Measurement of Local Scale Wave Transformation Effects at NCEX Using AROSS Imagery

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LONG-TERM GOALS

This work seeks an improved understanding of shoaling-wave phenomenology, particularly in areas of complex bathymetry, through the use of novel, large-area, high-resolution, remote-sensing approaches.

OBJECTIVES

This effort studies the transformation of deep-water waves to the surf-zone as they shoal over a large spatial domain with complex bathymetry. The investigation compares wave model output parameters, such as significant wave height as well as directional spectra, with the values obtained from an airborne, electro-optical, remote sensor. In addition, the airborne data will be used to evaluate and tune algorithms for retrieving water depths, currents and surf parameters. The retrieved parameter fields will be compared with results from video imagery obtained from the cliffs overlooking the experiment site.

APPROACH

This effort used the Airborne Remote Optical Spotlight System – MultiChannel (AROSS-MC) at the Nearshore Canyon Experiment (NCEX) to provide remotely-sensed, electro-optical data of shoaling waves from deep water through the surf zone. NCEX was a multi-institutional experiment that was conducted in Fall 2003 near Scripps Institution of Oceanography (SIO) in La Jolla, CA. AROSS-MC is a compact, turret-based optical system that has been designed and constructed for imaging ocean waves from commercial, aerial-photography aircraft. It consists of a bank of four digital cameras with filters for red, green, blue and near-infrared passbands; an IMU; a GPS receiver; and computer control. The system was designed to spotlight or stare at a specific geographic location for up to several minutes and collect time series of images along with precise navigational and pointing data. By mapping the imagery to a geodetic grid at the level of the mean ocean surface, the space-time characteristics of the waves can be extracted.

The bathymetry at the experiment site near SIO has large and abrupt variations due to a complex, nearshore canyon. These variations refract, and possibly reflect and/or diffract, the longer waves in the spectrum as they shoal. These several processes are complex, and understanding their relative contributions by including or excluding one or more of them in shoaling wave models is important. This process has been modeled and examined in wave tanks and modeled at full scale at this specific

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site. However, to the best of our knowledge, the relative effects of the various processes have not been studied at full scale. NCEX provided a unique opportunity to observe these waves as they shoal over this complex morphology using AROSS-MC. We observed circular areas of ~ 3 km diameter with 2 m resolution as we orbited various aimpoints on the water. By orbiting a target location, the system provided time-series imagery of the waves with as much as 10 minutes dwell at all points that were continually observed. By moving the aimpoint between subsequent collections, the entire shoaling region can be covered encompassing approximately 150 km^2.

Spectra were calculated from data cubes of imagery (two spatial dimensions plus time) which were de-meaned, cosine tapered, and Fourier transformed. The spectral estimates in the vicinity of the 2-D dispersion surface were integrated in the frequency dimension and the remaining k_x-k_y data re-scaled to *f-d* coordinates. In this process, the values are divided by k^2 to scale to wave amplitude units. The cosine angular dependence is not large except for waves traveling nearly orthogonal to the look direction. Thus, in this analysis, only data where the camera was looking more or less into or following the primary wave direction were used.

These spectra were compared to calculations from shoaling-wave models to aid the identification and investigation of the relative importance of physics not represented in the models.

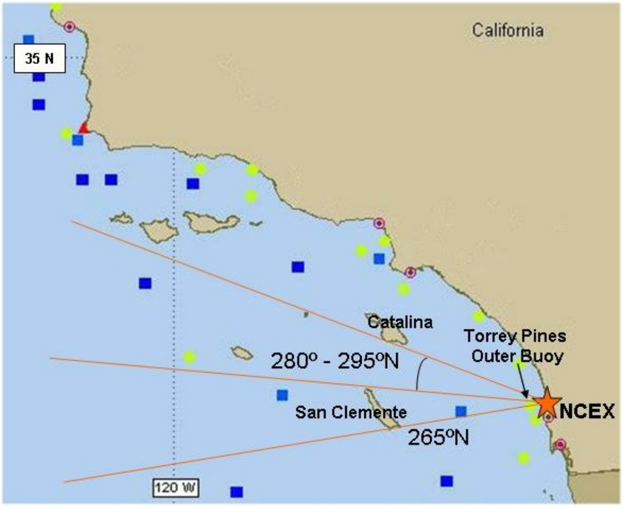

Figure 1: Large scale map showing the location of offshore wave measurements. The blue squares are NDBC buoy locations and the green dots are Scripps buoy locations.

WORK COMPLETED

Figure 1 is an overall diagram showing the wave exposure for the NCEX experiment area during our data collection, which was 30 Oct-10 Nov 2003. The general direction of swell and higher frequency waves was from North Pacific winds, WNW of the site. This is the general direction of San Clemente Island, and we find the waves at NCEX were distinctly bimodal. One beam came from the open channel north of the island (between San Clemente and the Santa Barbara Channel Islands) and the second from south of it.

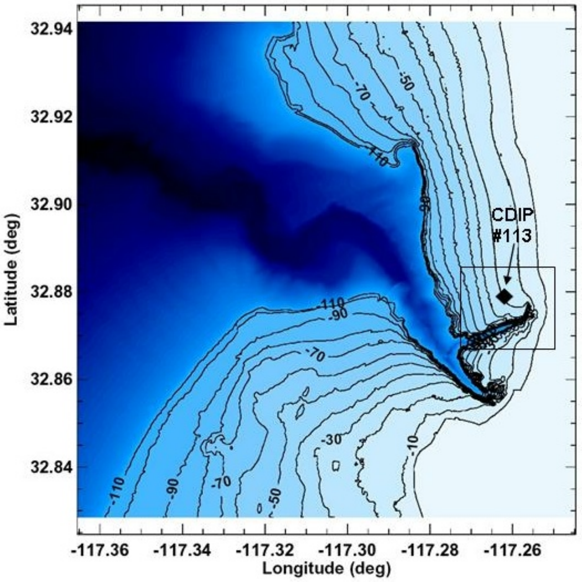

Figure 2: Bathymetry in vicinity of NCEX, with the nearshore study site (box), *and CDIP buoy location (diamond) indicated*

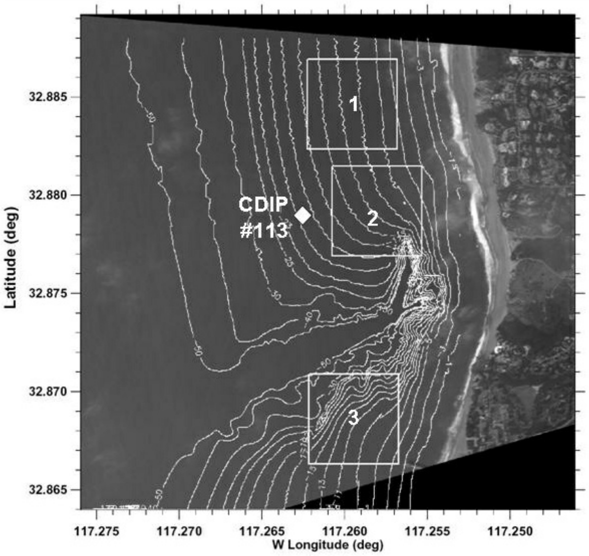

Figure 3: Three nearshore analysis locations on mapped image, with bathymetry and CDIP buoy location indicated

The general bathymetry of the site is shown in Figure 2 with the last labeled contour at 110 m, which is about the maximum depth felt by the swell. The box indicates our nearshore study site. Figure 3 is an image from AROSS-MC, mapped to geodetic coordinates, of the region indicated by the box in Figure 2. Three nearshore locations that we have examined in some detail are indicated in Figure 3. The squares represent the spatial size of the data cubes (512 m x 512 m). The southernmost square, near the SIO pier, was behind (in the shadow of) Scripps Canyon, the middle one was close to the influence of the canyon, and the northern one was more remote and presumably not affected by the canyon. Here, the shoaling region is one-dimensional, whereas the southern two have nearby 2-D variations. The specific data described here were collected on 10 Nov, one of the larger wave days at NCEX, when H_{mo} was ~0.8 m. The incident waves for this day were measured at the location of Torrey Pines

Outer buoy, which is in deep water at 32.93º N, 117.39º W (off scale to the left in Figure 2), with the buoy reporting $H_{mo} = 0.8$ m and direction roughly from the WNW. A mapped image from this collection is shown in Figure 4. The image has been filtered and smoothed to enhance the longer wavelengths, and shows an apparent herringbone pattern.

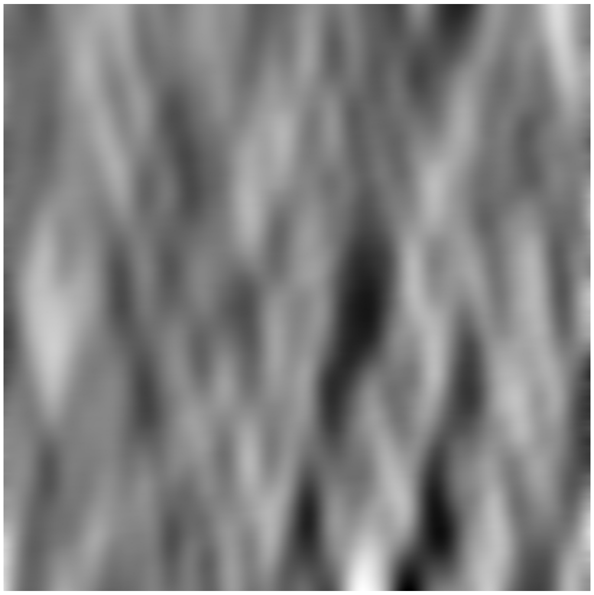

Figure 4: 750 m x 750 m single, mapped AROSS-MC image of filtered waves at Torrey Pines Outer buoy

A data cube (750 m x 750 m x 120 sec) was constructed and examined. This is larger than typically used in our analyses. However, the frequency and wavenumber resolution (and, thereby, the directional resolution) is determined by the size of the cube. Therefore, the data cube was made as large as reasonable to enhance resolution. For comparison, the nearshore box sizes were set at 512 m per side, with the same temporal extent, to balance our desire for maximizing the resolution while maintaining some useful spatial resolution of changes along the nearshore.

One potential utility of the AROSS directional spectrum is its use in forcing nearshore nowcast models. The high directional and frequency resolution has great appeal for models, which are discretized in frequency and directional space (so-called "third-generation" models). One example of these models is the SWAN model, which is in widespread use. Because we require an estimate of spectral energy at the forcing buoy for the model, we scale the AROSS directional spectra at the offshore buoy with the total H_{mo} as recorded by the buoy. The ensuing directional spectrum was then input to the model and propagated over the domain. In contrast we also input the actual buoy spectrum into the model for comparison.

RESULTS

Figure 5 and Figure 6 show the result for imagery collected over the Torrey Pines Outer buoy on 10 Nov at 2153 UTC. Figure 5 is the 2-D *f-d* spectrum and Figure 6 shows the marginal 1-D direction and frequency spectra. The directions are limited to 180 degrees only for plotting purposes, as the full 3-D spectrum resolves all directions. However little to no energy is propagating westward (seaward), so the plot is limited to the 180 degrees of interest for clarity. Figure 5 exhibits a bimodal spectrum that is due to the strong wave shadow of San Clemente Island. The northern beam apparently comes from the unobstructed channel north of the island, and the southern one from the south side. The peak frequency is 0.085 Hz, and is roughly in agreement with the buoy (peak frequency = 0.08 Hz, peak direction = 252º at 2201 UTC). We do not attempt to compare with the directions of the buoy since such instruments clearly do not have the resolving power for these waves. As noted previously, the relative spectral values are accurate in these plots, but the amplitude scale is unknown. Actual wave amplitude variance can be estimated by integrating these values and scaling with H_{mo}. Thus, relative values, such as the peaks of the two beams, are maintained, and the northern beam is somewhat stronger than the southern. In addition to these main beams, there is a much smaller, very narrow peak coming almost directly from 180 degrees with frequency closer to 0.05 Hz. As this buoy is far enough seaward, this direction is unobstructed, and this presumably is a wave beam from the Southern Ocean.

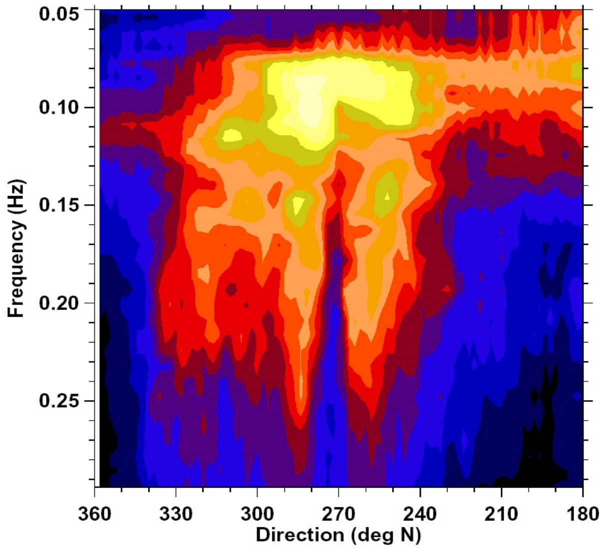

Figure 5: 2-D f-d spectrum of AROSS-MC data collected at Torrey Pines buoy on 10 Nov at 2153 UTC [Two swell peaks are evident at a frequency of 0.85 Hz with directions of ~290° and ~255°]

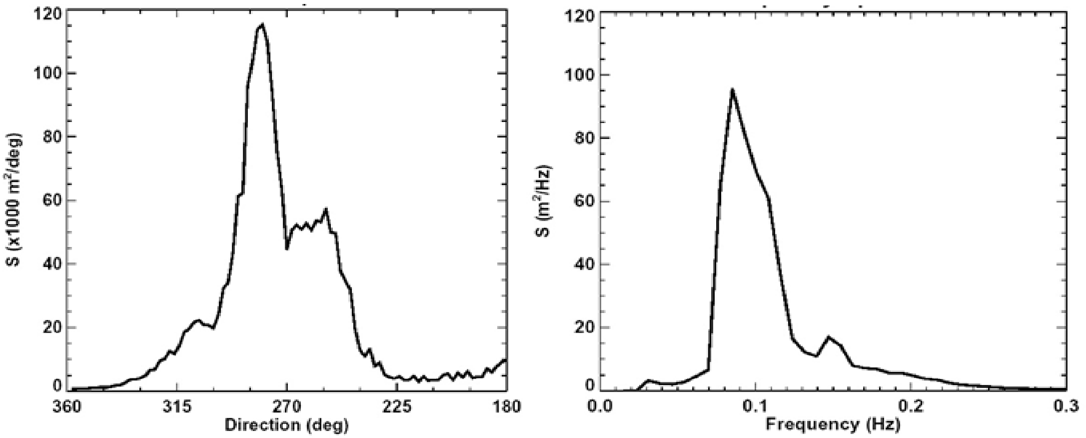

Figure 6: Marginal 1-D direction and frequency spectra of AROSS-MC data collected at Torrey Pines buoy [Two swell peaks are evident at a frequency of 0.85 Hz with directions of ~290° and ~255°]

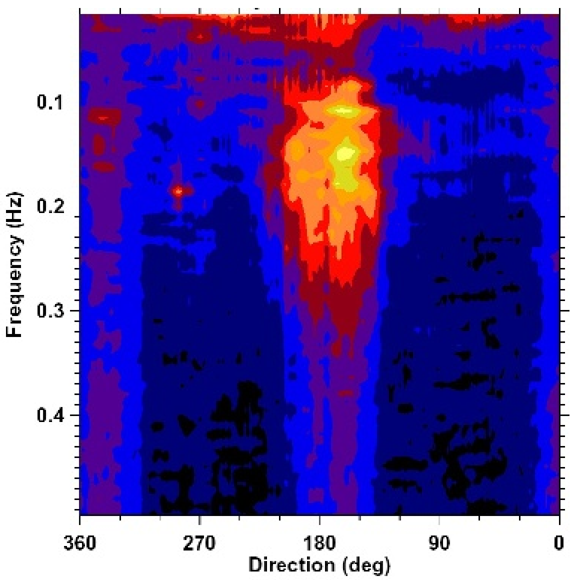

Figure 7: 2-D f-d spectrum of AROSS-MC data collected at Torrey Pines buoy with a Kelvin wake evident at 0.185 Hz and 270°

On a separate but related note, one of our collection sequences out at this deep buoy also captured a far field Kelvin wave wake, presumably from a large passing ship. This is exhibited in the spectrum, shown in Figure 7, at a frequency of 0.185 Hz and a direction of ~280° as a delta function, with actual width only limited by the size of the data cube. The feature is remarkably sharp compared with the ambient waves. Since the Kelvin wake of a passing vessel moving at a fairly constant speed will be narrowbanded, this result provides a direct measurement of the resolution of the AROSS system. In addition, it demonstrates the linearity and accurate construction of the spatial-temporal data sets, including the important procedure of the multiple-image mapping from the camera to geodetic coordinates.

Figure 8 shows the waveheight field for the NCEX site resulting from buoy forcing, as well as the same resulting from scaled AROSS spectra forcing. The results are virtually identical, highlighting the potential utility of AROSS in model initialization provided energy measure is available for scaling the AROSS spectrum.

A comparison of the directional spectra resulting from the buoy-forced and AROSS-forced model runs, at the location of CDIP buoy #113 (32.8789^o N, 117.2625^o W, see Figure 2) is shown in Figure 9. These spectra are expressed in model coordinates, with zero being due east, positive angles being north of east and negative angles south of east. The spectra look remarkably similar; the AROSS-forced case shows slightly more energy variations across directions in the high-frequency range. This may be due to the relative record lengths involved, as the buoy is representative of roughly one hour in time.

IMPLICATIONS/APPLICATIONS

The Navy currently does not have a consistent approach for providing accurate surf forecasts, primarily because of limited knowledge of bathymetry in and near the surf. This remote sensing approach will provide expeditionary forces with a capability for obtaining a self-consistent data set of water depths, currents, and directional spectra, thereby closing the present technology gap between offshore wave forecasts and the beach. In addition to closing this gap, this approach provides the capability to achieve these results from a very long, and safe, standoff range.

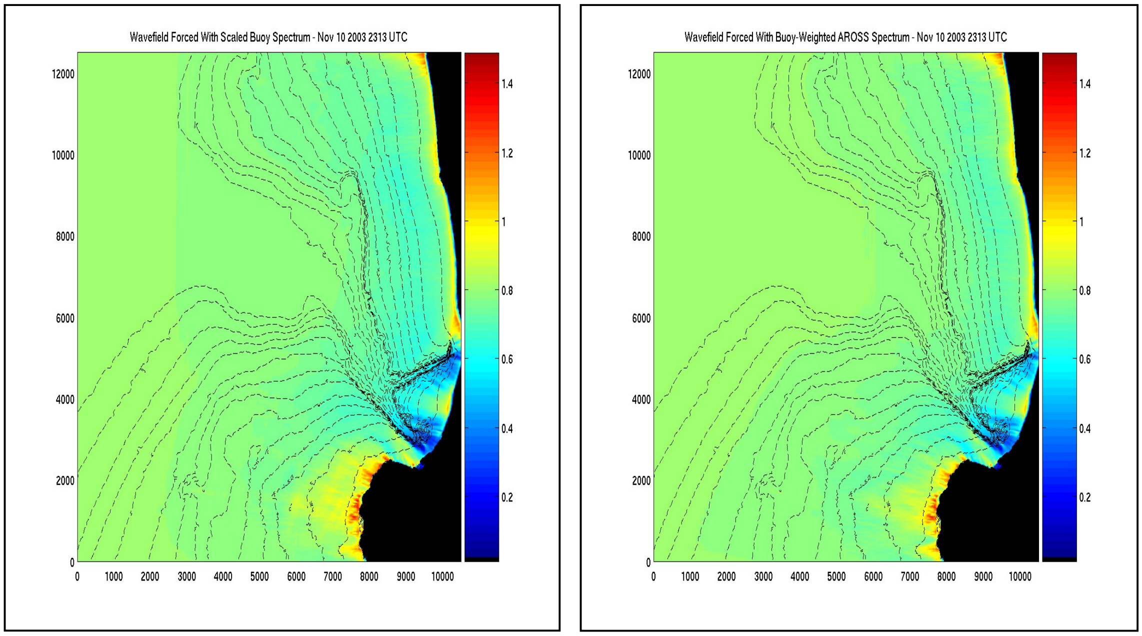

Figure 8: Significant waveheight as predicted by the SWAN wave model using two different forcings. Left: SWAN forced by Torrey Pines Outer buoy. Right: SWAN forced by scaled AROSS spectrum.

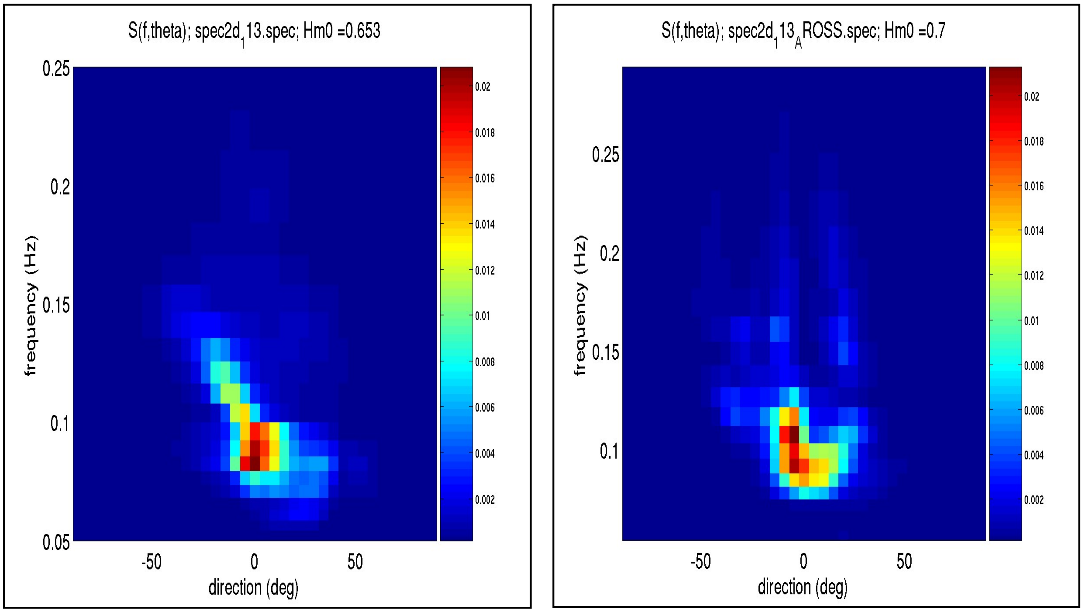

Figure 9: Directional spectrum from model at the location of Buoy #113. Left: SWAN forced by Torrey Pines Outer buoy. Right: SWAN forced by scaled AROSS spectrum. [Both spectra show a peak near 0 and 0.85 Hz. The buoy spectrum has a tail of energy from the peak and is between 0° and ~-40° and 0.85 Hz and 0.12 Hz. The AROSS spectrum only partially has this tail of energy and has two additional roll-off tails at ~-10° and ~30°]

The good quality spectra derived from an airborne sensor such as AROSS can aid in the development of shoaling wave models. A sensor of this type provides a means of comparing model results at more locations than where single, *in-situ* measurements are available. In addition, these results demonstrate that time-series imagery collected by AROSS sensors show excellent promise at providing data suitable for use in driving shoaling wave models over a large region where *in-situ* measurements may not be available.

TRANSITIONS

Elements of the water depth and current retrieval algorithms have been transitioned to the Tactical Littoral Sensing program (TLS) in the Littoral Warfare FNC for operational use on the COBRA turreted system. This system is planned to fly on the Sea Scout, which is the UAV component of the future Littoral Combat Ship.

RELATED PROJECTS

Areté Associates has developed an EO imaging system, based on the Airborne Optical Spotlighting System (AROSS) design, that collects time-series imagery of the ocean surface suitable for scientific research. The new system, AROSS-MC, is a multi-channel AROSS designed for low-cost production, through the use of commercial-off-the-shelf (COTS) components, and low-cost operation, through the use of commercial aerial photography airplanes. This work was funded under the SBIR Phase II contract N00014-02-C-0183 for Solicitation Topic N01-035, “Four Dimensional (4-D) Atmospheric and Oceanographic Instrumentation”. This program continues with further development and transition planning for MCM mission-specific algorithms in a Phase II Expansion effort.

Findings and algorithms improvements resulting from this effort will be incorporated into the NRL Littoral Environmental Nowcasting System (LENS) program that seeks to use remotely derived information to drive state-of-the-art models of littoral dynamics.

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