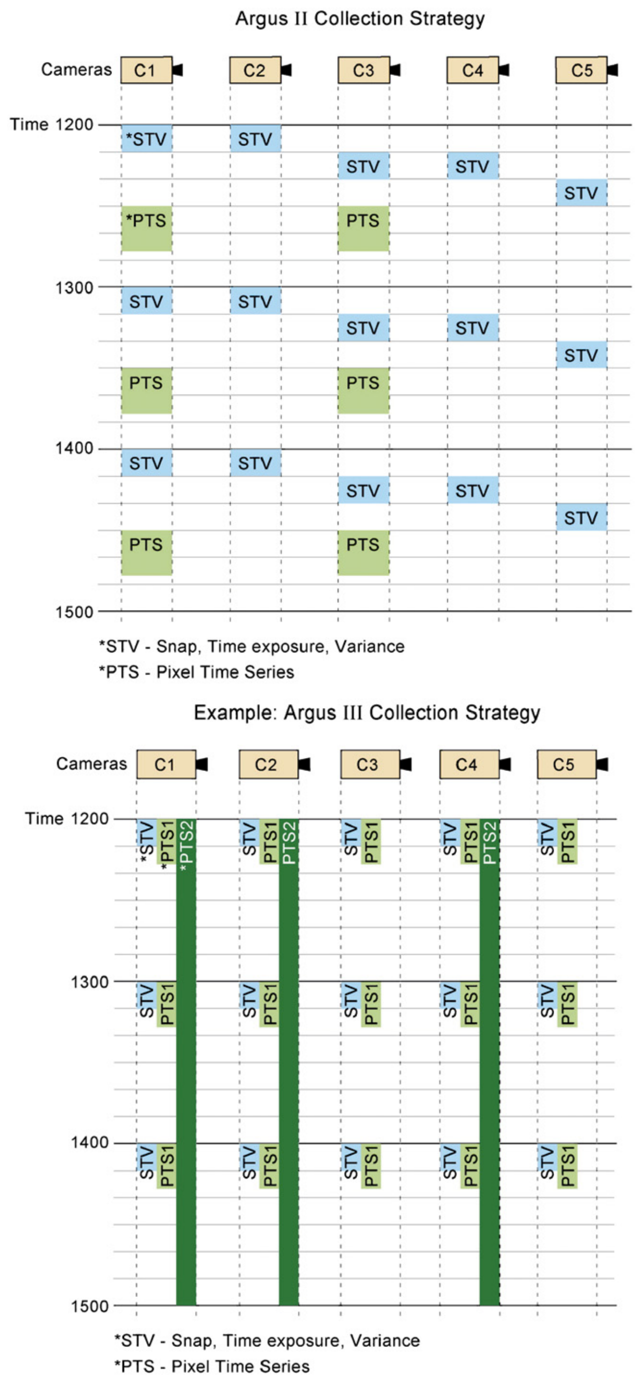

Fig. 7. Typical collection schedules for Argus II (upper) and Argus III (lower) Stations. Sampling includes image collections (STV indicates a snap, time exposure, variance image set, all computed at once) and pixel time series (PTS) collections. Since Argus II could only sample two cameras at any time, schedules involved rotating through camera pairs doing STVs, then a 17-minute PTS for two selected cameras. No such limitations exist for Argus III so collections can be synchronous through all cameras and short data runs can be embedded in longer runs.

data could be collected robustly at 2 Hz due to the SGI's video capability.

The limitation of Argus II lay in the fact that the SGI had only one video input and could digitize only one video signal at any instant in time. Selection of input from among a suite of cameras was made by a computer-controlled video switch and digitization of two cameras was handled by rapid switching between them. However, the data were not quite synchronous (1/4 s offset) and the finite switching time of the video switch meant that, at most, two camera inputs could be handled in this manner at any time. The lack of synchronicity introduced processing complications in pixel array data that spanned two cameras and meant that stereo analysis of surf zone waves was not possible due to wave motion in the intervening 1/4 s. The limitation to two inputs implied that pixel arrays that might naturally span many cameras could only be sampled from a sub-array that was constrained to two selected cameras. Thus data collection from a typical 5-camera station involved a sequence of sub-collections as shown in Fig. 7. While a very capable system, by the time of the start of the CoastView project in 2002, these problems limited the potential role of Argus II to both CoastView and the ongoing Argus Program, and a new generation was needed.

A.3. Argus III

The third and current generation of Argus was developed jointly by Irv Elshoff of Delft Hydraulics and John Stanley of Oregon State University. All CoastView sites except Teignmouth, England, are based on Argus III, while the Argus network hosted by the CIL (Appendix B) is in the midst of being upgraded at the time of this article.

Argus III is based on digital video cameras with 1024×768 pixel resolution, a considerable improvement in quality from Argus II (Fig. 6d). All cameras at a site are connected directly to a host Linux computer as digital devices, using FireWire connections. Cameras are pulsed (usually at 2 Hz) by a common external trigger so that frames are truly synchronous and stereo analysis of moving targets (waves) is possible. Pixel arrays can be designed to span any number of cameras. Pixel time series can be collected from all cameras at once and can be collected at the same time as other types of collections, such as time-exposure images. In fact, there is substantial flexibility in scheduling, including the potential for nesting short hourly pixel time series collections and timexes within a longer pixel time series collection such as might be needed to study low frequency wave motions (Fig. 7).

Appendix B. The OSU Argus Program

The Argus Program at Oregon State University was developed under the hypothesis that nearshore hydro- and morphodynamics are governed by a finite set of physical laws whose observable manifestations depended on a number of bulk site characteristics such as beach slope and wave height and period. By sampling a set of end-member beaches, insight into the underlying physics should be made obvious (this remains a hypothesis). The sites of the OSU program are listed in Table B1, along with the characteristics that were important in their selection. Most sites are collaborative with other groups, for example the CoastView Program.

Table B1
Argus sites developed as part of the OSU Argus research program. Sites were selected to span the parameter space of wave and beach conditions

Site	Beach characteristics*	Start date	Cameras in 2005
Duck, NC	Intermediate, micro-tidal, medium *T*, *H*	10/86**	8
Agate Beach, OR	Dissipative, meso-tidal, large *T*, *H*	06/92	4
La Jolla, CA (two stations)	Dissipative/intermediate, micro-tidal, swell-dominated, complex bathymetry	06/94	5
Monterey Bay, CA	Intermediate, active rip system, narrow directional spread	10/02	5
Waimea Bay, HI	Reflective, micro-tidal, unbarred	01/95	5
Perranporth, England	Dissipative, macro-tidal, large *H*, medium *T*	08/96	2
Teignmouth, England	Reflective, macro-tidal, small *H*, small *T*, estuary influence, complex bathymetry	02/99	5
Noordwijk, The Netherlands	Low-sloping, micro-tidal, small *T*, interannual multiple bar system	03/95	5
Egmond, The Netherlands	Low-sloping, micro-tidal, small *T*, interannual multiple bar system	12/97	5
Palm Beach, Australia	Intermediate, micro-tidal, active rip system	01/95	2
Muriwai, New Zealand	Dissipative, meso-tidal, large *T*, *H*	02/98	2

* *H* is wave height, *T* is period.
** Video-tape based until 01/93.

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