The Fatu Huku coral survey

An exercise on Coral Bleaching detection by satellite remote sensing (Sentinel-2 Earth Observations)

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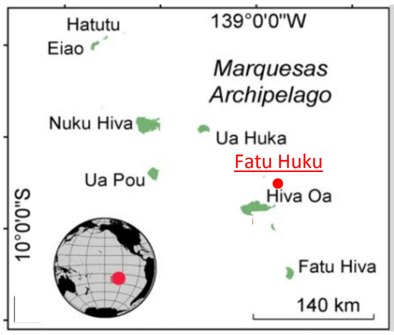
by F.R. Martin-Lauzer (ARGANS Ltd & ACRI), Antoine Collin (EPHE-CRIOBE),
Jean Laporte (ARGANS Ltd), Romain Serra (ACRI-HE)

Polyps live symbiotically with an alga, the zooxanthella, which converts light into carbohydrates. When stressed by photo-inhibitors, corals expel their algae, lose their colour – hence the name of the plague: **Bleaching** - and unless rapidly colonised again, die.

Mass bleaching occurs under thermal stress such as the one induced by the 2016 freakish El Nino. Fata Huku was chosen because we were sure we would be able to observe a bleaching event actually triggered by El Nino's temperature anomalies.

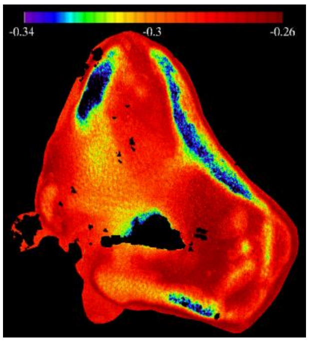


Moreover, Fata Huku happens to be a tricky area, because

- It combines a raised fossil coral atoll with a sunken live coral plateau battered by ocean swells.
- The surrounding waters are generally turbid due to suspended sediment
- The currents and swells forbid surveys most of the time
- The Marquesas is one of the world's most remote archipelago, not easily accessible by survey planes ⇨ There is no better method than satellite remote sensing to monitor such a place

⇨ In other words, if Sentinel2 can detect bleaching in Fatu Huku, it can detect bleaching everywhere.

To detect coral bleaching, colorimetric changes should be visible in the radiometric spectrum, i.e. the radiance L_{TOA} measured on Top-of-the Atmosphere should exceed the MSI Sentinel 2 signal/noise ratio, assuming all corrections for calibration drifts, cloud masking and Deglint have been applied properly.



Although neither the SEOM S2 vicarious calibration nor the SEOM S2 atmospheric correction study have been fully completed, we already had a prototype data processor for the S2 atmospheric correction and could use band ratios to avoid further vicarious calibration issues.

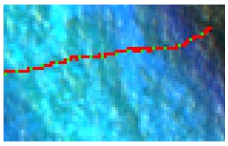
⇨ Assuming there are no sunglint corrections errors and that shadows have been masked, patches of colorimetric changes large enough to be detected by a qualified oceanographer can be attributed to a signal caused:

- either by changes of water constituents (e.g. green chlorophyll or yellow particles),
- or by sea-bottom changes.

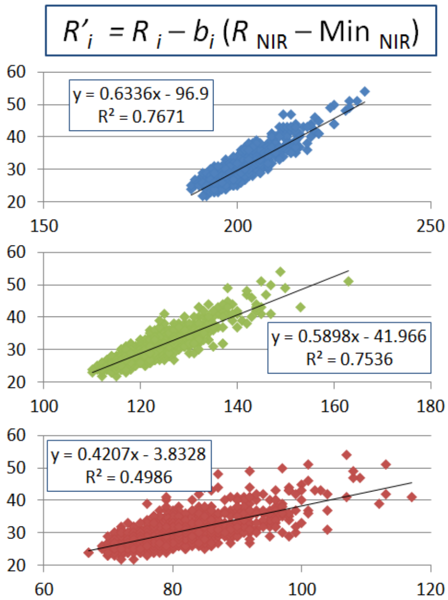
S2 data were processed as Landsat 8's or SPOT's, without using fully the S2 specificities. These will be used in a later stage and are expected to yield even better results.

The difficulties we met can be listed as follows:

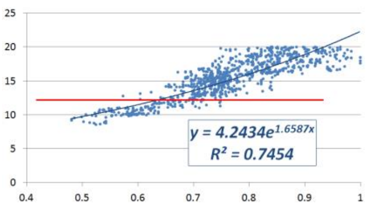
- Underwater camera vision was blurred, but thanks to the S2/MSI performances, the band 2 images were much more suggestive of sea-bottom details.



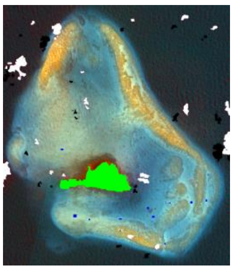
- S2 images were affected by sunglit, the “whitening” effect of which is detrimental to coral bleaching detection. To deglint, and bearing in mind that the Fatu Huku plateau is quite deep, we used the NIR dark pixels method combined with the hypothesis (somewhat debatable in the open ocean for a number of reasons such as the effects of aerosols, turbidity, etc.) that specular reflection indexes of light on waves facets are the same in NIR as with optical bands (cf. Goodman, Hedley or Lyzenga);
- Local weather conditions (aerosols, sea roughness, thermal convection…), which affect bleaching detection most, are still under investigation. However, these were less critical leeway and one can ascribe reasonably 75% of the anomalies to coral bleaching.



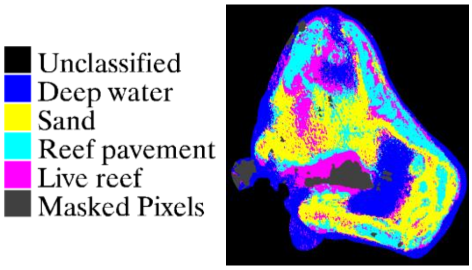
⇨ The S2 superior radiometric precision (compared to Landsat, Spot, Ikonos…) was proven effective in the traditional RGB & NIR bands. Next step will be to use the S2 other advantages: atmospheric correction bands at 20m spatial resolution, red bands 60 m spatial resolution to improve sunglint corrections.



Depths obtained by inversion of radiance (SDB) were compared to the echosounder’s with a reasonable level of precision until approximately 12 metres, where a Secchi-like cut-off due to sediment in suspension and the effect of sunglint caused the uncertainties to spread out.



Benthic habitats were classified against ground-truths (67 training pixels)



Detection of colourimetric changes was the most difficult part of the Fatu Huku bleaching survey. It was conducted in the following order:

1. EO data processing:➔ L1C➔ L2A (atmospheric correction, Rayleigh scattering, diffusion by aerosols).
2. Cloud and cloud shadow removal associated with sun geometry and radiance analysis.

3. Removal of sun glint: L2A➔L2B (correction of sea-surface conditions likely to increase sky reflectance and interfere with bottom albedo and signature).

4. Detection of threshold:

$$\left[\frac{\delta L_w}{L_w}\right]_{threshold} \cong \frac{1}{t}\frac{L_t}{L_w}\left(\frac{\Delta L_t}{L_t} + \Delta t \cdot \frac{L_w}{L_t} + \frac{\Delta L_{os}}{L_{os}}\frac{L_{os}}{L_t} + \frac{\Delta L_{atm}}{L_{atm}}\right)$$

- $O(10)$
- Signal to noise ratio of S-2/MSI: $(S/N)_{MSI}$ $o(5.10^{-3})$
- Systematic error drifts of S-2/MSI during detection sequence: err_{MSI} $o(10^{-2})$
- Error in the assessment of diffusive propagation of light coming out of the water: $o(10^{-2})$
- Error on assessment of sun glint on white caps $\frac{\Delta L_{os}}{L_{os}} = O(10^{-1})$: $o(3 \cdot 10^{-3})$ Glint dynamic component; $o(10^{-2})$ Static component
- ? a priori $O(5 \cdot 10^{-2})$

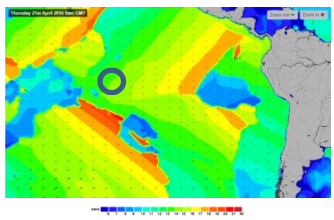
After filtering the various causes of radiance variations occurring in the atmosphere, in the ocean, at the sea surface, above and in the vicinity of Fatu Huku, the sensitivity could be increased significantly.

Band ratios used for the identification of water constituents were then introduced to improve the detection threshold $l_w^{(i,j)} = \frac{L_w^*(\lambda_j)}{L_w^*(\lambda_i)}$, the Blue B2 band being used as a reference, thanks to its lesser attenuation in sea water.

Weather and oceanographic conditions were taken in due consideration to understand better the environment and optimise the filtering, e.g.

☜ Alto cumulus, no haze (21st of April 2016)

Calm oceanographic conditions ☞



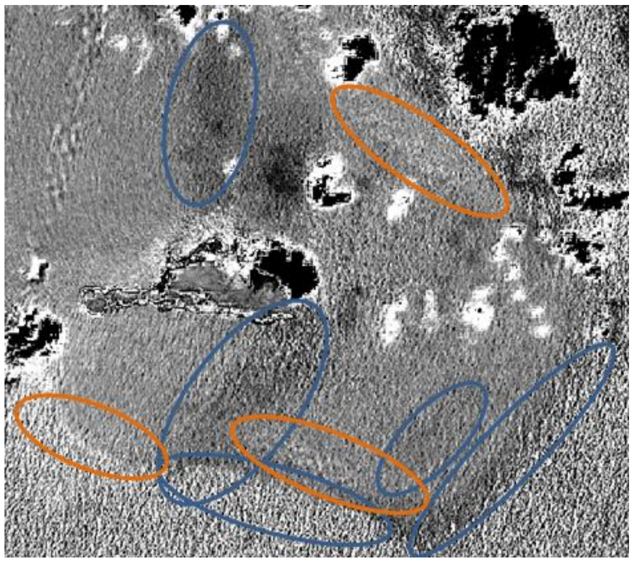
In the absence of tidal effect, the very faint colourimetric anomalies observed between these two dates:

$$l_w^{(B_3,B_2)}\big|_a(21Apr) - l_w^{(B_3,B_2)}\big|_a(11Feb)$$

could only be attributed to green/blue relative changes in light transfer and bottom albedo.

The faintest "red" positive anomalies detected from February to April 2016 are all located on the shallow live reef and never on the surf zones. They can most likely be attributed to bottom changes (bleaching).

The stronger, broader and randomly spread "blue" negative anomalies are linked to the water column and sea surface changes.



They can be attributed to turbidity (resuspension of sand and transport by current, backscatter and aerosols), not to an increase of symbiots photosynthetic activities as confirmed by using B2, B3 depth invariant indexes.

Our refined analysis led to reject the aerosol factor (unlikely to affect significantly such a rock) and sunglint corrections errors (improbability demonstrated by reduction to the absurd).

The effect of local turbidity is still to be investigated, and pseudo depth invariant indexes $\delta L \cdot e^{Kh}$ are to be plotted to confirm the reality of coral bleaching. An element of confusion is brought by scientific publications on coral bleaching, e.g. Andrefouet's and Yamano & Tamura's conflicting conclusions, but all agree that radiometric signatures show a higher reflectance of light and an increase of the green/blue ratio.

Further detailed investigations of local atmospheric conditions, light transfer, aerosols Rayleigh scattering, and the respective contributions of coral bleaching and turbidity variations are to be made to confirm there is no bias in our preliminary analysis[1], and of course, the processing chain for detection of coral changes, including set-up of the thresholds, is still to be fully developed.

However, we can conclude with almost certainty that Sentinel 2 has been able to detect the faint reflectance anomalies affecting the Fatu Huku deep coral reef, which could most likely be attributed to coral bleaching.

[1] A full version of this report including detailed analysis can be found on the Sen2Coral ftp site.