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Research Article

HYPERSPECTRAL OBSERVATION OF INTERNAL WAVES

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ABSTRACT
The nature of surface manifestations over internal waves was investigated with a new hyperspectral scanner on board the International Space Station. From observed internal wave patterns in an area close to the Strait of Gibraltar, it was found that the observed increase in radiance is mainly due to reflected solar irradiance.

Key Words: *Internal Waves, Hyperspectral Imager for Coastal Ocean (HICO), Spectral Analysis*

INTRODUCTION
Frequent vertical displacement of the pycno and/or thermocline by internal waves leads to alternating convergence and divergence movements that modify sea surface roughness. This surface effect makes it possible to detect internal waves in various parts of the electromagnetic spectrum from aircraft or satellite altitudes with various techniques through remote sensing, as reviewed by Klemas (2012). Related to the vertical displacement of the pycno and/or thermocline is the mixing of nutrients into the euphotic zone that initiates increasing primary production. Thus, internal waves may be responsible for the change in primary production by modifying the compensation depth of marine phytoplankton. Productivity and chlorophyll concentrations are not always related to internal waves, as was shown for the South China Sea, in areas where internal waves occur frequently (Yang *et al.*, 2010). However, the effects of the internal wave undulations may be parametrically disguised as an apparent vertical diffused flux of nutrients with the underlying mechanism principally different from turbulent diffusion (Kahru, 1983).
The building of convergence and divergence zones related to the dynamics of internal waves also leads to accumulation of organic surface films that compress over the area of convergence and create lines parallel to the wave crest. In response, capillary waves are damped over the convergence and change in sea state over the divergence zone, modifying the optical behavior of the air-sea interface. Depending on the view angle, either of the two zones may appear either bright or dark.

In the visible part of the EMS, internal waves are recognizable through changes in ocean color, and the question arises whether physical or biological processes are responsible for varying reflectance or radiance from the air-sea interface or the water column underneath. In the following, observations of internal waves from the International Space Station with a Hyperspectral Imager for the Coastal Ocean (HICO) will be described. Data were collected in the vicinity of the Strait of Gibraltar over a spectral range of 0.4 μm to 0.9 μm, with a spectral resolution of about 6 nm and a ground resolution of about 100 m (Corson *et al.*, 2010; Lucke *et al.* 2010; Davis *et al.*, 2010). Radiance spectra were extracted, and in order to negate partially the atmospheric contribution, the sensor to target path radiance data were referred to water that was considered to be low in chlorophyll concentration. The resulting difference spectra were viewed at the same view angle to keep the atmospheric pathlength the same for each scene element. Therefore, the difference spectra signify the contents or processes related to changes in the water leaving radiance of the target, thus providing qualitative information on the nature of its scatterers and absorbers. This approach further assumes that between the analyzed pixels, the atmosphere is comprised of a homogeneous layer pathlength.

OBSERVATIONS

The internal wave package in Figures 1a and b is shown in an enhanced image at 0.646 µm with the difference spectrum in Figure 1c. The appearance of internal waves has been detected in the Strait of Gibraltar for many years, and it was found that they are mainly generated by the interaction of a tidal flow and the bathymetry (Apel et al., 1975; Frassetto, 1960; Ziegenbein, 1970; Ziegenbein, 1969 and 1970; Lacombe and Richez, 1982; Armi and Farmer, 1985; 1988; La Violette and Arnone, 1988; Alpers et al., 1996; Jackson, 2004).

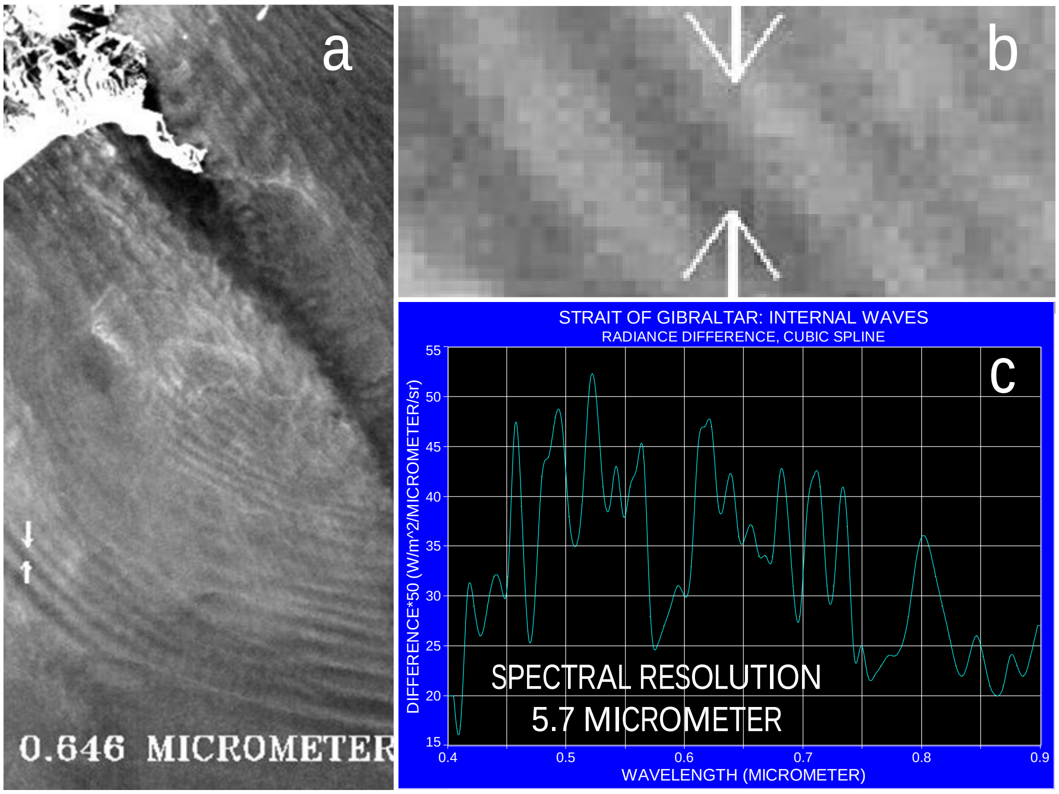

Figure 1: (a) HICO sub-image showing location where internal waves with a wavelength of about 1000 m were observed at a view angle of 11 degrees to the south/right of the direction of motion of the ISS; (b) enlarged image (a) at 0.646 µm to enhance the presence of internal waves; (c) difference spectrum (50*radiance in W $m^{-2}\mu m^{-1}$ sr^{-1}) between bright and darker part of the wave package as indicated by the arrows.

The spectral analysis given in Figure 1c indicates that increased radiance values are mainly caused by reflected solar irradiance. This conclusion is based on the spectral location of merged Fraunhofer lines that are observed in radiance data but can also be recognized even in atmospherically corrected remote sensing data (Szekielda et al. 2009). The above conclusion is verified with spectra that were derived with the same procedure applied in the observation for the offshore region of the South West coast of Spain as shown in Figures 2a and b where coastal water (Case 2 water) is compared with offshore Atlantic Ocean water, whereas Figures 2c and d show the difference spectrum from an algal bloom in Long Island Sound.

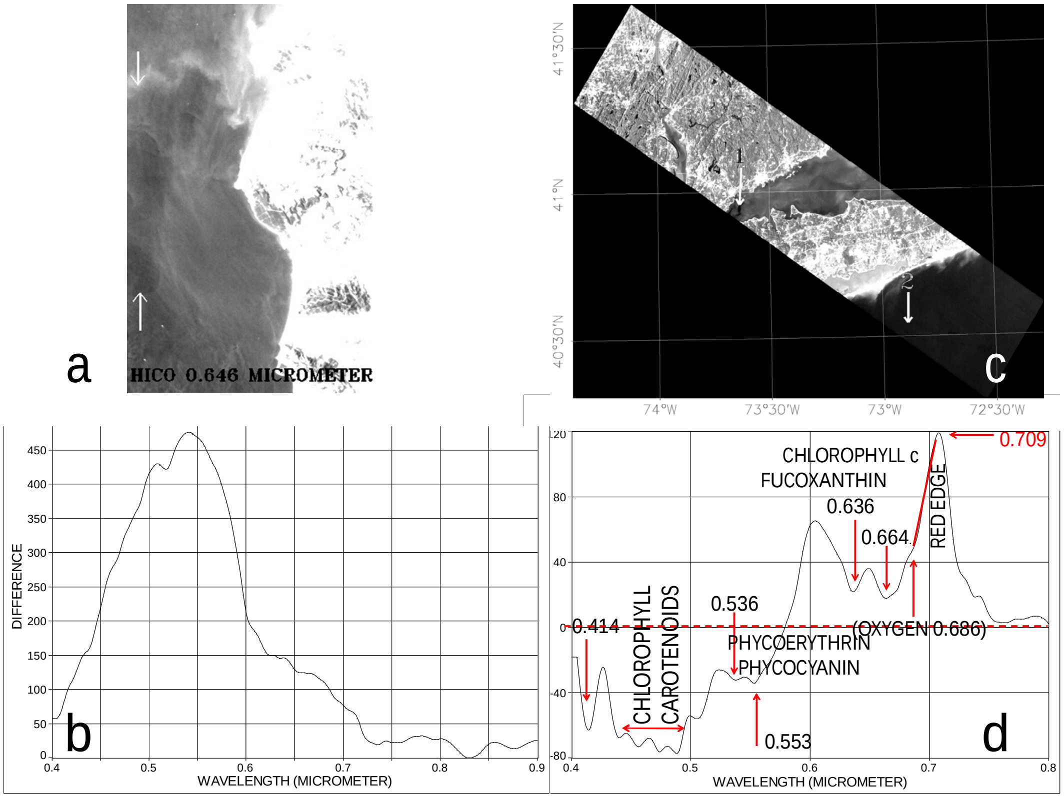

Figure 2: Spectra extraction from HICO images in the offshore region of the South West coast of Spain as shown in 2a and b where coastal water (Case 2 water) is compared with offshore Atlantic Ocean water. Figures c shows the location for an algal bloom in the Long Island Sound with the corresponding difference spectrum in figure d.. Numbers in figure d and arrows indicate the spectral position of the main absorbing photosynthetic pigments. Arrows in Figures 2a and c indicate the location of the analyzed spectra.

The target spectrum derived from the coastal area of Spain has the typical spectral response of suspended sediments and the difference spectrum derived from a plankton bloom in Long Island Sound reveals the spectral locations of the major photosynthetic pigments. From this comparison, it is evident that the observed high radiance pattern over the internal waves is due largely to changes in sea state and most probably through action by capillary waves but not through increased biomass. This conclusion might be valid only for the observed image shown in this study, but more observations with HICO are available and will be further analyzed.

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