Video From Earth Orbiting Satellites (for Oceanographers)

Ron Abileah
jOmegak
San Carlos, CA, USA
abileah@jOmegak.com

Stefano Vignudelli
Consiglio Nazionale delle Ricerche (CNR)
Pisa, Italy
stefano.vignudelli@pi.ibf.cnr.it

***Abstract*— This paper reviews video capabilities from Earth orbiting satellites and applications to ocean remote sensing. Videos for purpose of this paper are sequences of images on a fixed location with frame rates in the range of 0.1 to 30 Hz. The number of video capable satellites is increasing. Applications include directional wave spectra, ocean surface currents, surf zone dynamics, and others. Some applications are illustrated, and others are suggested for future research.**

Keywords—satellite imaging, video, wave spectrum, ocean currents, surf zone

I. Introduction

There is a steadily growing number of Earth orbiting satellites that provide short 'video clips,' which for the purpose of this paper are sequences of images on a fixed location with frame rates in the range of 0.1 to 30 Hz.

Videos from orbiting satellites open up new possibilities for remote sensing of ocean phenomena. This paper is a summary of rapidly evolving satellite capabilities (two just coming online as this is written) and oceanographic applications that are being developed and tested.

Applications that are already at least partially demonstrated (in this paper and earlier publications) include: directional wave spectra, ocean currents, bathymetry, surf zone dynamics, and sub-surface visibility. Additional application that are suggested for future research include: marine mammals census, detection of flotsam, river hydrology, sea ice motion, and winds over water.

Space video systems can be grouped into three broad categories: full frame, repointing push-broom, and multispectral push-broom. Satellites in these categories are summarized in Table I with the inter-frames time interval (*dt*) and dwell time.

The full frame systems fit the conventional usage of the term 'video.' They use two-dimensional imaging array to capture the entire image area. The camera pointing is continuously slewing to stay fixed on the area of interest over the dwell time. The frame rates are 3-30 Hz.

The repointing systems are push-broom imagers with the ability to mechanically repoint and make repeated sweeps on the area of interest. It typically takes 2 s to sweep the image areas, and 8 s to record the image and repoint for the next image. So the time between images is 10 s, or 0.1 Hz frame rate. The principle use for repointing is 3D image reconstruction over land. However it is also a proven way to observe temporally varying ocean phenomena.

In multispectral push-broom systems each spectral band is imaged by a dedicated linear array. The linear arrays are physically staggered in the image focal plane leading to small time delays in the passage of each band over a fixed point on Earth surface. The multispectral cube is thus a short video clip, typically at ~10 Hz.

All the repointing systems are also multispectral push-brooms and can thus provide data on two time scales, 10 Hz and 0.1 Hz.

TABLE I. VIDEO CAPABLE SATELLITE SYSTEMS

	Satellite	***dt (s)***	***dwell (s)***
Full frame	Skybox (Google/Skybox, USA)	0.033	90
	Iris (UrtheCast, Canada)	0.33	60
Repointing pushproom	IKONOS2 (Digital Globe,USA)	~10	~40
	WorldView2 (Digital Globe.USA)	~10	~400
	WorldView3 (Digital Globe, USA)	~10	~400
	Pleiades (Airbus Space and Defence , Europe)	~15	?
Multispectral pushbroom	SPOT-5 (Airbus Space and Defence, Europe)	2.04	2.04
	Landsat-8 (NASA, USA)	~0.12	1
	Sentinal-2 (ESA, Europe)	?	?

A number of considerations will dictate which video satellite is best for a particular application. For example, footprint areas vary from 2 to 10000 km^2, revisit intervals vary from days to infrequent, and cost (free to expensive). SPOT-5 and Landsat-8 (and soon to be operational Sentinel-2) provide the large area footprints and frequent revisits required for directional wave spectra studies. Landsat-8 would edge out SPOT-5 on cost consideration because the images are free. But SPOT-5 has a much longer historical record.

Additional considerations for specific applications are the pixel resolution (varying from 1 m to 30 m), *dt* (0.1 s to 10 s),

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dwell time (1 s to 100 s), and whether the camera can be pointed off nadir.

II. Description of Systems

A. The Skybox and UrtheCast satellites

In 2009 a Silicon Valley startup, Skybox Imaging, announced plans to offer on-demand high-resolution panchromatic 30 Hz video from Earth orbit. The first two of a planned 24-satellite constellation were launched in 2013-2014. The video image footprint is 1 km x 2 km with a pixel resolution of ~1 m at nadir. Further technical details can be found in [1].

The video capability is operational and we obtained several samples (including surf zone, reefs, harbors, and rivers) for evaluation. However, the promised video-on-demand service has not materialized. The acquisition by Google in late 2014 appeared to have changed Skybox Imaging business focus. It is not possibly at this time to order video for a particular time and place.

More recently Urthecast ('Earth-cast'), based in Vancouver, Canada, announced plans for video service, similar to the Skybox vision. Few details are known at this time.

It remains to be seen whether full frame video from Earth satellites will become a reality. There has been much press hype but no compelling applications mentioned so far. The most often mentioned is monitoring vehicle traffic on roads and in shopping centers. We doubt these application alone will sustain a space video business!

B. IKONOS and WorldView satellites

IKONOS, launched in 1999 by SpaceImaging, was the first commercial satellite with re-pointing capability.

IKONOS pixel resolution is 4 m in multispectral, 2 m in panchromatic. IKONOS is now operated by DigitalGlobe. DigitialGlobe subsequently launched WorldView2 in 2009, WorldView3 in 2014 with pixel resolution improved to 2 m in multispectral bands, ½ m in panchromatic. DigitialGlobe also increased the number of spectral bands, including notably the Coastal Blue band (400-450 nm).

The typical image footprint is 25 km cross track and 25 km along track. Longer along track lengths are possible.

Consecutive images can be taken in either forward-forward, reverse-reverse, or forward-reverse push broom modes. In forward-forward (reverse-reverse) mode all image scans start from the north (south) end and sweep south (north). The *dt* is a constant ~10 s for the entire image. In the forward-reverse mode the area of interest is first scanned north to south, than reversed to south to north. There is a saving in the time delay to start of the next image. However it also makes the *dt* variable over the image, from 7 s at one end to 11 s at the other end.

C. Pleiades

The European Pleiades is a constellation of two satellites, 1A and 1B, with camera pointing agility similar to the IKONOS and WorldView satellites. Astrium calls this the Persistent Surveillance mode. Pointing can be up to 30^o off nadir, re-pointing at 15 s intervals. The image footprint is 20 km x 20 km. Delivered images are digitally enhanced to 50 cm, but the actual pixel resolution is 70 cm at nadir.

D. SPOT-5

From a video perspective the SPOT-5 is a unique design. Two push-broom cameras are used in the High Resolution Geometric (HRG) acquisition mode. The first captures green, red, and near IR images at 20 m resolution (there is also a SWIR image with 40 m resolution), and the other takes a panchromatic image at 10 m resolution. Each camera is pointed 0.527^o off nadir along-track, but in opposite directions, which introduces a time difference for a fixed point on the ground. A two image video can thus be constructed with one of the multispectral bands combined with the panchromatic image, separated by 2.04 s.

E. Landsat-8

Landsat-8 is the first in the Landsat series with 11-bit radiometric resolution, as compared with 8-bit in earlier satellites. This is a significant improvement for marine applications. There are 11 band channels. The first eight are relevant for our purpose: seven multispectral bands with 30 m pixel resolution, and the panchromatic image with 15 m resolution, which stacked in time order make a video clip of eight frames in ~1 s.

Relative to the panchromatic band the time differences are blue - 0.136 s, coastal - 0.253 s, near IR - 0.422 s, red - 0.521 s, green - 0.645 s, SWIR 2 - 0.832 s, and SWIR 1 - 0.949 s.

There is a slight complication one must be cognizant of. The 185 km image swath is stitched from 14 focal plan modules (FPMs). One FPM covers a 13.2 km along-track strip. The temporal order of the bands is reversed between odd to even numbered FPMs, [3]. In the left most strip the panchromatic band is first, SWIR-1 is last. In the next strip the order is reversed; and so forth. There is additional time delay between FPMs.

The simplest way to deal with the time reversal is to split the original image into 14 strips, process each strip as an independent video sequence with the appropriate time sense, then stitch the results back to the full image footprint. We illustrate this with an example in Section III.E.

Landsat-8 images are free and very easy to access. While all Landsat images have been and continue to be accessible from the USGS web portal, Landsat-8 images are now also stored in the Amazon Web Services (AWS) cloud ([2]) where access is even simpler. Mathworks provides a free Data Explorer to search the AWS archive. There is also a toolbox of Matlab functions to customize your own data exploration and down loading. Our customized version lets us click a location on a world map, then goes off unattended to retrieve all images at that location. Two years of images are downloaded and stored on our local hard drive in about 10 minutes.

F. Sentinal-2

Sentinel-2 was put into orbit on June 23, 2015. It is planned to be a two satellite constellation, 2-A and 2-B. The design is similar to Landsat-8 but with 3X higher pixel resolution and 5-day revisit frequency (3X compared to Landsat-8). The orbits are synchronized with Landsat-8 to increase revisit rate to 3 days using all three satellites.

Sentinal-2 images will be free and available to download from an ESA portal, similar to Landsat-8.

At the time of this writing one marine scene image of the Venice-Lido area was provided for evaluation. Directional waves spectra were computed over part of the scene. There are also internal waves.

III. EXAMPLES OF VIDEO APPLICTIONS

A. Surf zone wave morphology (Using Skybox video)

A number of different ways to utilize video imagery in the surf zone have been proposed. Past research used cameras fixed on shore towers with oblique views off shore [4-7] and 'satellite' viewing from a tethered balloon [8].

In Reference [4] video time averaging is used to accentuate wave breaking over sandbars. In Reference [5] intermittent visibility in between wave breaking is exploited to image the bottom. References [6-7] invert wave crest tracks into bathymetry. Reference [8] measures the along-shore current.

Video from space opens up the possibility of applying all the above techniques to remote beaches worldwide. Skybox is especially well suited. All these applications require frame rates of 1 Hz or higher, resolution of 1 m, and dwell times of 30 s or more. Skybox is the only existing system that meets these requirements.

The example in Fig. 1 used a 30 s Skybox video over Pendleton Beach, CA) with Yoo's [6-7] method for tracking wave crests. The next step (which we have not done yet) is to invert the tracks into bathymetry.

B. Imaging bottom beyond the surf zone (Skybox)

Beyond the surf zone, in deeper water, visibility of the sea bottom is limited by light attenuation and surface waves glint.

Temporal averaging can be used to filter out the wave glint [9]. The requirement is frame rate of 1 Hz or greater, and dwell time of one wave period of longer. Again, Skybox is the only current system that meets the requirements,

Averaging also reduces camera noise and enables visibility of lower radiance levels. The two benefits, wave filter and noise averaging, combine to improve visibility of the bottom up to depths of 30 m, depending on water turbidity.

Fig. 2 shows an example with the Skybox Duck NC video before and after averaging 900 image frames (30 s). The SNR improvement is 30 dB. In this case there were no surface waves. All the SNR gain came from noise averaging. In cases with surface waves the SNR gain would be much greater.

C. Wave spectra (WorldView2)

WorldView-2 and 3 (and their predecessor IKONOS) are well matched to the requirements for directional waves spectra, bathymetry, and currents.

Here we illustrate directional wave spectra. Details for bathymetry are slightly more complicated and described in [11-12]. Currents are illustrated with SPOT-5 in the next subsection.

Computing the directional spectrum requires two or more images. The algorithm for two images is as follows. The image is subdivided into sub-images; typical sub-image areas are 200 m x 200 m. Let $F_1(k)$ and $F_2(k)$ be the complex Fourier transform of the two sub- images, where k is the wavenumber. Compute the complex cross-spectrum $C(k) = \langle F_1(k)\, F^*_2(k) \rangle$. The power spectrum is $P(k) = |C(k)|^2$.

The power spectrum has 180° ambiguity in wave direction. The ambiguity is resolved by the sign of $arg(C(k))$. Note that $arg(C(k))$ is proportional to wave phase velocity x dt. In the noise free case the sign can be correctly determined no matter how small dt is. But with noise dt must be large enough to prevent noise from flipping the sign the wrong way. The rms for $arg(C(k))$ is $tan(1/SNR)/\sqrt{2} \approx 1/\sqrt{2}\cdot SNR$. With WorldView 2 the typical SNR in the range of 10-20 dB and we can reliably determine wave directions with dt as small as 0.1 s. So WorldView 2 images can be used either individually, with the short time delays of up to 0.3 s between the eight bands, or with image pairs in repointing mode (10 s).

Using single images is easier and cheaper. There is, however, a further consideration: single images generally do not capture the complete wave spectrum. Wave visibility is a product of the true ocean spectrum and a view-dependent transfer function.

To illustrate this point we use a long sequence of repointed images. Such data requires a special satellite tasking request. Digital Globe provided us with two long sequences over the West (windward) coast of Oahu, Hawaii, (Table II). One data set covers a 50° variation in view direction, centered in a direction towards the sun; the second data set covers a 170° change in view direction in the opposite direction (away from the sun). Reference [10] has extensive discussion of the 40-image data set.

TABLE II. WORLDVIEW-2 DATA SETS

	Number of images	*Satellite Azimuths*	*Sun Azimuth*
Mach 31, 2011	7	306 to 259	147
July 30, 2011	40	19 to 186	96

Fig. 3 shows the power spectra at 50 s intervals in the 40-image data set. Arrows indicate the direction of the satellite (blue) and sun (red). The predominant wave heading is due west, the sun illuminating the backside of waves. The spectrum changes from one view to the next. In the first (azimuth = 21°) there is no hint of waves in either the image or its power spectrum. (A visual inspection of the images showed that at in this view the only visible ocean surface features are breaking waves.) As the view angle advances waves gradually become more visible. They are most prominent in the range 39°-150°, when wave crests are perpendicular to the view. Conversely views perpendicular to the wave direction have the least wave visibility

There a similar conclusion with the 7-image data set (not shown here).

Whenever there are multiple wave systems there is no single view angle that is optimum. A range of view directions is required.

D. Currents (SPOT-5)

The directional spectrum is only one step away from current. The phase, *arg(C(k))* (see previous section) is proportional to the sum of the gravity wave phase velocity and ocean current. By subtracting the theoretical phase velocity for gravity waves we are left with the current velocity.

The short waves (e.g., $k > 0.05$ c/m) feel the current very near the surface; the long waves ($k < 0.02$ c/m) feel the current 10s of meters below the surface. The difference between short and long waves measures the vertical current shear [13].

De Michele et al. [14] were the first to suggest and demonstrate measurements of ocean surface velocities with SPOT-5. We are now taking it a step further and separating total velocity into the wave phase velocity, near surface current, and the vertical shear. The goal is to make the extensive archive of SPOT-5 images useful for historical study of tides and currents.

So far the analysis has been completed on one test image acquired over Le Reunion Island. This is the same image used in [14]. Fig. 4 is the first result on current vectors and vertical shear. Unfortunately there is no in situ truth for verification. Additional SPOT-5 data sets for this study will be selected based on availability of ground truth.

E. Directional wave spectra (Landsat-8)

Fig. 5-6 are examples of directional and non-directional wave spectra using Landsat-8 panchromatic paired with SWIR1, with $dt \sim 1$ s. The spectra cover wavenumbers range of -0.017 to +0.017 c/m.

Each two-dimensional spectrum is for a 12 km x 12 km analysis area, aligned with the FPM boundaries (Fig. 5). Fig. 6 zoom-in is better to illustrate the spectrum details. The dominant wave direction is found in this case to be SSW. The features at long wave numbers, and approximately perpendicular to the waves, are probably wind streaks.

As with SPOT-5 the ocean currents can be mapped. However, the accuracy of Landsat based currents is yet to be verified with ground truth.

Landsat (and SPOT) images are always nadir and viewing at 10:30 local time; the camera view and sun geometry are fixed. It is thus a hit and miss for wave visibility, depending mostly on wave orientation. On the other hand, these images are much more affordable and practical for oceanographic studies.

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REFERENCES

[1] P. d'Angelo, G. Kuschk, and P.Reinartz, *Evaluation of Skybox Video and Still Imagery,* The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-1, 2014 ISPRS Technical Commission I Symposium, 17 – 20 November 2014

[2] Landsat on AWS, http://aws.amazon.com/public-data-sets/landsat

[3] J. Storey, M. Choate, and K. Lee, *Landsat 8 Operation Land Imager On-Orbit Geometric Calibration and Performance*, Remote Sens. 2014, 6, 11127-11152 (note: Fig. 2 and 3 in this reference are the most pertinent to this paper)

[4] Holland, T.K.; *Holman, R.A.; Lippmann, T.C.; Stanley, J.; Plant, N., "Practical use of video imagery in nearshore oceanographic field studies," IEEE Journal of Oceanic Engineering, vol.22, no.1, pp.81,92, Jan 1997*

[5] L. B. Clarke and B. T. Werner, *Synoptic imaging of nearshore bathymetric Patterns,* Journal of Geophysical Research, Vol. 108, No. C1, 2003

[6] J. Yoo, H. M. Fritz, Kevin A. Haas, P. A. Work, C. F. Barnes, *Depth Inversion in the Surf Zone with Inclusion of Wave Nonlinearity Using Video-Derived Celerity,* Journal of Waterway, Port, Coastal, and Ocean Engineering 137, 95-106. Online publication date: 1-Mar-2011.

[7] J. Yoo, *Nonlinear Bathymetry Inversion Based On Wave Property estimation From nearshore Video Imagery,* PhD Thesis, Georgia institute of Technology, December 2007

[8] S. Takewaka and T. Nakamura, *Surf Zone Imaging with a Moored Video System*, Coastal Engineering 2000: pp. 1211-1216

[9] R. Abileah, *The Utility of Video Image Sequence Combined With Multi-spectral Ocean Imaging,* of Ocean Optics XIV Conference, 10-13 November 1998, Kailua-Kona, HI

[10] K. R. Lee,*Using Multi-Angle WorldView-2 Imagery to Determine Ocean Depth Near Oahu, Hawaii*, Masster's Thesis, Naval Postgraduate School, Moneterey, California, September 2012.

[11] R, Abileah, *Mapping Shallow Water Depth From Satellite,* ASPRS 2006, Reno, Nevada, May 1-5, 2006

[12] R. Abileah, *Mapping near shore bathymetry using wave kinematics in a time series of WorldView-2 satellite images,* Geoscience and Remote Sensing Symposium (IGARSS), 2013 IEEE International , vol., no., pp.2274,2277, 21-26 July 2013

[13] R. H. Stewart and J.W. Joy, *HF Radio Measurements of Ocean Surface Currents,* Deep Sea Research, Vol. 21, 1039-1049 (1974).

[14] M. de Michele, S. Leprince, J. Thiebot, D. Raucoules, R. Binet, *Direct Measurement of Ocean Waves Velocity Field from a Single SPOT-5 Dataset,* Remote Sensing of Environment 119, 266-271.

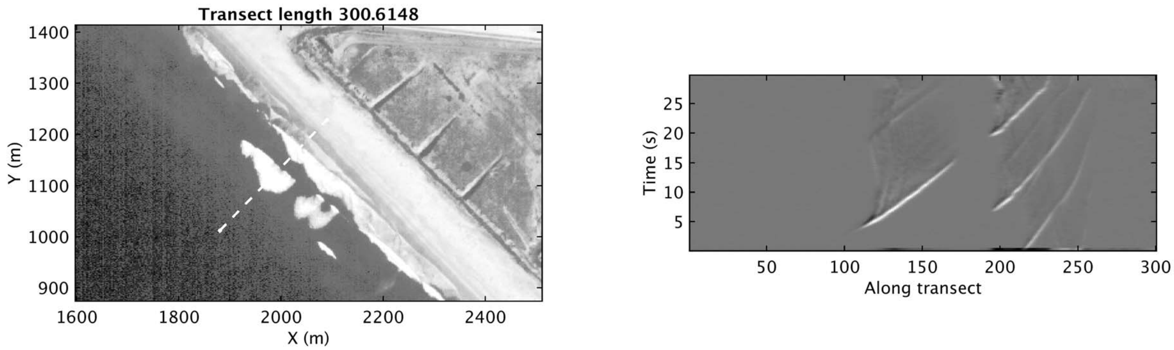

Fig. 1. Surf zone waves at Camp Pendleton Beach. R: 300 m transect line used for analysis shown overlaid on one image. L: 30 s history of wave crests along transect line.

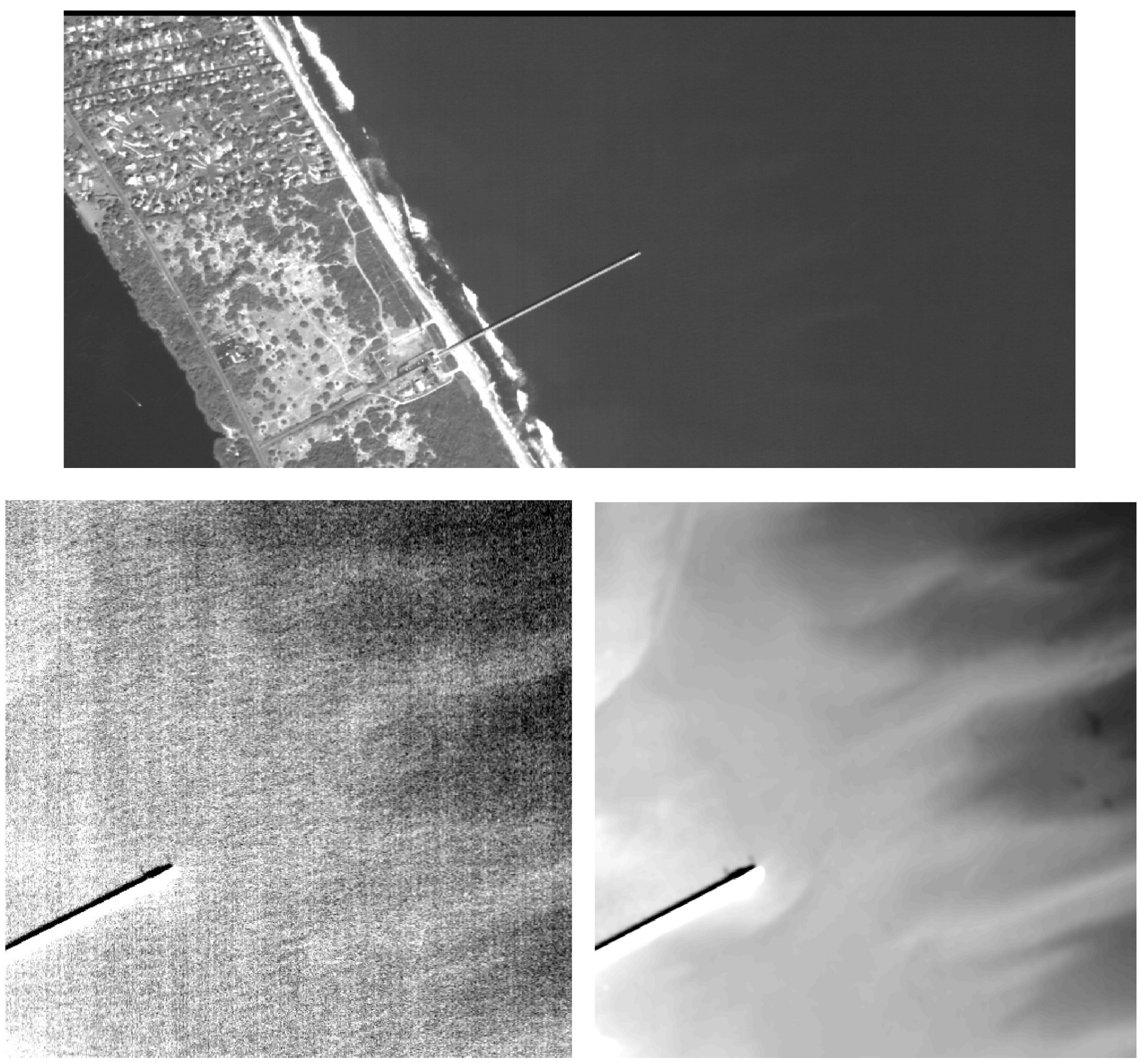

Fig. 2. Top: A single Skybox image centered on the pier at the USACE Field Research Facility, Duck, NC. Lower left: zoom on end of pier in one image frame; Lower right: zoom on 900-frame (30 s) average

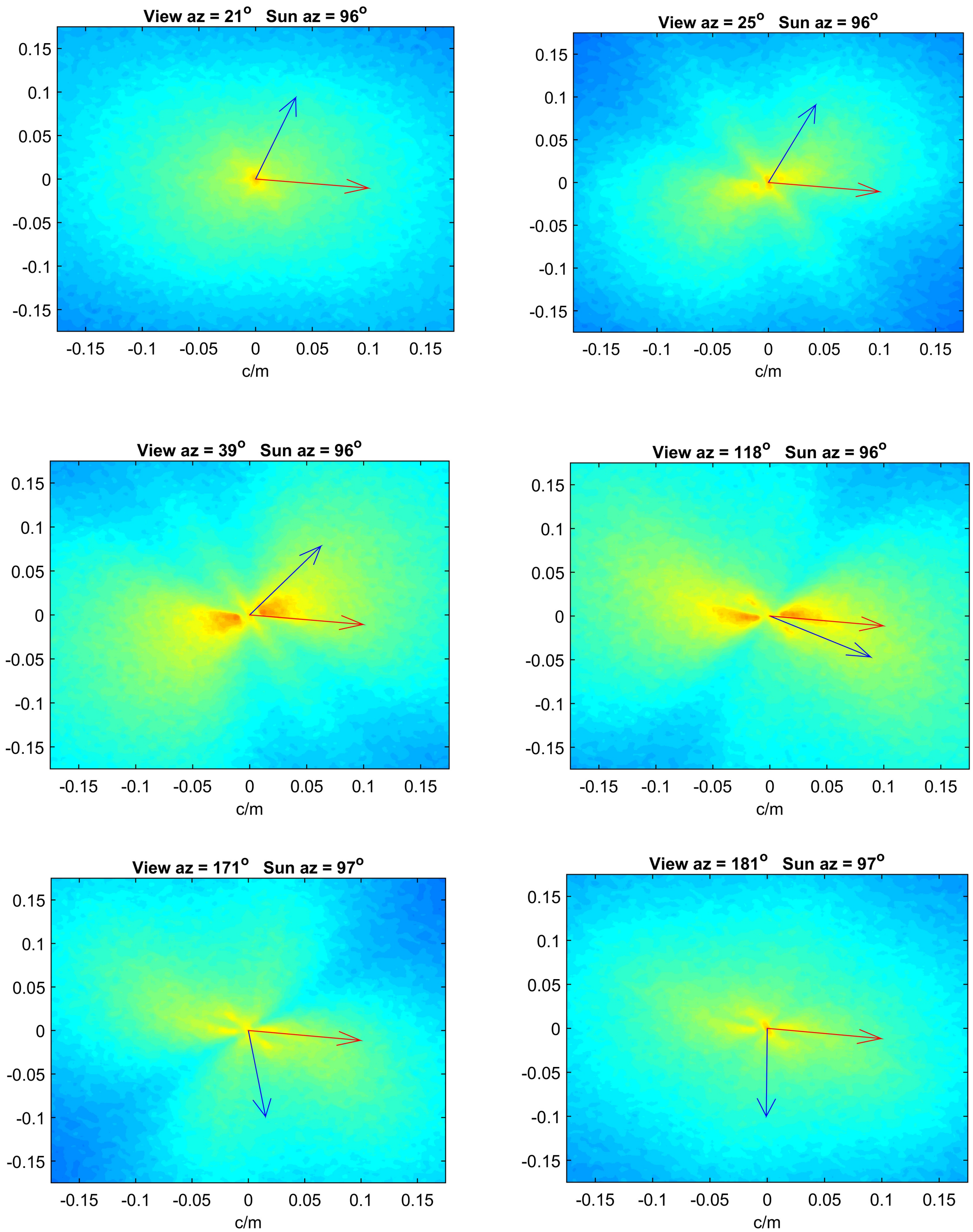

Fig. 3. Wave spectra at six view angles. Wind waves were propagating WSW, towards Makapuu Point, Oahu, Hawaii. Red arrows point to the sun; blue arrows point to satellite.

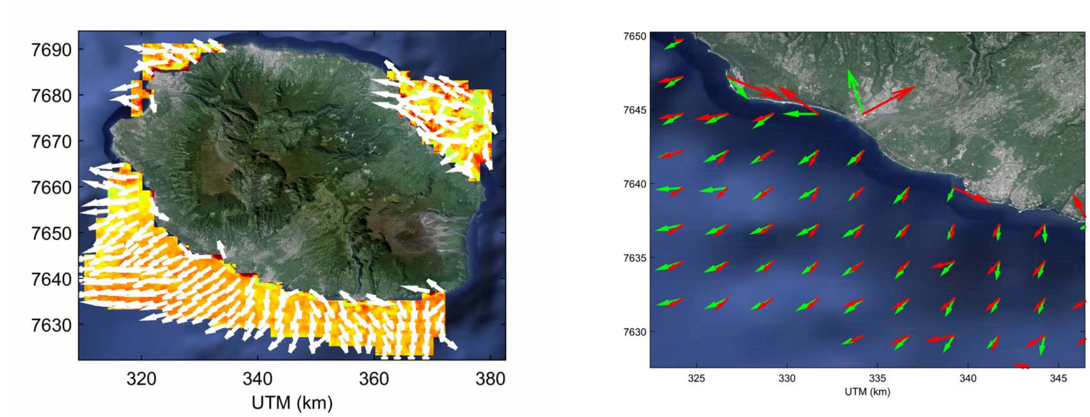

Fig. 4. Currents derived from SPOT-5 image of La Reunion Island. L: Current vectors computed of the entire 60 km x 60 km image area. Current magnitude is shown in color, direction in vectors. R: Zoom-in on a portion of the South coast showing current vectors and vertical shear.

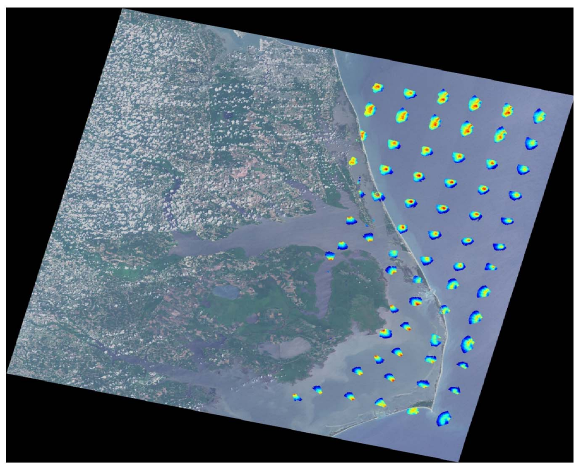

Fig. 5. Directional wave spectra in a Landsat image of Outer Banks, North Carolina. Analysis areas are 12 km x 12 km, aligned with the FGM boundaries running N-S along track.

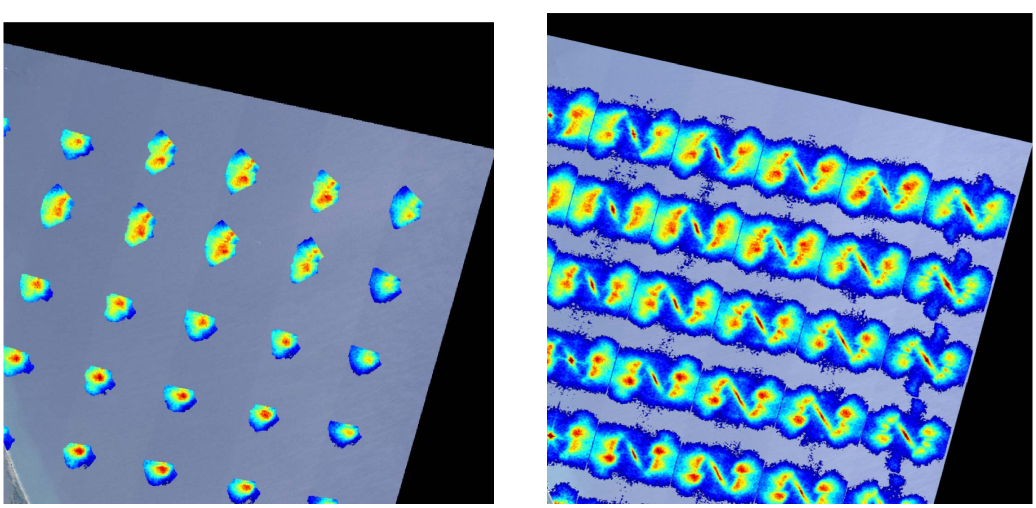

Fig. 6. Close up on spectra in the NE corner of the Outer Banks image. L: directional wind wave spectra; R: non-directional spectra.