THE UNIVERSITY OF ADELAIDE

On Using Airborne Optical Vertical Polarisation to Remove Sea Surface Reflectance for Enhanced Visualisation of Seagrass and Other Benthos

Thesis presented for the degree of

Master of Science

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4 Cross Polarisation Experiment

For this experiment a null hypothesis was developed, the aim being to disprove the null hypothesis. The null hypothesis is that:

> "Imaging of vertically polarised photons at critical angles makes no improvement in contrast between seagrass beds and surrounding substrate, when the same feature is compared at the same angle and the same time using vertically and horizontally aligned filters."

The images captured using a camera with a vertically polarising filter were the experimental variable. The images captured using a camera with a horizontally polarising filter were the control.

Some of the research in this chapter was presented as a conference paper (see Appendix 4).

4.1 Methods

4.1.1 New Design

Based on the results of the pilot experiment a new experiment was designed. Dual identical cameras were to be used, and the single variable was the orientation of the polarisation filter. The vertically polarized filter was to be the experimental variable and the horizontally polarized filter the experiment control (Stokes Q parameter)[50]. Further, no infra-red band was needed as the pilot experiment showed that the same effect would be present in both visible and infra-red bands. It was decided to shift the study area further north to coincide with the concurrent 2007 DEH Adelaide seagrass project.

4.1.2 Planning

As with the 2006 pilot data capture, the critical environmental conditions were: calm sea conditions with minimal wave action, with preferably wind from the land, mid morning sun in the east and over land, near austral summer solstice, and no recent rainfall events sufficient to cause stream flow or storm water run-off.

[50] Another option was to have no filter at all on the control camera (Stokes *I* parameter), but that would require a different f-stop to the variable camera (a separate variable).

Data capture was off the Adelaide metropolitan coastline. This area was chosen due to the concurrent Department for Environment and Heritage seagrass mapping project over this location[51] (Cameron 2008a).

The flight lines were designed based on two factors. One was knowledge of the seagrass extents off the Adelaide coastline. The former Port Adelaide sewerage treatment outfall off Port Malcolm had caused extensive seagrass loss around the outfall (Neverauskas 1987b, Bryars and Neverauskas 2004, Hart 1997). There had been seagrass loss around a pipe break nearer shore (Hart 1997). This known feature was visually distinctive from the air. There were different ecological patterns in the seagrass from north to south which could give visual clues as to location[52]. A bathymetric isodepth trend, such that shallow waters extended further from shore in the northern reaches than in the southern reaches around Brighton (Thomas and Clarke 2002), meant that the flight lines would need to tend shorewards from north to south. Brighton jetty is also a distinct feature for pilot visual navigation.

The second factor was the sun angle during that season and time of day. Two runs were directly away from the sun and towards the sun. At this time of year at around 9:30 am ACDT this would be approximately west and east. Two other runs had the sun on the left and the other on the right, but off-set from the sun at 45 degrees and 135 degrees[53].

GPS was planned to be captured for flight line locational purposes, rather than photogrammetric mapping.

4.1.3 The Experiment

Engineering mounting took place on Sunday 11 November 2007 at the aircraft hanger at Murray Bridge aerodrome (figures 33 to 36). The aircraft used was the Cessna 180[54] used in the pilot data capture in 2006. This time the translucent shield

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[51] Flown using a Vexcel UltraCam$_D$ 4-band digital camera on 28 December 2007, and georectified using GPS and IMU. No refraction correction was applied. The estimated ground positional accuracy was around 1 metre. Resolution was 50cm in the panchromatic band.

[52] Personal observation from earlier seagrass mapping (e.g. Hart 1997) and visible in Cameron (2003) and Cameron (2008a).

[53] See Lee et al, 1997 for lack of polarisation effects at 90 degrees to sun angle.

[54] Aircraft call sign VH-PJE, serial number 31130, manufactured in 1954 by the Cessna Aircraft Company (Airport-Data.com 2008, Civil Aviation Safety Authority 2008).

covering the underside camera port was removed to fit the bulkier cameras. The risk of oil spots on the lens filters was deemed acceptable as the drop-off in image quality would not affect the overall experiment.

Two Canon EOS 5D cameras[55] were mounted on a bracket in the aircraft at an angle of 30 degrees forward from nadir. The chip orientation was portrait, so as to maximize the forward view (from near-nadir to beyond the Brewster angle of 53 degrees).

Figure 33 - Aircraft VH-PJE used for polarisation flight.

Figure 34 – Two Canon EOS 5D cameras and mounting bracket. Note the slimmer body Canon 350D camera on the left for comparison.

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[55] The cameras both had Canon EF 24mm 1:2.8 lenses with the filters forward mounted of the lens. Each filter was a 58mm Hoya Pro1 Digital PL (circular polarisation) and were orientated horizontally and vertically (external frame of reference) on each cameras once mounted in the aircraft

Figure 35 - Interior view of camera port and camera bracket (with cameras mounted).

Figure 36 - Camera mounted 30 degrees forward from nadir.

On the day of the flight (Tuesday 13 November 2007) the cameras were re-mounted on the bracket in the aircraft. Spatial Scientific Technologies Pty Ltd undertook the mounting and image capture flight. As the aircraft was configured as a two seater due to the camera mount, only the pilot (Steve Barlow) and camera operator (Paul Dare) were on the flight.

One polarisation filter was adjusted to be horizontal on one camera, and the other adjusted to vertical on the other. A test picture was taken on the ground at 9:43 am.

Conditions were optimal, with clear skies and calm conditions (Appendix 1). Ocean turbidity was expected to be minimal due to at least ten days since the last rainfall event.

As planned, the flight was from the coast eastwards from Point Malcolm (Semaphore South/ West Lakes) to a location seven nautical miles off-shore. Then from that location tracking roughly south-eastwards to Brighton jetty[56]. Then the reverse course (a reverse figure 7 shape) back to Point Malcolm. A run of photography was captured over the Adelaide central business district (CBD) (figure 37).

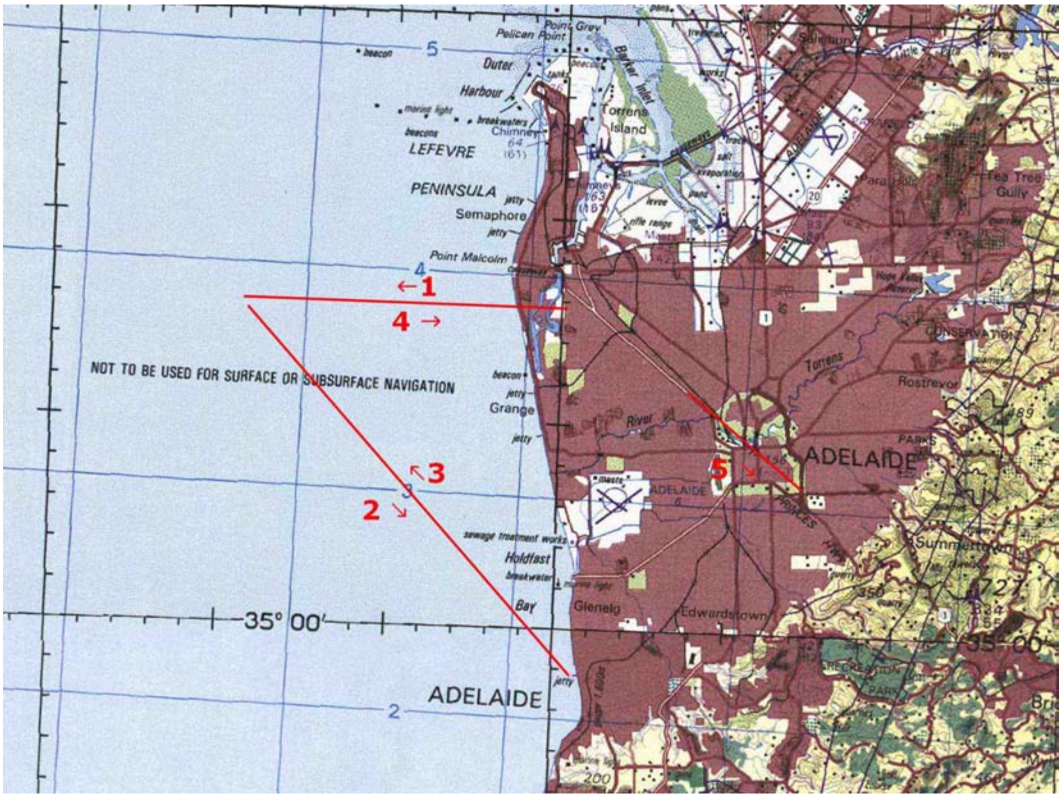

Figure 37 Flight lines for the November 2007 experiment.

The image capture started at 10:21am and finished at 10:52am Australian Central Daylight Time (GMT +10hr 30min). 257 image pairs were captured excluding one test image taken on the ground.

Unfortunately the GPS recording failed just after take off, so no aircraft positional information was digitally captured. The mapped flight lines were created using pilot records. This data was not critical to the experiment and so the experiment did not need to be reflown.

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[56] "(34 deg 51.5 min, 138 deg 28.5 min) to (34 deg 51.5 min, 138 deg 20 min) was the east to west course - coastline to offshore point. (34 deg 51.5 min, 138 deg 20 min) to (35 deg 1.5 min, 138 deg 31 min) was the south-easterly course - offshore point to Brighton Jetty. The same course was then flown in reverse." Paul Dare *pers comm.* 2007.

4.2 Results

4.2.1 Polarisation results

Selected frames have been included in the thesis to illustrate specific findings. Other frames could have been used as the effects illustrated are found on all similar frames. In all of the following image pairs the horizontal polarisation (H) images are on the left and the vertical polarisation (V) images on the right. Note that the airframe is visible at the forward edge of the H images. The colour images are balanced thumbnail images as produced by the camera software. The panchromatic images are the full resolution green band which has been balanced, contrast stretched and sharpened using an 11 by 11 filter, based on the findings of the pilot experiment. The same enhancements have been applied to each image pair.

Inspection showed little to no difference between the horizontal polarised and vertically polarised images when the sun is behind the aircraft in Run 1 from Point Malcolm to seven nautical miles offshore, in figures 38 and 39. Both showed distinct differences between seagrass meadows and exposed substrate. Figure 38 shows areas of historical seagrass loss near to the shore (light blue), with the existing seagrass meadows further seawards (dark blue).

Figure 39 shows the extensive area of seagrass loss around the now abandoned sewerage sludge outfall. The outfall is at 12 metres depth. The line of seagrass loss due to pipe burial in the seafloor is visible in the foreground. This is apparent on both horizontally polarised and vertically polarised images. Natural sand blow-outs (Shepherd and Sprigg 1976, Fotheringham 2002) are visible within the seagrass meadows on both images.

Enhancing and balancing the green band of the images shows similar subsurface information in the lower two-thirds of co-temporal horizontal and vertical polarisation frames. The top third shows little to no information in the horizontal polarisation frames, whereas the vertical polarisation frames clearly show benthic detail around the Brewster angle (figures 40 and 41).

Figure 38 Frames 0524 (horizontal polarisation left) and 4505 (vertical polarisation right) - crossing the coast at Point Malcolm with west to the top of frame, north to the right.

Figure 39 Frames 0535 (horizontal polarisation left) and 4516 (vertical polarisation right) - abandoned sewerage sludge outfall off Point Malcolm.

Figure 40 Enlargement of the top of frame 0543 (horizontally polarised) showing minimal detail.

Figure 41 Enlargement of the top of frame 4524 (vertically polarised) showing significantly more detail at depths of more than 12 metres.

Two runs (Run 2 and Run 3) were at approximately 45 and 135 degrees to the sun, with possible significant errors due to aircraft orientation. Note that all of these angles are approximate when compared to the actual images as the aircraft yaw, and therefore forward pointing of the camera, varies due to wind velocity and aircraft crabbing. Each run would have a different yaw to compensate for both wind direction and speed.

Run 2 at a solar angle of 45 degrees had a significant amount of specular sun reflectance. When comparing the horizontal and vertically polarised imagery over areas with benthic detail there was not much difference near nadir (figure 42). However more benthic detail was visible on the vertically polarised image near the Brewster angle (top of frame).

Figure 42 Comparison of horizontally polarised (frame 0613 left) and vertically polarised (frame 4594 right). Note the improvement in contrast of benthic detail top right of the frame 4594. Top of frame towards south-east.

Comparisons of imagery on Run 3 showed that the vertically polarised image was similar in imaging benthic detail as that of the horizontally polarised image (figure 43) except for a slight improvement around the Brewster angle. This was similar to Run 1.

These images show significant variations in the patterns of benthic flora and benthic geomorphology, sufficient for ecological mapping. The area shown in figure 42 has a relatively steeper slope compared to areas further north captured by the cameras, but shows little loss of detail due to the water column. The underwater dunes visible in figure 43 are a well known feature of the Adelaide marine environment. These are at a water depth of 7 to 8 metres (Fotheringham 2002).

Figure 43 Comparison of horizontally polarised (frame 0673 left) and vertically polarised (frame 4654 right). Top of frame towards north-west.

The final run had a solar azimuth of 68 degrees, rather than 90 degrees; therefore the sun was approximately 22 degrees left of the easterly track of the aircraft. The solar altitude was 56 degrees. Significant differences are apparent when directly viewing the sun reflection (Run 4, east to the top) in figure 44.

Enlargements (figure 45) of the just-submerged Point Malcolm breakwater (figure 46) at the Brewster angle (top part of enlargements) show marked differences. Note the removal of nearly all wave action, including breaking waves, and sun glint. The breakwater is barely visible in the left enlargement, yet is clearly visible in the right enlargement. Dark areas further off-shore are remnant seagrass beds (*Posidonia* spp.) and detrital matter. On the enlargement of frame 4735 the return of sun glint away from the Brewster angle (towards the bottom of the enlargement) is evident.

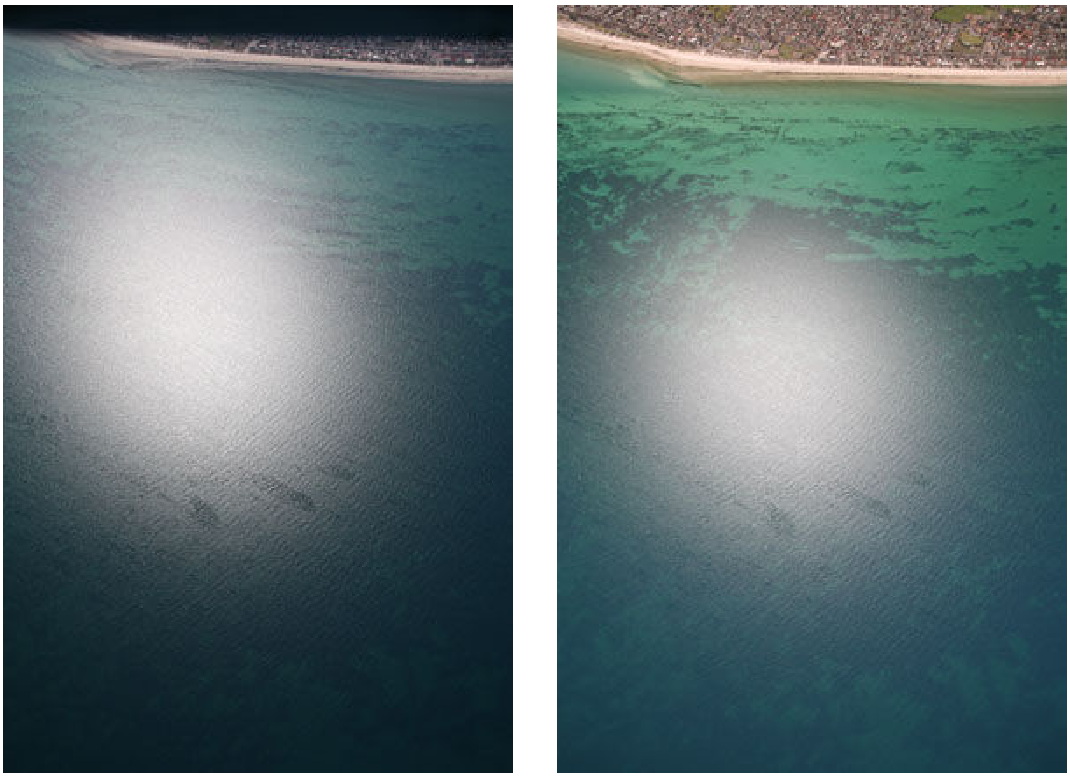

Figure 44 Frames 0754 (horizontal polarisation left) and 4735 (vertical polarisation right) - approaching coast with full sun reflection. Top of frame to the east.

Figure 45 Enlargements of frames 0754 (horizontal polarisation left) and 4735 (vertical polarisation right) showing the Point Malcolm breakwater.

Figure 46 Point Malcolm geotextile breakwater seen from shore at low tide.

4.2.2 Inland Water Bodies

Further differences between the horizontally and vertically polarised images were apparent in inland waters, especially where there is turbulence and/or turbidity. For example, the channels joining West Lakes and the Port River (figures 47, 48 and 49) show significant removal of sky reflectance and sun glint, even though the surface is turbulent (Run 4). The tide is going out so the water is flowing from right to left (south to north)[57].

[57] High tide at Port Adelaide (Outer Harbor) was at 6:29am ACDT at 2.56 metres above Chart Datum. Low tide was at 12:09pm ACDT at 0.28 metres above Chart Datum. Australian Bureau of Meteorology. The frames were captured at 10:51am.

Figure 47 Frames 0761 (horizontal polarisation left) and 4742 (vertical polarisation right) – overview.

Figure 48 Enlargement of frames 0761 (horizontal polarisation left) and 4742 (vertical polarisation right) at Port Adelaide.

Figure 49 West Lakes/ Port River barrier on left.

Likewise Torrens Lake (usually turbid) in the Adelaide parklands shows significant differences (figure 50). Note the lack of reflectance of the white fountain in the lake near the Torrens Weir in the vertically polarised image, whereas the shadow is visible in both enlargements (Run 5, south-east at top) (figure 51). This shows that the direct reflection of the fountain (figure 52) on the water surface is removed, yet the shadow of the fountain is clearly darkening the turbid material (figure 53) in the water body itself. Also, the blue sky reflectance is removed, showing the turbid waters directly.

Figure 50 Frames 0763 (horizontal polarisation left) and 4744 (vertical polarisation right) – overview.

Figure 51 Enlargement of frame 0763 (horizontal polarisation left) and frame 4744 (vertical polarisation right) at the Torrens weir in the Adelaide parklands. Note the blue sky reflectance on frame 0763 and the visible brown turbidity on frame 4744.

Figure 52 Fountain in Torrens Lake.

Figure 53 Turbidity in Torrens Lake (unpolarised image).

4.3 Discussion

In this section the original aims and the null hypothesis are discussed, and further exploration of the amount of improvement in imaging benthic detail with sun angle undertaken.

4.3.1 Review of Aims

The null hypothesis for the experiment was that:

> "Imaging of vertically polarized photons at critical angles makes no improvement in contrast between seagrass beds and surrounding substrate, when the same feature is compared at the same angle and the same time using vertical and horizontally aligned filters."

The aim of the experiment was to disprove the null hypothesis.

The original research aims were to investigate the use of polarisation, in conjunction with light intensity and wavelength, as another information parameter in the optical remote sensing of marine benthic flora, and to apply polarisation parameters to detect seagrass beds in coastal waters.

The results clearly show that the aims have been met. Polarisation (as an adjunct of intensity and wavelength) has been shown to have sufficient extra information to enable the sea surface reflectance to be removed at time of image capture.

Likewise seagrass beds are clearly delineated in the imagery in detail, appropriate for mapping of ecological features.

Initial inspection of the data showed that the experiment has disproven the null hypothesis. Run 4, directly towards the sun, showed sun glint, and wave action in the horizontally polarising filtered image sufficient to mask almost all subsurface detail. The vertically polarising filtered imagery removed the glint, even from breaking waves. Therefore imaging of vertically polarized photons at critical angles makes *a great* improvement in contrast between seagrass beds and surrounding substrate *at certain geometries compared to imaging of horizontally polarized photons.* (Italics indicate experimental constraints on the results).

4.3.2 Sun Aspect Geometries

Analysis was required to explain why the sea floor was visible towards nadir in both sets of imagery acquired while flying away from the sun (down sun). One hypothesis is that depolarisation occurs during the atmospheric path length post reflectance (Curran 1981), resulting in equal amounts of orthogonal polarized light from the surface reaching the cameras. This is unlikely as the same effect would occur on the run towards the sun, and this is not the case. Therefore the depolarisation hypothesis is dismissed.

Another hypothesis is that the polarisation properties of incident photons are different depending on the geometry, at least for sky reflectance. As the conditions were relatively calm on the water, there is no lambertian or specular sun reflection back to the camera. Therefore the only surface reflectance was from the Rayleigh scattered sunlight from the sky on the water surface. Sky reflectance is polarised at 90 degrees from the sun, such that the incident photons were vertically polarised[58] (orientated in the east-west direction) in the west at the time of image capture. This can be shown by a simple pair of polarised sky images (see figure 54)[59]. The geometry was such that there was very little horizontally polarised sky reflecting off the water. The majority of the vertically polarised sky scatter was therefore refracted into the water. This meant that there was minimal sky reflectance from the water surface when flying away from the sun. This would account for the overall similarity between the co-temporal images.

Only at the Brewster angle was there a significant difference between the frames on down sun images. At this angle all horizontal component was blocked on the vertically polarised images.

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[58] Technically the polarisation electric vector was aligned or parallel with lines joining the sun-antisun points on the celestial sphere. At the time of image capture the polarisation electric vector was aligned approximately east-west. Images captured with the sun aspect at 180 degrees (Run 1) this corresponds to a vertical polarisation in the aircraft coordinate system.

[59] Note that the geometry of the polarisation due to Rayleigh scatter at 90 degrees to the sun is three dimensional, so that the effect is an arc or band across the sky.

Figure 54 Sky Rayleigh scatter at 90 degrees to sun (facing west with sun behind camera) through a vertically polarising filter (left) letting vertical polarised light through and producing an even toned image, and a horizontal polarising filter (right) blocking vertical polarised light, the visibly darker and less blue sky showing the lack of a horizontal component.

Another hypothesis is that the waters were so clear that minimal surface reflectance was occurring, with quantum theory predicting 4% Therefore the images should be 96% similar. Conditions were too good on the day. Only when specular and lambertian sun reflectance was near the Brewster angle as in the down sun images was there enough difference between the vertical and horizontal components to be measurable.

Therefore slightly poorer environmental conditions on the day may have given stronger differentiation between the vertical and horizontally polarised images.

4.3.3 Other Sun Aspect Geometries

Two runs were at approximately 45 degrees and 135 degrees to the sun. At 90 degrees to the sun the same sky polarisation effect as down sun images would have been evident (i.e. no difference). However Lee et al. (1997) has already shown that with the same instrument set-up[60], their results showed no significant variation between polarised and unpolarised values at flight lines orientated 90 degrees to the sun[61]. There was no perceived benefit from repeating their experiment.

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[60] A single vertical polariser mounted in front of the sensor, with the sensor tilted 30 degrees up from nadir, and flown 90 degrees to the sun, then flown without a vertical polariser. This is similar to the pilot image capture north-south flight lines along the coast (chapter 3), however no non-filtered imagery was captured for comparison, hence this experiment.

[61] Lee et al, (1997) suggest that the result was due to the partial polarisation of the underwater light field, rather than the effect of polarized Raleigh sky scatter as demonstrated here.

The run at 45 degrees to the sun did show improvement in the contrast between seagrass and substrate. This was similar to the run towards the sun, probably due to the similar aspect to the sun between the two runs.

Fougnie et al. (1999) recommended that a vertically polarised analyser at 135 degrees to the sun at 45 degrees aspect (near the Brewster angle) would optimally remove the effects of sky reflectance[62]. This was approximately the geometry for the north west run.

Comparisons of imagery on the north west run showed that using the vertically polarising filter was less effective in imaging benthic detail. This was due to there being less horizontal component reflected from the sea surface to block. Again this would be due to sky polarisation at 90 degrees from the sun and similar to the down sun run.

4.3.4 Overall Pattern

This pattern of results is consistent with polarisation due to Rayleigh scatter. Overall the four runs showed that the closer the flight line comes to the sun, the better the vertically polarising filter strips away surface reflectance, due to there being more horizontal component. Away from the sun, except at the Brewster angle, the environmental conditions were such that the overall images had good depth penetration anyway.

4.3.5 Significance

The experiment has shown that the use of vertical polarizing filters can strip away significant surface reflectance at the Brewster angle. The remaining image is the benthic seafloor or any material suspended in the water column. Away from the Brewster angle the image depends on the conditions on the day, as with normal nadir-viewing aerial photography.

The technique can improve overall underwater visibility where the sky reflectance is polarised, but this depends on the solar geometry and aircraft flight path.

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[62] Fougnie et al (1999) also claim that water bodies polarise incident skylight, which is actually a surface effect (Feynman 1985).

Operationally this methodology can be used for remote sensing of turbidity, or any other form of ocean colour detection, such as algal blooms, suspended solids, and dissolved organic matter. It can be used for detection of underwater objects, such as submerged whales in areas where sunglare may be a problem.

The use of vertical polarisation filters would be useful when capturing oblique coastal photography. For instance the South Australian Department for Environment and Heritage has a program of oblique coastal aerial photography for monitoring purposes. This method would eliminate unwanted sunglare from the images.

5 Conclusions and Future Directions

5.1 Summary of Findings

The main finding of this series of polarisation experiments is that sea surface reflection is removed by using vertically polarised filters at, and around, the Brewster angle of 53 degrees off nadir when viewing sunwards. This reflection includes sky reflectance, lambertian sun glare, reflection due to wave action, and turbulence, but not direct solar specular reflection. This improves the imaging of benthic flora compared to horizontally polarised imagery, and by extension non-polarised imagery.

Other related findings are that sky polarisation at an aspect of 90 degrees to the sun affects the proportion of horizontal and vertically polarised surface reflectance; vertically polarised filters remove sea surface reflectance similarly in both visible and near infra-red; any turbidity or other water column material present is clearly visible once the water surface reflectance is removed; and photointerpretation is the preferred interpretation approach for Bayer pattern filter cameras.

5.2 Improvements on Current Experiment Design

Polarisation, as the third property of light, has many potential remote sensing research applications. To measure the four Stokes polarisation parameters would need a single camera which splits the incoming incident light into three beams. One beam would then pass through a vertical polarising filter, the second through a horizontal polarising filter, while the third would pass through a polarising filter at 45 degrees to the other two. This would give the Stokes Q, U and V polarisation parameters. Adding the three parameters results in the fourth Stokes polarisation parameter I.

The use of CMOS chips without Bayer pattern filters would allow for quantitative analysis of the imagery. The three polarisation-band image would cover the entire spectrum the chip was sensitive. For marine applications a green filter forward of the lens would remove noise from unwanted parts of the spectrum.

For marine remote sensing the chip orientation would be horizontal to maximise coverage at the required angle, and the camera tilted so as to be centred on the

Brewster Angle. A mechanism to stabilise the camera so as to be independent of aircraft roll, pitch and yaw during operational image capture would increase the precision of the experiment geometry. A differential GPS and Inertial measurement unit (IMU) would allow for photogrammetric reconstruction of the image geometry and seagrass mapping with minimal or no ground control (depending on positional accuracy required).

5.3 Advanced Experimental Design

Another option other than a frame camera would be a vertically polarised line scanner oriented at 53 degrees as in either a conical or windscreen wiper action, or in a total 360 degree rotation. This would give imagery solely captured at the Brewster angle, the image built up as the sensor platform moves along its flight path, or orbit if in space. This would build a continuous strip of Brewster angle imagery, where each pixel is vertically polarised. The design of a Brewster-angle vertically-polarised line-scanner would be the next step for a device to sample at the critical angle (figure 55).

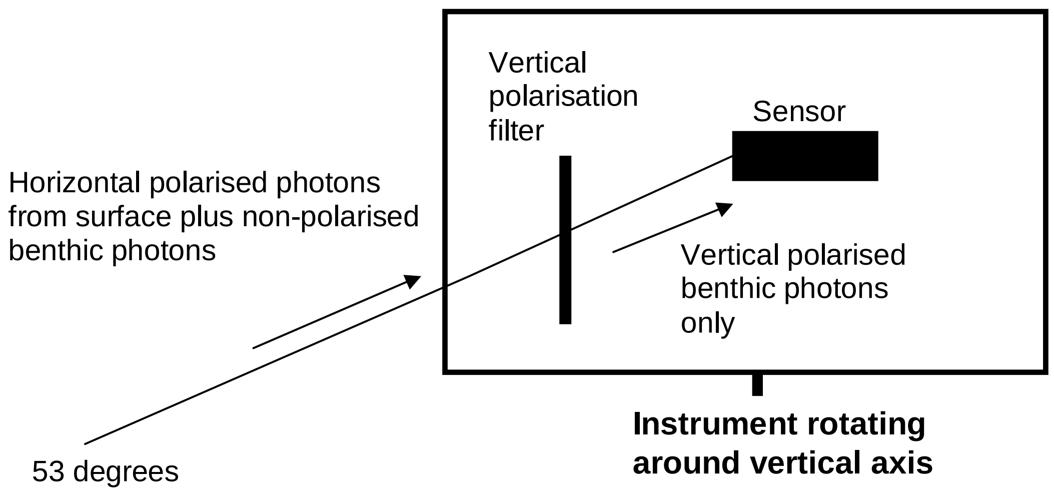

Figure 55 Potential schematic for Brewster angle 360 degree sensor (side view).

The sensor would have a 360 degree field of view as the instrument or its optics, for instance a rotating mirror, would collect a ring of scan lines at or near the Brewster Angle (figure 56). If the sensor platform was moving horizontally, then the sensor would collect an offset series of scan lines (figure 57). These scan lines would be stitched into a scene, where each and every pixel would be vertically polarised at or near the critical Brewster Angle wherever it was in the resultant image (figure 58).

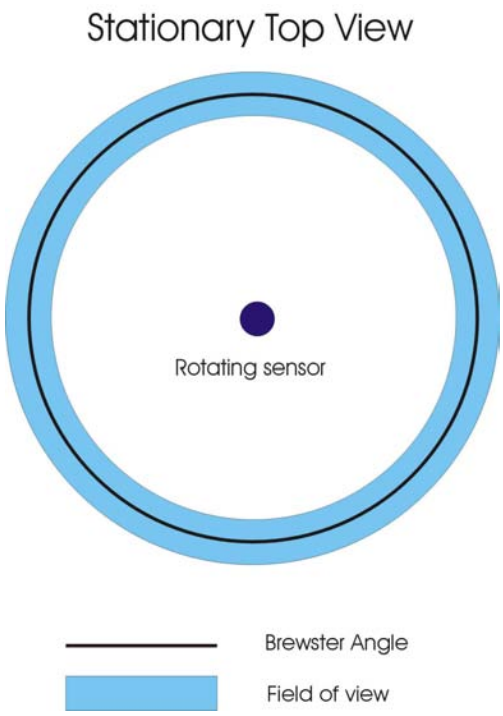

Figure 56 Top view of rotating vertical polarisation sensor when stationary. Note that every pixel is at or near the Brewster Angle.

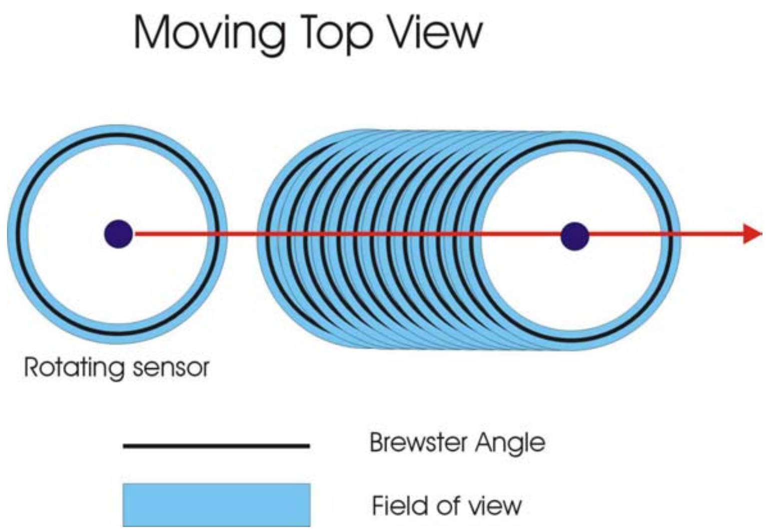

Figure 57 Top view of rotating vertical polarisation sensor moving from left to right. Note how the overlapping scan lines build up rings or spirals of pixels at the Brewster Angle.

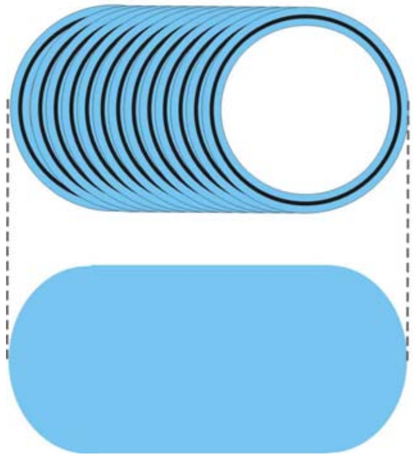

Figure 58 Resultant image created from overlapping scan lines at the Brewster Angle. Every pixel is vertically polarised at the Brewster Angle.

5.4 Further Research

To further explore the application of polarisation using the experimental design utilized in this study, images would need to be captured in sub-optimal environmental conditions to find the empirical limits of the methodology. This would include conditions when the ocean waves are larger and steeper, and so varying the surface reflectance angles away from the Brewster angle. The removal of cloud reflection (Mie scatter) from the imagery at various angles would also need to be explored. Further investigation of the advantages of polarisation for removal of near-surface reflectance would require multispectral imaging of actual turbidity plumes from stream or storm water discharges, or of ocean colour.

For a more detailed exploration of polarisation parameters in the remote sensing of marine benthic flora, a sensor that records, or can generate, the four Stokes polarisation parameters as independent variables would be necessary. Commercially available sensors of this type currently exist for terrestrial and industrial applications. These can be mounted in an aircraft[63].

Due to the geometry-dependent nature of polarisation image capture, previous studies have not fully explored the possible information contained in this property of

[63] A non-polarisation version was test mounted in an aircraft early in the pilot test design stage of this study.

light. Remote sensing has expanded its imaging capability in spectral range and resolution, radiometric resolution and microwave polarity. Optical polarisation remote sensing is a field that, using the new polarisation line scanner design introduced in this thesis, explores the optical polarisation properties of matter in the environment at critical angles. There has been little use of polarisation remote sensing for vegetation analysis, or other non-marine research applications of polarisation such as desert pavement and soils from the air. These areas hold potential for new discoveries using this underutilised property of light.

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7 Appendix 1 – Meteorological conditions on Tuesday 13 November 2007

7.1 Introduction

The meteorological conditions were monitored before and during the flight. This was to ensure optimal conditions. If conditions were sub-optimal the flight may have been delayed to another day, or reflown.

The conditions monitored were rainfall over preceding days to check for storm and run-off turbidity, wave action, wind speed and direction, and cloud.

7.2 Previous Rainfall

Due to the Mediterranean type climate in the study area (Schwerdtfeger, 1976), and the resultant summer drought, plus the existing 2007-08 major drought, there was minimal non-rainfall fed stream flow. The only turbidity source would be due to major rainfall events (Holmes and Iversen, 1976).

There was no significant rainfall enough to cause storm water run-off or stream flow. In the preceding month of October there was between 25 and 50 mm of rainfall in the study area (figure 59). In the week prior to the flight there was no significant rainfall (figure 60). Likewise on the day of the flight there was no rainfall over the study area (figure 61).

The coastal waters were therefore expected to be clear, as was the case when the resultant imagery was analysed.

NOTE:
This figure is included on page 106 of the print copy of the thesis held in the University of Adelaide Library.

Figure 59 Rainfall for the month of October 2007 (courtesy Australian Bureau of Meteorology).

NOTE:
This figure is included on page 106 of the print copy of the thesis held in the University of Adelaide Library.

Figure 60 Rainfall for the week ending 12 November 2007 prior to the flight (courtesy Australian Bureau of Meteorology).

NOTE:
This figure is included on page 107 of the print copy of the thesis held in the University of Adelaide Library.

Figure 61 Rainfall for the day of the flight 13 November 2007 (courtesy Australian Bureau of Meteorology).

7.3 Wave Action

As wave action is a combination of local winds and distant fetch (Crapper 1984), the Cape du Couedic (Kangaroo Island) wave observations were monitored for an indication of waves due to distant winds (figures 62 and 63).

NOTE:
This figure is included on page 107 of the print copy of the thesis held in the University of Adelaide Library.

Figure 62 Cape du Couedic maximum wave height measurements (red) and significant wave height (blue) (courtesy Australian Bureau of Meteorology).

Figure 63 Cape du Couedic peak energy period measurements (green) and average wave period (blue) (courtesy Australian Bureau of Meteorology).

This showed that there was wave action due to winds in the Southern Ocean.

7.4 Wind Speed and Direction

Local winds have an influence on waves (Crapper 1984). Ideally the conditions for the flight would either be calm, or a light breeze from the east off the land. The national forecast was for light easterly winds due to a high pressure (anti-clockwise) south of the study area (figure 64). The forecast was for easterly winds with a mild swell[64].

7.5 Cloud

The day and time of flight was predicted to be cloud free. The satellite cloud images showed this to be the case (figure 65).

7.6 Summary

The conditions for image capture were optimal on the morning of 13 November 2007.

64 'Australian Government Bureau of Meteorology Forecast for Adelaide Metropolitan Waters Issued at 5:15 am ACDT on Tuesday 13 November 2007 was for winds at E/NE 8/13 knots and the sea at 0.5 m rising to 1 m with the sea breeze. Swell south of Marino Rocks was forecast at W/SW at 0.5 metres'. Australian Bureau of Meteorology.

NOTE:
This figure is included on page 109 of the print copy of the thesis held in the University of Adelaide Library.

Figure 64 Mean sea level analysis 13 November 2007 (courtesy Australian Bureau of Meteorology).

NOTE:
This figure is included on page 109 of the print copy of the thesis held in the University of Adelaide Library.

Figure 65 Visible image at 10:00am ACDT 13 November 2007 during the data capture flight (courtesy Australian Bureau of Meteorology).

8 Appendix 2 – Comparison of horizontally polarised and vertically polarised frames

8.1 Introduction

This selected subset of frames from run 1 on the experimental flight of 13 November 2007 demonstrates the differences in benthic detail at, and around, the Brewster Angle, near the top of each frame. Compare the top quarters of each frame pair. This set of frames crosses the deep seaward extents of the Adelaide seagrass meadows and shows details on the deeper, non-vegetated substrate. This deeper benthic detail has never been imaged in any previous remote sensing seagrass study off metropolitan Adelaide.

In the following frame pairs the horizontally polarised image is on the left, and the vertically polarised image is on the right.

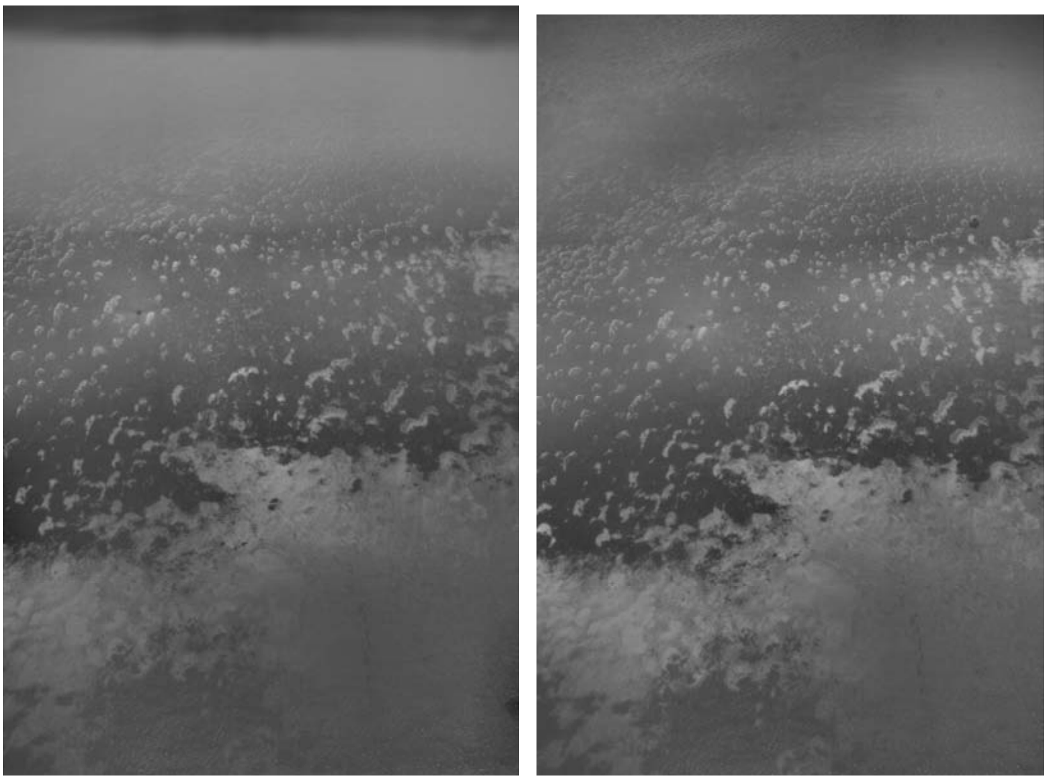

Figure 66 Frames 0539 (horizontal polarisation) and 4520 (vertical polarisation) compared.

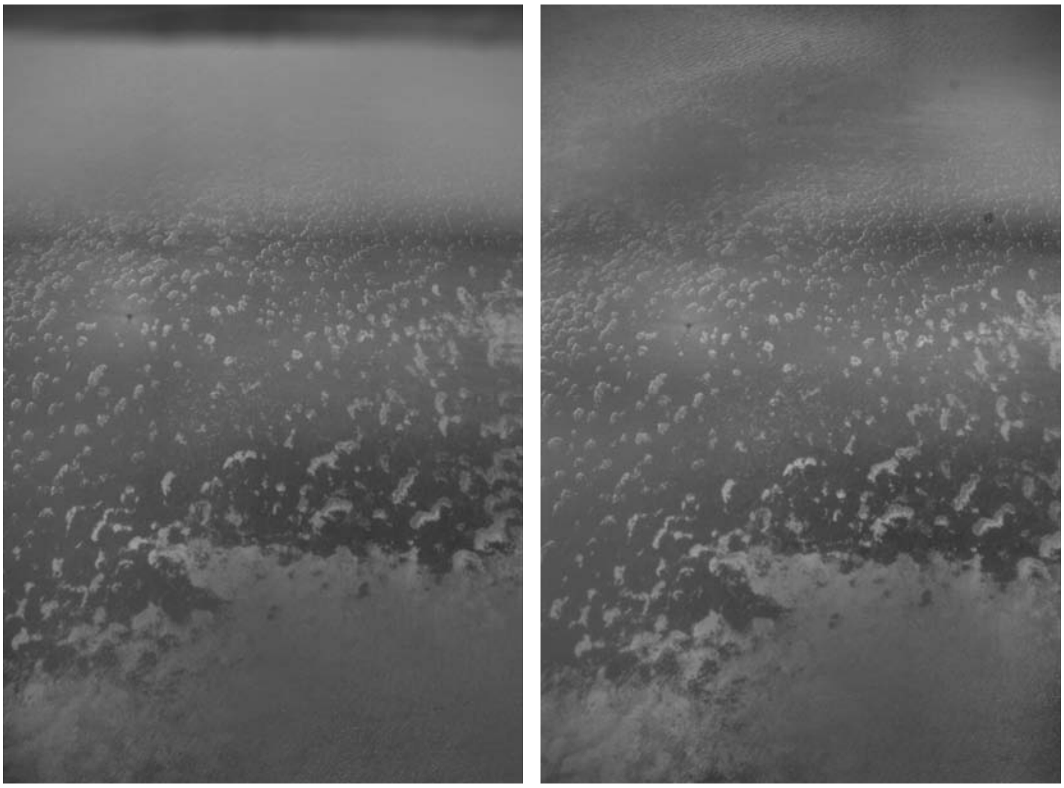

Figure 67 Frames 0540 (horizontal polarisation) and 4521 (vertical polarisation) compared.

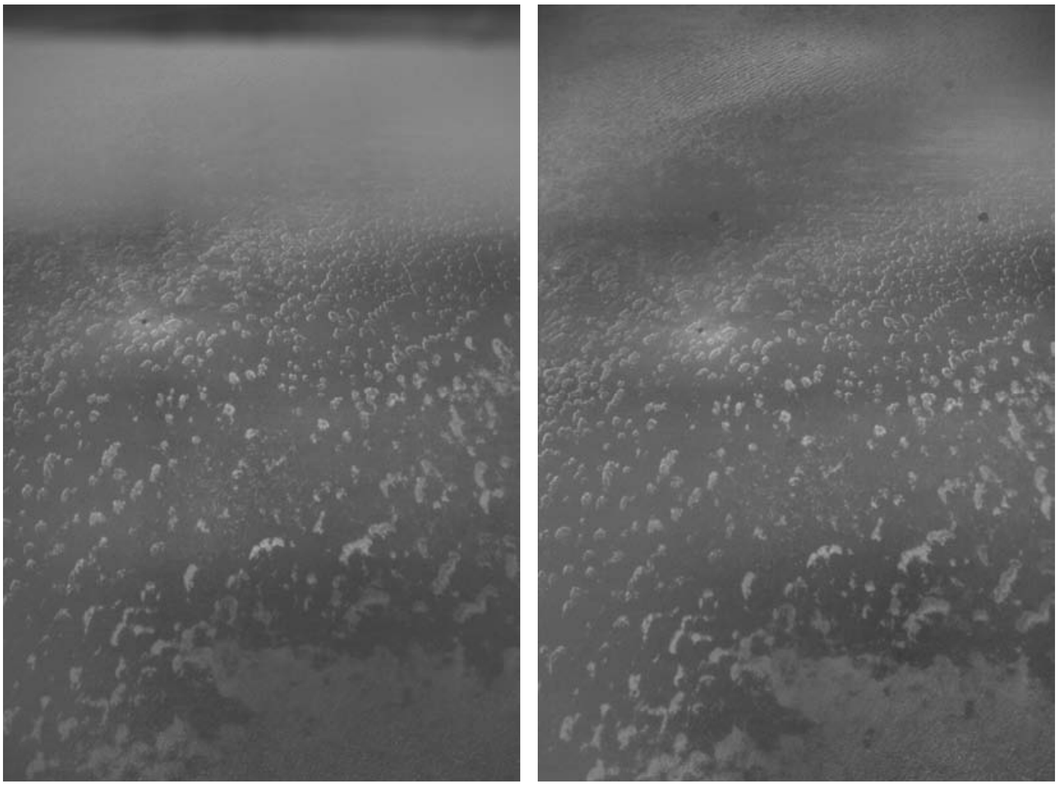

Figure 68 Frames 0541 (horizontal polarisation) and 4522 (vertical polarisation) compared.

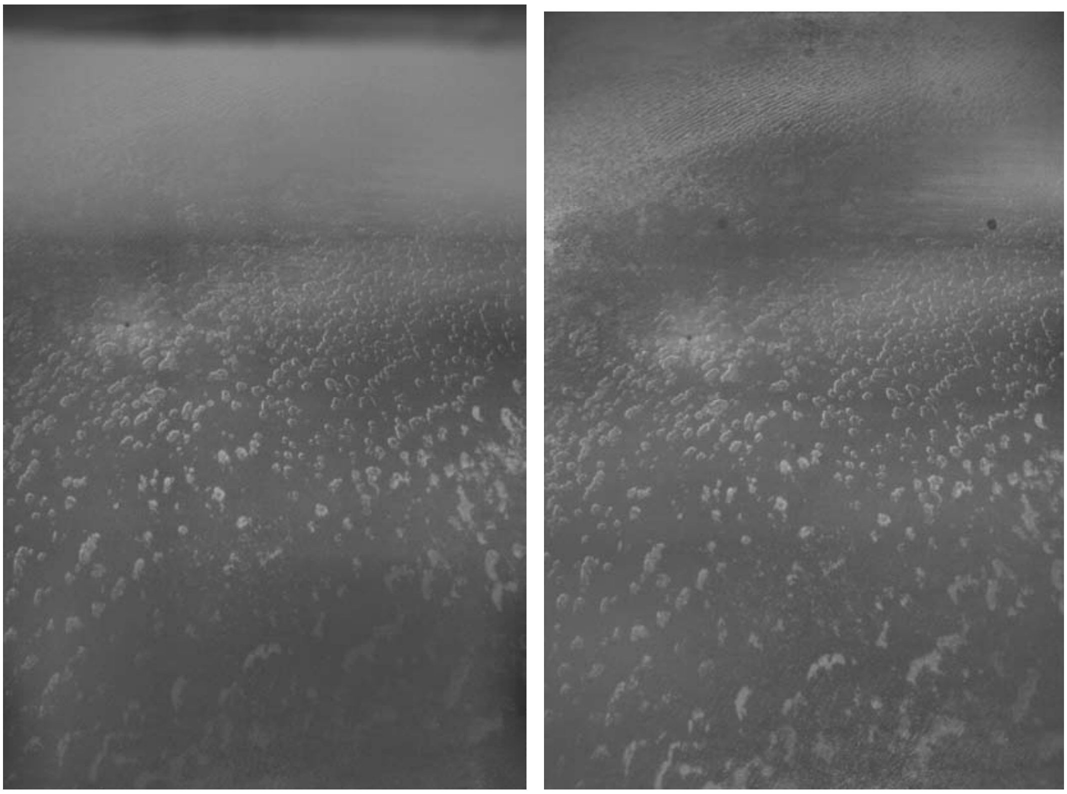

Figure 69 Frames 0542 (horizontal polarisation) and 4523 (vertical polarisation) compared.

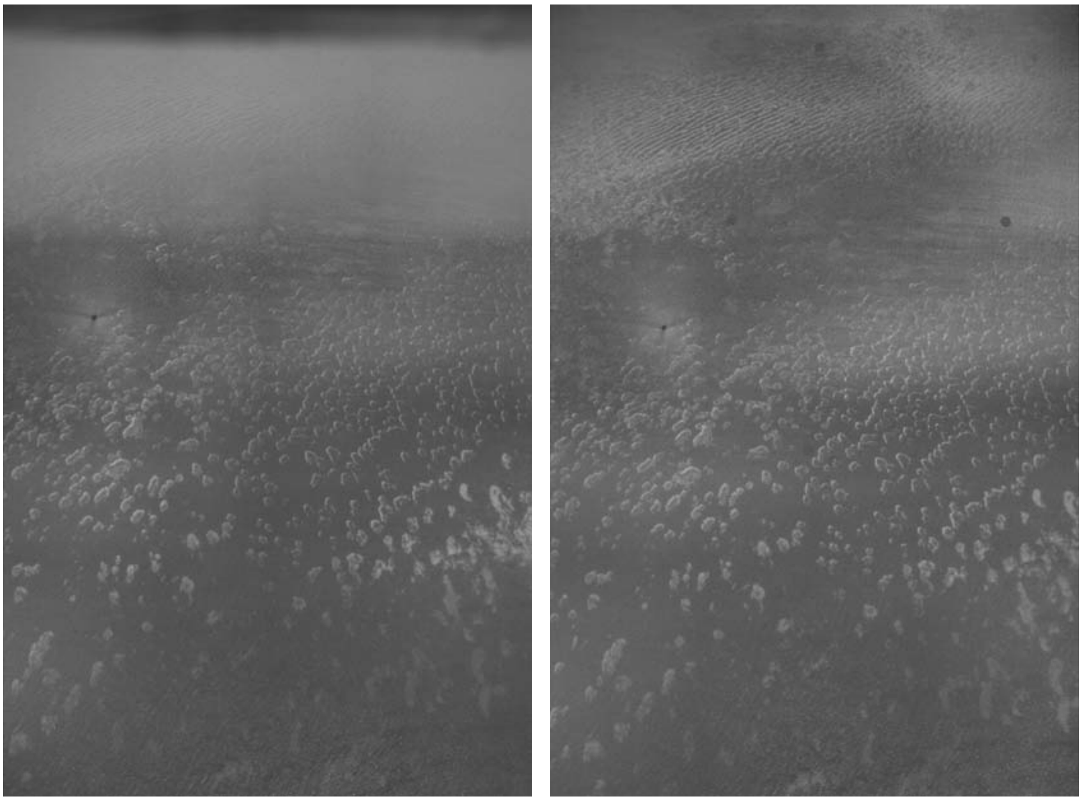

Figure 70 Frames 0543 (horizontal polarisation) and 4524 (vertical polarisation) compared.

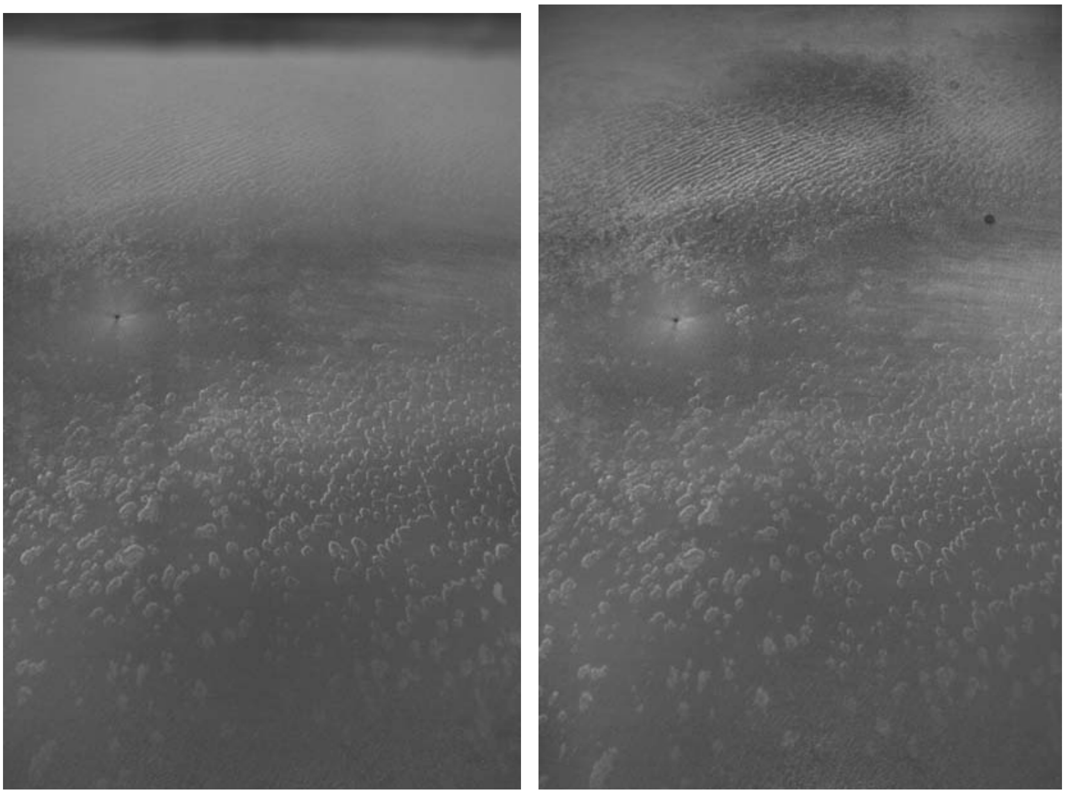

Figure 71 Frames 0544 (horizontal polarisation) and 4525 (vertical polarisation) compared.

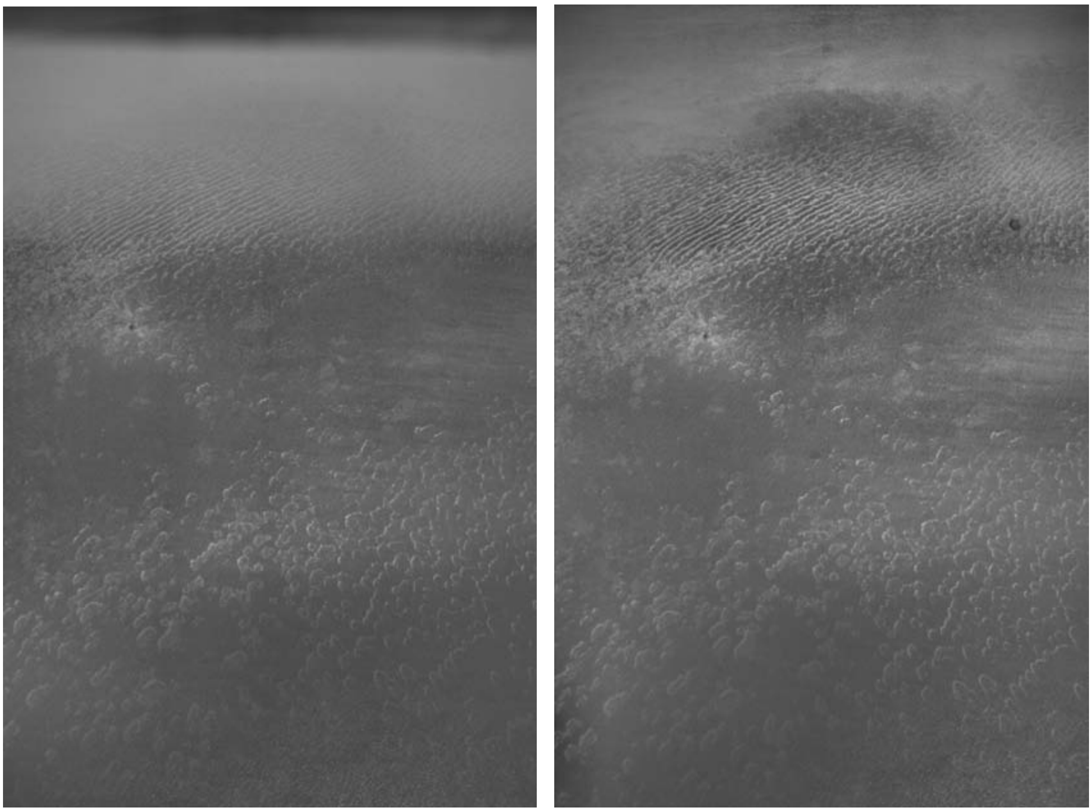

Figure 72 Frames 0545 (horizontal polarisation) and 4526 (vertical polarisation) compared.

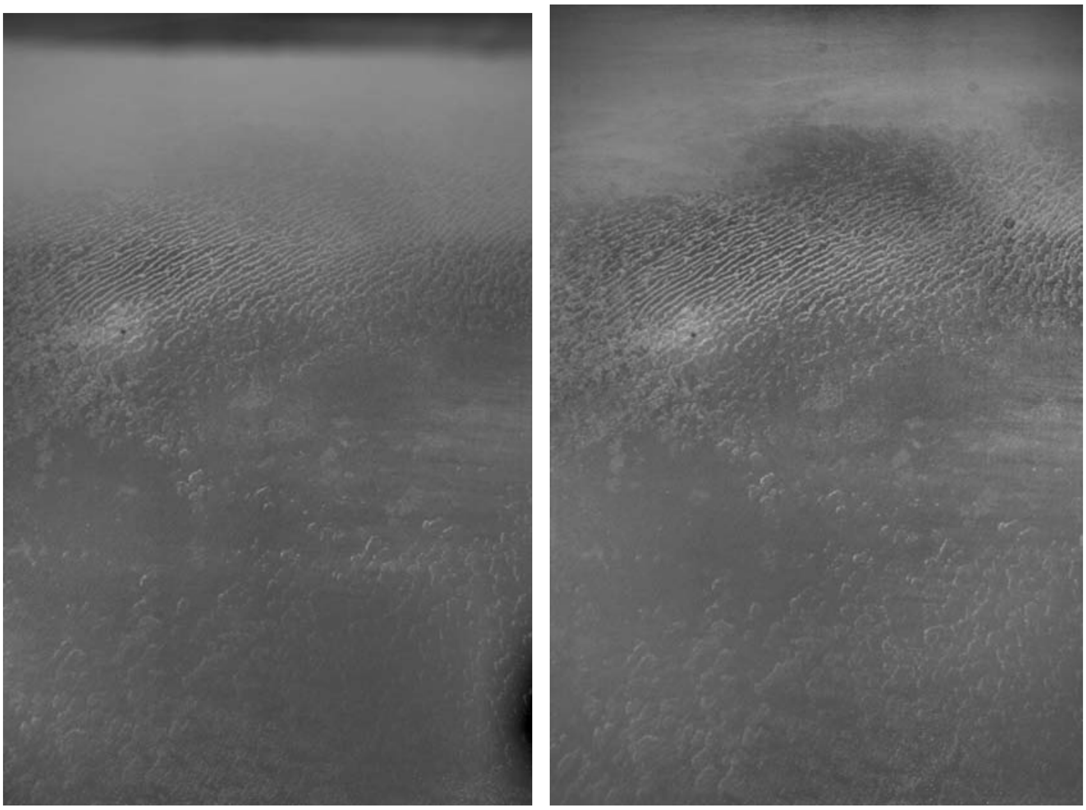

Figure 73 Frames 0546 (horizontal polarisation) and 4527 (vertical polarisation) compared.

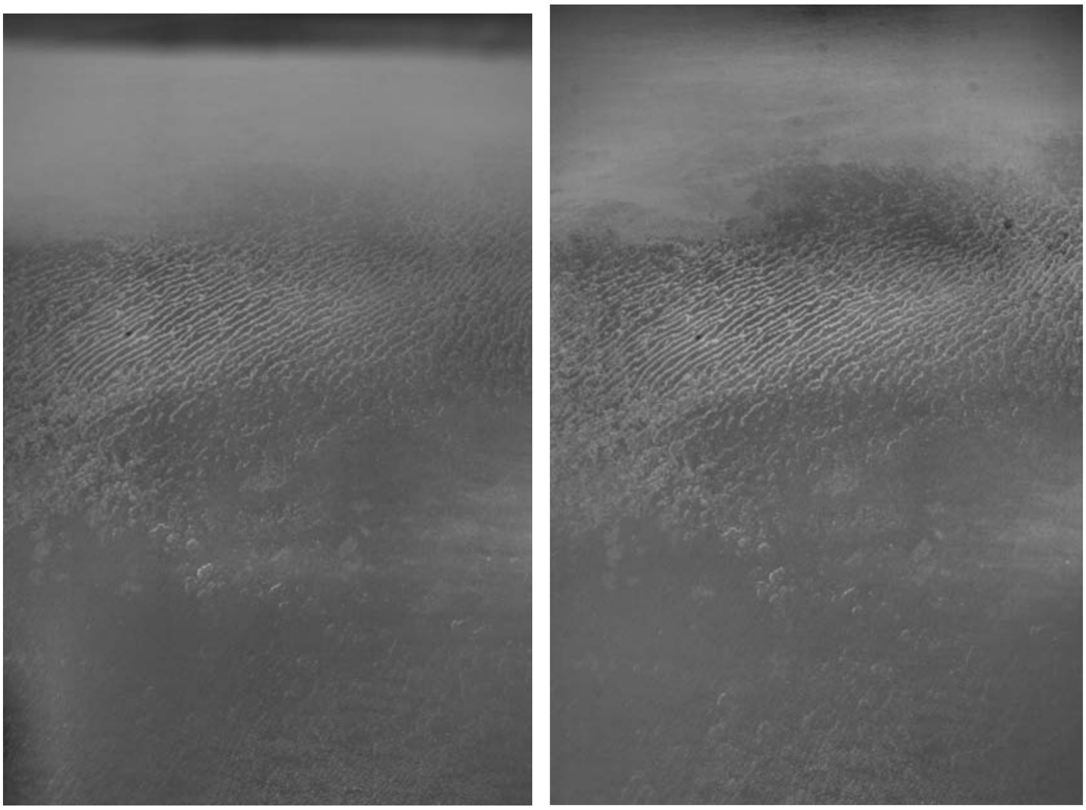

Figure 74 Frames 0547 (horizontal polarisation) and 4528 (vertical polarisation) compared.

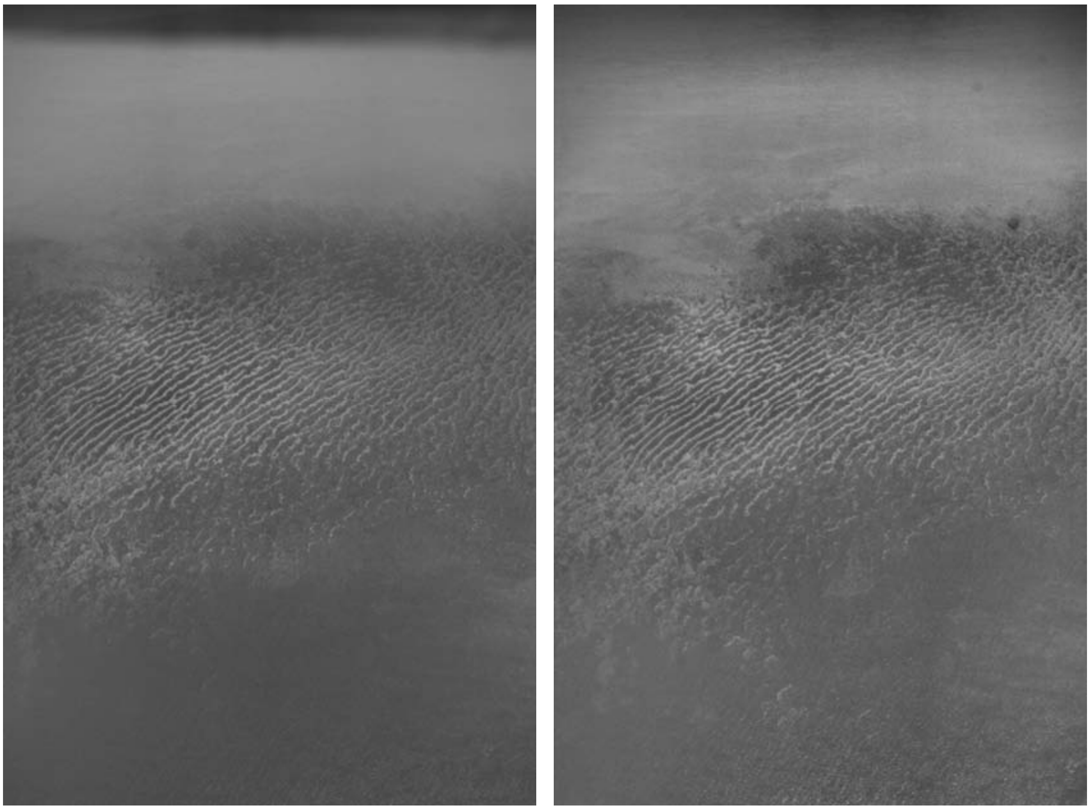

Figure 75 Frames 0548 (horizontal polarisation) and 4529 (vertical polarisation) compared.

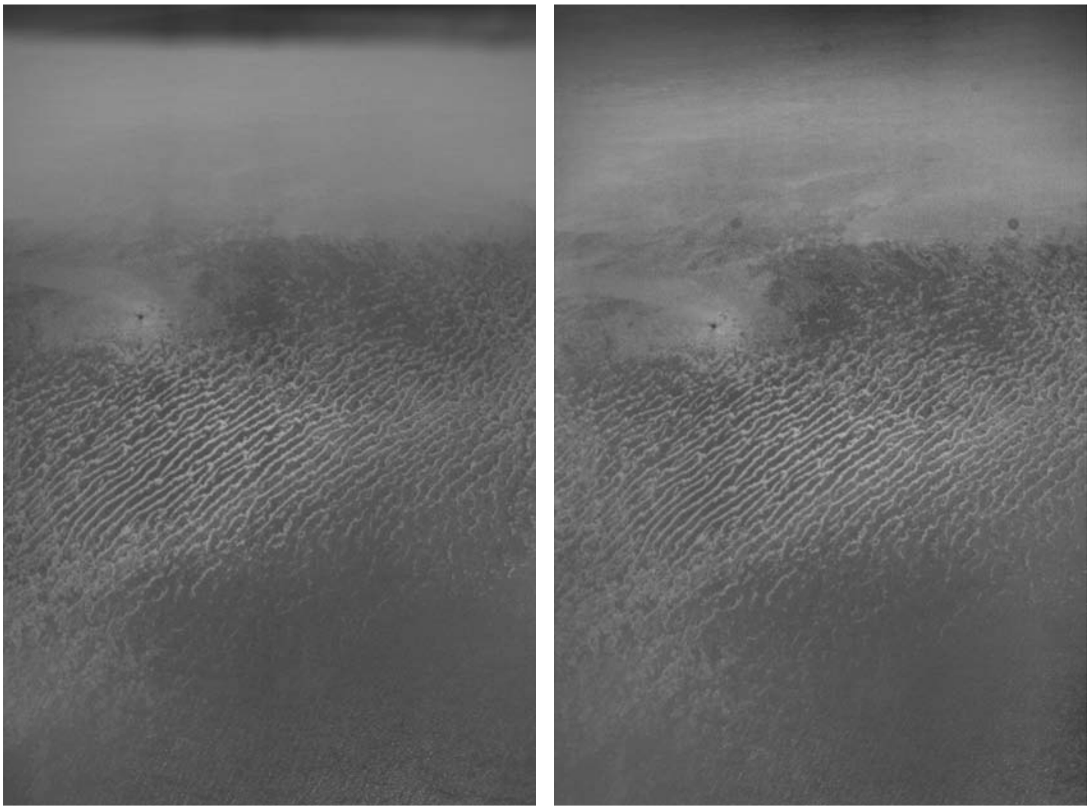

Figure 76 Frames 0549 (horizontal polarisation) and 4530 (vertical polarisation) compared.

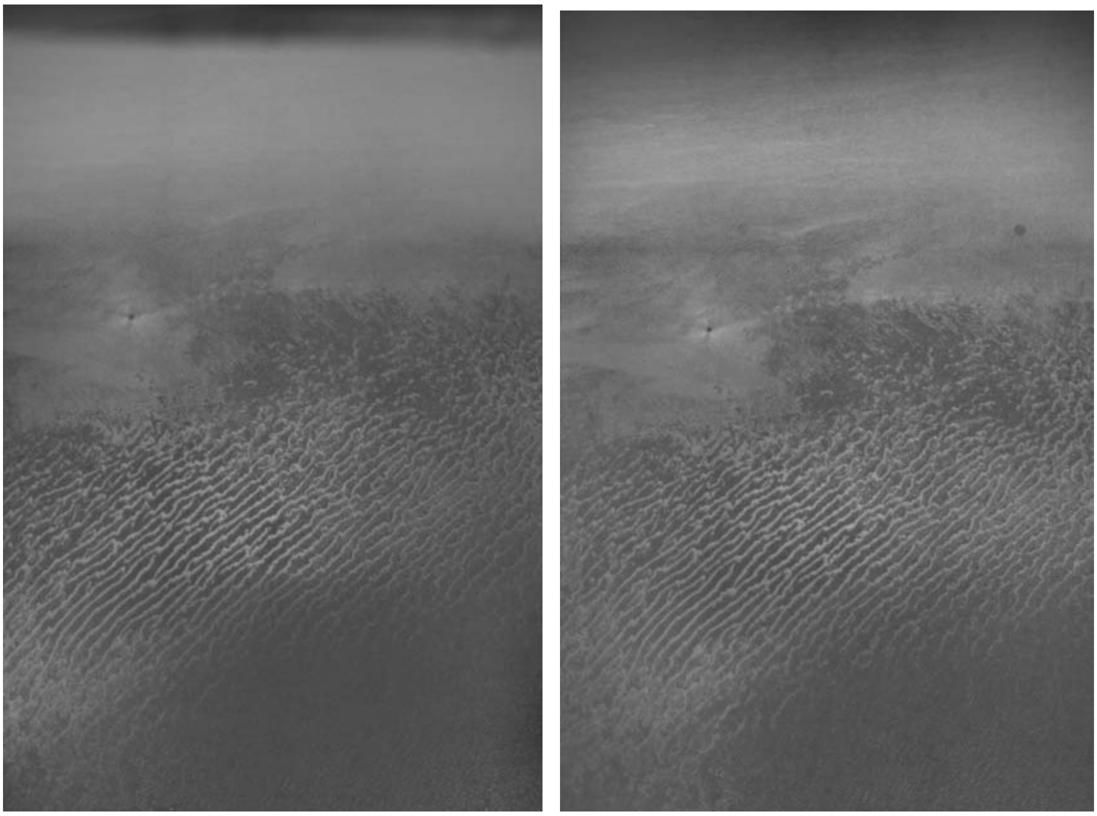

Figure 77 Frames 0550 (horizontal polarisation) and 4531 (vertical polarisation) compared.

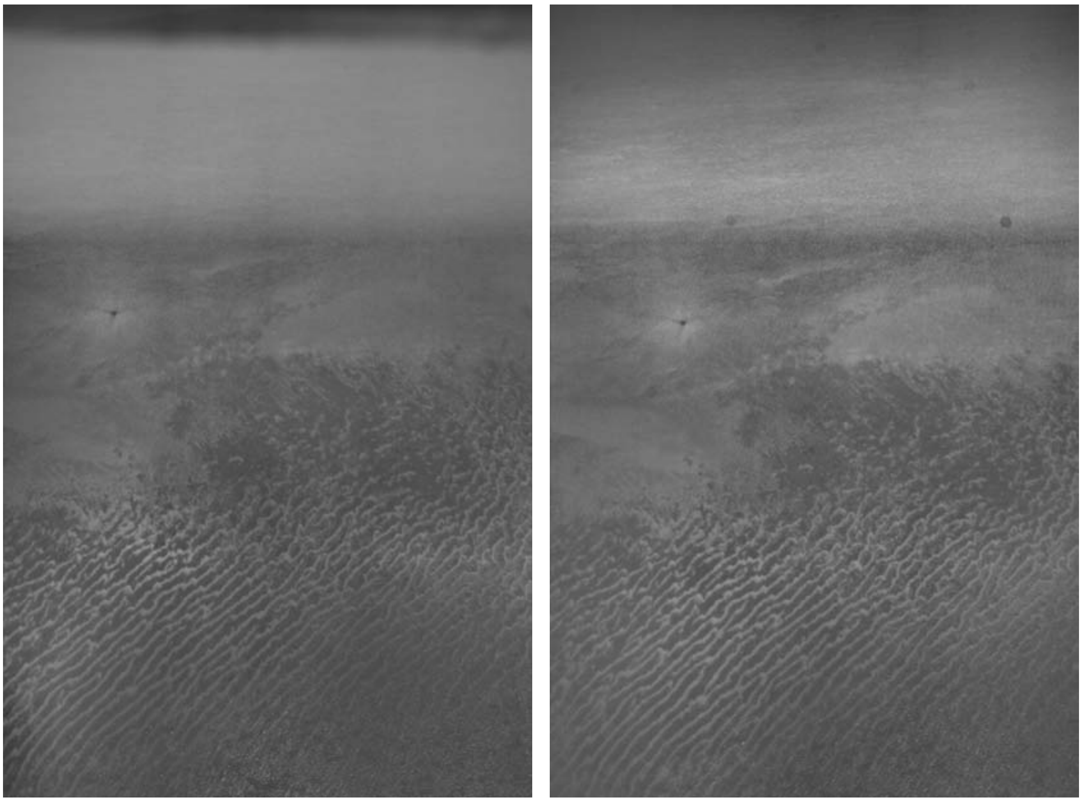

Figure 78 Frames 0551 (horizontal polarisation) and 4532 (vertical polarisation) compared.

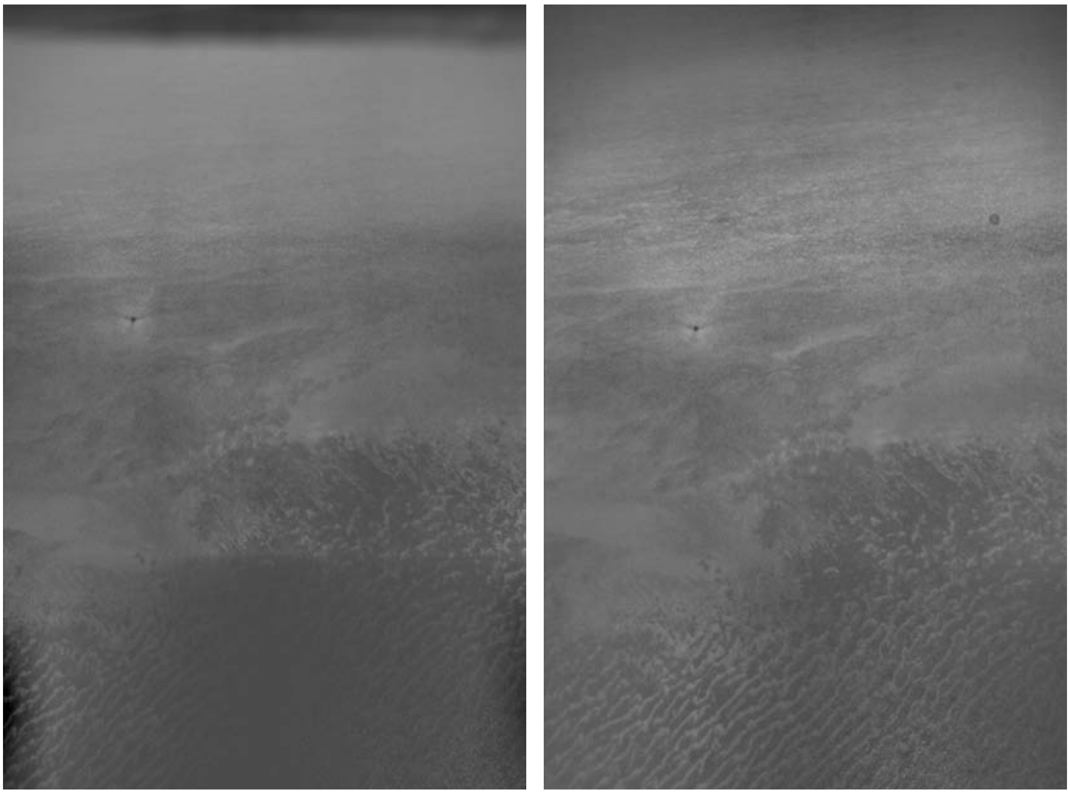

Figure 79 Frames 0552 (horizontal polarisation) and 4533 (vertical polarisation) compared.

The subsequent frames in this run show no benthic detail at the Brewster Angle. Further frames in this run show no detail near nadir either. This would be due to complete absorption and scatter due to depth, or the lack of distinguishing sea floor features, or both.

9 Appendix 3 – Conference paper 1

David Hart, Megan Lewis, Paul Dare, Bertram Ostendorf (2006) Seeing seagrasses sidewards: Marine angiosperms and the Stokes' polarization parameters, proceedings *13th Australasian Remote Sensing and Photogrammetry Conference,* Canberra ACT, 20-24 November 2006.

SEEING SEAGRASSES SIDEWARDS: MARINE ANGIOSPERMS AND THE STOKES' POLARIZATION PARAMETERS

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KEY WORDS: Polarization, Marine vegetation, Small-format, Digital cameras, Multispectral

ABSTRACT:

Mapping of marine benthic flora using remote sensing techniques has been used to assess the dynamics of environmental conditions in coastal areas. Studies used panchromatic/colour aerial photography and/or medium resolution multispectral satellite imagery to create time series showing the change of seagrass distribution. While successful within their project parameters, these studies were limited by conditions at time of image capture, such as sun-glare, turbidity, wave action and low contrast in deeper waters due to absorption and scattering. The use of polarized multispectral imagery has the potential to overcome, or at least reduce these problems such that a finer detail of benthic flora may become visible. This paper explores the theoretical background in the application of polarization for mapping seagrass and other marine benthic flora. It also discusses a possible operational design using a low cost airborne multispectral camera.

Hart, D., Lewis, M., Dare, P. & Ostendorf, B. (2006) Seeing seagrasses sideways: Marine angiosperms and the Stokes' polarization parameters.
Proceedings of the 13th Australasian Remote Sensing and Photogrammetry Conference, Canberra ACT, 20-24 November 2006.

10 Appendix 4 – Conference paper 2

David Hart, Megan Lewis, Bertram Ostendorf (2008) Stripping away sky reflectance, waves and turbulence for benthic mapping: Imaging the seafloor not the surface, proceedings *14th Australasian Remote Sensing and Photogrammetry Conference,* Darwin NT, 29 September – 3 October 2008.

STRIPPING AWAY SKY REFLECTANCE, WAVES AND TURBULENCE FOR BENTHIC MAPPING: IMAGING THE SEAFLOOR NOT THE SURFACE.

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Abstract

This paper presents the results of an airborne experiment using horizontal and vertical polarising filters on a pair of co-mounted 12.8 megapixel Canon 5D digital cameras. These cameras were mounted in the underside camera port of a light aircraft, both cameras inclined at 30 degrees off-nadir. One camera had the polarisation filter oriented vertically and the other oriented horizontally. Forward-looking, overlapping, oblique aerial photography was captured over known seagrass meadows off the Adelaide metropolitan coastline, plus inland urban water bodies. The portrait oriented field of view allowed a progression on the image from near-nadir to beyond the critical Brewster angle of 53 degrees.

Results show the removal of sky reflectance, turbulence and wave action on the vertically-oriented filter imagery compared to the horizontally-oriented filter imagery in both clear and turbid waters. For clear waters the removal of sky reflectance, waves and surface turbulence allowed visualisation of the seafloor suitable for benthic mapping in areas of seagrass. However in turbid water the removal of surface effects still did not allow the seafloor to be visualised due to multiple scatter in the body of the water. This method therefore also has application in differentiating clear and turbid waters on oblique photography.

Hart, D., Lewis, M. & Ostendorf, B. (2008) Stripping away sky reflectance, waves and turbulence for benthic mapping: Imaging the seafloor not the surface.
Proceedings of the 14th Australasian Remote Sensing and Photogrammetry Conference, Darwin NT, 29 September - 3 October 2008.

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