Aerospace wetland monitoring by hyperspectral imaging sensors: A case study in the coastal zone of San Rossore Natural Park

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ABSTRACT

The San Rossore Natural Park, located on the Tuscany (Italy) coast, has been utilized over the last 10 years for many remote sensing campaigns devoted to coastal zone monitoring. A wet area is located in the south-west part of the Natural Park and it is characterized by a system of ponds and dunes formed by sediment deposition occurring at the Arno River estuary.

The considerable amount of collected data has permitted us to investigate the evolution of wetland spreading and land coverage as well as to retrieve relevant biogeochemical parameters, e.g. green biomass, from remote sensing images and products. This analysis has proved that the monitoring of coastal wetlands, characterized by shallow waters, moor and dunes, demands dedicated aerospace sensors with high spatial and spectral resolution.

The outcomes of the processing of images gathered during several remote sensing campaigns by airborne and spaceborne hyperspectral sensors are presented and discussed. A particular effort has been devoted to sensor response calibration and data validation due to the complex heterogeneity of the observed natural surfaces.

1. Introduction

Wetlands are areas where the water level is at or near the soil surface for a significant part of the growing season, and the soil is covered by active vegetation during the period of water saturation. Although wetlands cover 1% of the Earth’s surface, they are biogeochemically active areas due to their high productivity and redox gradients. In particular, wetlands are major natural sources of reduced gases such as methane and sulphur compounds and can have high rates of denitrification and nitrogen fixation. Moreover the frequency and the amplitude of floods are relevant parameters for the investigation of ecological processes occurring in wetland areas, and their changes strongly affect the wetland hydrology.

Coastal wetlands are remarkable ecosystems in terms of environmental health, geomorphologic distinctive features, typical vegetation and faunal associations, and human activities related to this singular environment. Coastal wetlands are characterised by shallow waters, moor and dunes, which require dedicated models for a full understanding of their characteristics.

In the past, almost the entire coastal zone along the Tyrrhenian Sea was covered by wetlands. The fast development of anthropogenic activities, mainly linked to settlements, industry, transport and tourism, destroyed and limited many wet areas (Azzari et al., 1999; Azzari and Magazzini, 2003; Vallega, 1998). On the basis of regional policies, more sensitive to environmental problems, the trend towards re-naturalization of the environment has brought the restoration of some wetlands.

The Migliarino, San Rossore, Massaciuccoli Regional Park represents an important example of this trend. The Park, 240 km² wide, is located as reported in Fig. 1 at the seaside near Pisa and its central part between the Serchio and Arno rivers is named San Rossore. The Park contains many different ecosystems among which a wet area, near the Arno River mouth, is named Natural Reserve Area of Lame di Fuori. This is a system of ponds and dunes caused by the sediment deposition occurring at the river estuary and which is now affected by coastal erosion.

Data collected by aerospace imagers can be used to improve wetland classification and to assess their spatial and temporal distribution. To take advantage of this opportunity the sensor response has to be carefully calibrated, moreover mathematical and physical models should be developed (Ramsey et al., 1997, 1992) to interpret the gathered data.

In the last 10 years the San Rossore Natural Park, well known by the scientific community as a site for environmental studies, has been designed by our institute as the main test site for remote sensing campaigns. During this period many measurement campaigns have been performed using hyperspectral airborne sensors, first to calibrate and validate the acquired data and then for
atmosphere, coastal and vegetation monitoring (Bernasconi et al., 2002), light pollution monitoring (Barducci et al., 2003), sea and ground temperature and emissivity measurements (Barducci and Pippi, 1996). Moreover San Rossore is utilized as test site for the CHRIS/PROBA mission (Barnsley et al., 2004; Barducci et al., 2006) in the framework of the European Space Agency EOPI cat. 1-LBR Project ID.2832 “Assimilation of biophysical and biochemical variables in biochemical and hydrological models at landscape scale”.

Data gathered by aerospace sensors in the wet area of Lame di Fuori, have been used to study wetland spreading and land coverage type changes over time, as well as to derive relevant biogeochemical parameters, e.g. green biomass, from physical parameters like spectral reflectance maps.

2. Coastal wetland in the San Rossore Natural Park

The Park (latitude, 43.6–43.9° N; longitude, 10.2–10.5° E; altitude, 5 m a.s.l.) consists of a coastal forest of about 40 km², a sandy shore and inland marshes, larger in the past, before they became part of a land reclamation project. The richness of the flora in arboreal and herbaceous species is favoured by local climatic conditions characterized by wet autumns, winters and springs, followed by very dry summers. The area closer to the sea is mainly covered by pine (Pinus Pinaster Ait. and Pinus Pinea L.) and ilex (Quercus Ilex L.) forest. The beach, consisting of mainly calcareous sand, is characterized by dunes where several herbaceous species grow: pioneer species along the shoreline, species building and fixing the sand, and species living in the back of the dunes.

The presence of many classes of vertebrates is a remarkable aspect of the San Rossore Natural Park, where the populations of wild boar and fallow deer are dominant in this area. The avifauna is the most representative faunistic group in the Park. The diversity of environments and their interpenetration also give the opportunity to observe the avifauna populations of the adjacent habitats.

The most peculiar habitat of the Park is the wetland, which is mainly represented by the marshes located in the Natural Reserve Area of Lame di Fuori (see Fig. 2). This large wetland covers approximately 655 ha and it is of fundamental importance as an over-wintering and stop-over site for avifauna. The complex of retrodunal pools of the reserve is directly related to the winds and sea currents which started the formation of the dune system. Under favourable conditions, when dunes begin to form, a consolidated sandbank builds up in front of the dunes. The new, growing beach tends to join the pre-existing shore and causes a sheet of water to accumulate between the new dune and the old coastline. Finally, further sediments are deposited closing any connections with the sea and a proper retrodunal lagoon is formed. Over the centuries, these basins, initially lagoons, then retrodunal and coastal pools, gradually turned into depressions adjacent to the dunes, as depicted in Fig. 3, becoming a suitable habitat for the development of mesohygrophilous forests.

3. Remote sensing activities

Several images have been acquired over San Rossore for more than 10 years by several optical sensors mounted on different satellites and aircrafts as reported in Tables 1 and 2.

Aerospace sensors evolved over the years from multispectral to hyperspectral sensors, thereby passing from scanning devices to

![Fig. 1. Map of Migliarino, San Rossore, Massaciuccoli Regional Park.](image)

![Fig. 2. Lame di Fuori Natural Reserve Area habitat.](image)
push-broom imaging spectrometers. The increased spatial and spectral resolution and radiometric accuracy allow a better assessment of the observed surface characteristics.

The Thematic Mapper commercial series operates up to 8 wide spectral bands ranging from the visible to the thermal infrared at 20 m of spatial resolution and 9 bit of radiometric accuracy. Recently it has been flanked by other systems like Hyperion, operating at a similar spatial resolution but with a 12 bit of radiometric accuracy and 220 spectral bands between 0.40 and 2.50 μm, 10 nm wide. Moreover sensors like MERIS and MODIS, at 15 and 36 bands respectively, whisk-broom spectrometers with spatial resolution of 100 m, are providing a full coverage of the Earth for scientific applications. Since 2002 the push-broom imaging spectrometer CHRIS has been operating onboard a PROBA platform with pointing capability (see Table 3 for the related characteristics). Along the same orbit CHRIS can acquire a set of 5 hyperspectral images of the same area at +55°, +36°, 0°, –36°, –55° viewing angles, enabling bi-directional reflectance function (BRF) investigations (Barducci et al., 2004b).

The spatial and spectral resolutions of the spaceborne hyperspectral sensors are not sufficient to meet the requirements for many environmental applications. Airborne hyperspectral sensors are needed, since the ground texture in the highly populated areas and the spectral features to be detected are so subtle that a few meters in spatial resolution and a few nanometers in spectral resolution are required.

For this purpose some hyperspectral sensors have been utilized over San Rossore among them MIVIS, VIRS-200 and the recently developed HYPER/SIM-GA, whose main characteristics are reported in Tables 4, 5 and 6 respectively. MIVIS is a whisk-broom imaging spectrometer operating outside the atmospheric absorption bands from the visible to the short wave infrared (0.4–2.5 μm) and into the thermal infrared (8.2–12.7 μm). VIRS-200 is a push-broom imaging spectrometer utilizing 20 narrow spectral bands selectable among 240 placed between 0.4 and 1.0 μm. The newly developed HYPER/SIM-GA is a system consisting of two push-broom imaging spectrometers operating in the visible and near infrared with 512 spectral bands, and in the short wave infrared with 256 bands.

Due to the advanced characteristics of these systems and the high accuracy of the data that have to be acquired by these instruments, careful calibration has to be performed in the laboratory before and after each campaign. If this is not possible, the calibration together with the validation activity must be performed in the field during the sensor overflights. For these activities ground measurements are needed as well as some laboratory measurements performed on collected samples. In addition atmospheric measurements are required to improve the accuracy of the

**Table 1**

<table>
<thead>
<tr>
<th>Platform</th>
<th>Sensor</th>
<th>Date</th>
</tr>
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<tbody>
<tr>
<td>LANDSAT</td>
<td>TM</td>
<td>3 May 1997</td>
</tr>
<tr>
<td>LANDSAT</td>
<td>TM</td>
<td>23 August 1997</td>
</tr>
<tr>
<td>MIR space station</td>
<td>MOMS-2P</td>
<td>15 March 1997</td>
</tr>
<tr>
<td>MIR space station</td>
<td>MSU-SK</td>
<td>17 February 1998</td>
</tr>
<tr>
<td>TERRA and AQUA</td>
<td>MODIS</td>
<td>Many acquisitions from 2004 to 2006</td>
</tr>
<tr>
<td>PROBA-1</td>
<td>CHRIS</td>
<td>30 acquisitions from 2002 to 2006</td>
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**Table 2**

<table>
<thead>
<tr>
<th>Platform</th>
<th>Sensor</th>
<th>Date</th>
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<tbody>
<tr>
<td>Lear Jet</td>
<td>ATM</td>
<td>4 August 1990</td>
</tr>
<tr>
<td>CASA-212</td>
<td>MIVIS</td>
<td>10 November 1999</td>
</tr>
<tr>
<td>CASA-212</td>
<td>VIRS-200</td>
<td>21 June 2000</td>
</tr>
<tr>
<td>CASA-212</td>
<td>MIVIS HYPER/SIM-GA</td>
<td>13 September 2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9 July 2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 December 2005</td>
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* Night flights.

**Table 3**

<table>
<thead>
<tr>
<th>CHRIS-PROBA main characteristics</th>
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<tbody>
<tr>
<td>Instrument type</td>
</tr>
<tr>
<td>Push-broom imaging spectrometer</td>
</tr>
<tr>
<td>Field of View</td>
</tr>
<tr>
<td>Number of images</td>
</tr>
<tr>
<td>acquired over the same area</td>
</tr>
<tr>
<td>Spatial resolution</td>
</tr>
<tr>
<td>Number of spectral channels</td>
</tr>
<tr>
<td>Spectral range</td>
</tr>
<tr>
<td>Spectral resolution</td>
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<tr>
<td>Digitalization</td>
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</table>
corrected data. The aim is to radiometrically correct the raw data to obtain at-sensor radiance (so called Level 1B data) and then to correct these data for the atmospheric effects in order to retrieve the spectral reflectance (Level 2) of the observed surfaces.

At the same time, data quality assessments have to be performed by the analysis and removal of the coherent disturbances and the evaluation of the signal to noise ratio (Barducci et al., 2005).

4. Physical and biogeochemical parameters retrieval

The physical parameters (at-sensor radiance and surface spectral reflectance) obtained from the remotely sensed data can be utilised firstly to retrieve the spectral vegetation indices defined as the reflectance ratio, or the normalised difference computed for two wavelengths. The normalized difference vegetation index (NDVI), the fraction of absorbed photosynthetically active radiation (FPAR), the water index (WRI), and the photo-chemical reflectance index (PRI) are some of the parameters that are relevant to vegetation and soil characterization.

Through these vegetation indices it is possible to assess many biogeochemical parameters (Gitelson et al., 2006; Gonzales et al., 2004; Rahman et al., 2004; Running et al., 2004), like land cover, forest stand age, canopy height, leaf area index (LAI), net primary production (NPP), net ecosystem production (NEP), chlorophyll concentration, photosynthetic efficiency, leaf water content, carbon and water balances, foliar nitrogen, biomass, all considered in various models for understanding wetland ecosystems.

For example, PRI has been proposed as a tool for the estimation of leaf and canopy light-use efficiency and photosynthesis from remote-sensing data. The application of the index is based on more than 15 years of spectroscopic studies at the leaf level, providing a sound physiological basis. When exposed to an excess of irradiation, plants cannot use all the absorbed energy and as a photoprotective process they increase both fluorescence and thermal energy dissipation without evident damage to the photosynthetic apparatus. This photoprotection process, based in the antennas, is generally detected as ΔpH-dependent non-photochemical chlorophyll fluorescence.

Under prolonged high irradiance, damage to the photosynthetic apparatus may occur. The main function of xanthophyll cycle pigments (zeaxanthin, antheraxanthin and violaxanthin) in chloroplasts is to increase non-radiative dissipation of excess irradiance as heat in the antenna of PSII and protect chloroplasts. This photo-protective process, based in the antennas, is generally detected as ΔpH-dependent non-photochemical chlorophyll fluorescence.

### Table 5

<table>
<thead>
<tr>
<th>Instrument type</th>
<th>Push-broom imaging spectrometer</th>
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</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>20 bands, 0.43–0.83 mm (FWHM 20 nm)</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>8 bands, 1.15–1.55 mm (FWHM 50 nm)</td>
</tr>
<tr>
<td>Spectral range (spectral resolution)</td>
<td>64 bands, 0.28–1.17 mm (FWHM 360 nm)</td>
</tr>
<tr>
<td>Number of across track pixel</td>
<td>10 bands, 0.21–0.72 mm (FWHM 80 nm)</td>
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<tr>
<td>Instantaneous field of view</td>
<td>1.13 mrad</td>
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<tr>
<td>Digitalization</td>
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### Table 6

<table>
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<th>Instrument type</th>
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</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>400–1000 nm</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>2.4 nm</td>
</tr>
<tr>
<td>Number of spectral channels</td>
<td>512</td>
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<tr>
<td>Number of across track pixels</td>
<td>1024</td>
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<tr>
<td>Field of view</td>
<td>0.7 mrad</td>
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<tr>
<td>Instantaneous field of view</td>
<td>1.3 mrad</td>
</tr>
<tr>
<td>Digitalization</td>
<td>12 bit</td>
</tr>
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![Fig. 4. Examples of in-field measurements at San Rossore test site. (a) solar spectral irradiance. (b) CO2 and H2O fluxes. (c) spectral reflectance of different ground coverage.](image-url)
quenching (NPQ, Demmig-Adams, 1990), as the zeaxanthin binding with chlorophyll protein complex in the antenna of PSII also induces NPQ of chlorophyll fluorescence as well as electron transport and provides protection against high irradiance. The possibility of detecting the zeaxanthin content by the foliar reflectance at 531 nm normalized to the 570 nm reference was proposed by Gamon et al. (1990) and synthetized in the PRI, and could open the way to directly determining light use efficiency (LUE) by remote sensing.

The classification method, traditionally utilized to process the remotely sensed data, and which is based on the assessment of dominant plant types, is not very useful because it does not reflect differences in biogeochemical cycles.

Since wetlands have an important function in processing methane, carbon dioxide, nitrogen and sulphur, and in sequestering carbon, the parameters to characterize the role of wetlands in biogeochemical cycling of trace substances are: hydrology, temperature, primary production, vegetation type, soil type, salinity, chemical information, transport of organics and sediments, topography and geomorphology (IGBP Report 46, 1996).

The challenge is to establish a functional parametrization of wetlands, integrating the fluxes related to trace gases, hydrology, nutrients and other variables into regional and global biogeochemical models.

5. Remote sensing campaigns: outcomes from data processing

The data collected at San Rossore during recent years have allowed us to test the usefulness of some of those vegetation indices and to make multi-temporal analyses of wetland spreading and land coverage. In order to achieve these results high spatial and spectral resolution imaging sensors are required, in particular to

Fig. 5. Reflectance spectra calculated from: (a) CHRIS image acquired on 8 August 2005, and (b) HYPER/SIM-GA image acquired on 15 December 2005. In situ reflectance measurement acquired on a sandy target is plotted to validate the remote sensed data.

Fig. 6. (a) True-colour image from the spectral reflectance map, and (b) NDVI map obtained using MODIS channel 2 and 1 during the San Rossore overpass in May 2004.

Fig. 7. Comparison of PRI measured in the field on 8 September 2004 on 13 sampling areas and PRI retrieved from the CHRIS image acquired the same day. In the graph averages and standard deviations are reported for each area.
identify the ground texture as accurately as possible. Moreover the spectral range, the number of spectral channels and their radiometric accuracy are extremely important to retrieve the biogeochemical parameters discussed above.

To better correct the atmospheric effects on the acquired remotely sensed data (Barducci et al., 2004), air temperature, pressure, and relative humidity, spectral and total solar irradiances, CO₂ and H₂O concentrations at the top of forestry canopy level, spectral reflectances of natural surfaces are measured during all remote sensing campaigns, as shown in Fig. 4.

Examples of reflectance spectra, extracted from atmospherically corrected images acquired by either airborne and spaceborne sensors, are plotted in Fig. 5. To validate the remotely sensed data, in-field reflectance measurements are also shown.

In the following, an overview of the results obtained during various remote sensing campaigns are reported to point out the key parameters and relevant instrumental characteristics useful for wetlands studies.

5.1. MODIS remote sensing campaign

Since 2000, the MODIS spectrometer has routinely acquired the San Rossore Natural Park at 500 m of spatial resolution, as a FLUXNET and CARBOEUROPE site.

MODIS spectral channels allow the determination of several vegetation indexes, among which the NDVI defined as: \( \frac{R_{868} - R_{645}}{R_{868} + R_{645}} \), where \( R \) is the reflectance at a given wavelength in nm indicated by the suffix. This vegetation index is used to estimate the leaf area index parameter.

A MODIS true-colour image acquired over San Rossore in May 2004 is shown in Fig. 6a, and the relevant NDVI map is displayed in Fig. 6b using a grey scale, where brighter pixels represent high values of NDVI.

Due to the coarse spatial resolution, this map cannot be easily validated due to spectral mixing.

5.2. CHRIS remote sensing campaigns

More than 30 CHRIS acquisitions over the San Rossore test site have been performed since 2003 within the framework of the European Space Agency EOPI Cat.1-LBR Project ID.2832 “Assimilation of biophysical and biochemical variables in biochemical and hydrological models at landscape scale”.

This considerable amount of data allows us to perform multi-temporal analysis and to continuously improve our understanding of different biogeochemical processes such as those involved in the change of vegetation status as observed in areas that are strongly affected by anthropogenic activities (Barducci et al., 2005b).

In September 2004, preliminary estimates of canopy PRI and NDVI from CHRIS images were compared with leaf-level measurements from different plots corresponding to different vegetation types including some in wetlands (Raddi et al., 2005). LAI and hence NDVI is known to be correlated with fertility and light-use
efficiency, and this could explain the relationship with PRI. To this aim the following relationships are utilized:

\[
PRI = \frac{(R_{531} - R_{570})}{(R_{531} + R_{570})}
\]

\[
NDVI = \frac{(R_{782} - R_{675})}{(R_{782} + R_{675})}
\]

where \( R \) is the surface reflectance at the given wavelength (in nm) indicated by the suffix.

The preliminary analysis of one CHRS image, acquired on 8 September 2004 at 0° along a track pointing angle, demonstrates the feasibility of PRI measurement from space. A good relationship (see Fig. 7) was observed between the PRI measured at the leaf level as ground truth and PRI calculated from CHRS imagery \( (R^2 = 0.45) \). The correlation improves \( (R^2 = 0.57) \) when the helm oak stand is excluded. The PRIground vs PRICHRIS is also maintained for the images at 36° and -36° along track pointing angles giving \( R^2 \) of 0.69 and 0.41, respectively.

Despite the noise of such a small signal, values are coherent across the image and differences among and within vegetation...
types are clearly visible, as is apparent from a comparison of PRI and NDVI images in Figs. 8 and 9, respectively. In order to monitor seasonal changes in PRI and NDVI over the wet areas of Lame di Fuori Natural Reserve Area, CHRIS acquisitions on 27 March and 8 September 2004 are considered. The related results are displayed in Figs. 8 and 9 for along track pointing angle of 0°.

5.3. HYPER/SIM-GA remote sensing campaign

On 15 December 2005 the new push-broom imaging spectrometer HYPER/SIM-GA flew for the first time over San Rossore for a calibration and validation remote sensing campaign. During the flight the instrument, whose main characteristics are reported in Table 6, acquired hyperspectral images from 0.4 up to 2.5 μm with a spatial resolution of 1 m (in the VNIR) and 2 m (in the SWIR) and a spectral resolution of 2 nm (in the VNIR) and 5 nm (in the SWIR).

Images acquired over the wetlands of Lame di Fuori are reported in Fig. 10a and b, and Fig. 11 also shows some relevant details. The SWIR composite colour image (red, 1256 nm; green, 972 nm; blue, 1615 nm), shown in Fig. 10b, provides evidence of vegetation water content (green zones) and the presence of several pools (black zones).

Due to the high spatial and spectral resolution of this new instrument, the reflectance spectra, extracted from both VNIR and SWIR images, are free from spectral mixing. In Fig. 12, reflectance spectra coming from a sandy pixel, a forestry pixel, and a sea pixel are plotted as examples.

High spatial resolution NDVI and PRI maps in Fig. 10c,d point out fine differences in land cover and vegetation structures. In particular the PRI map shows light use efficiency in some floodplain areas.

The HYPER/SIM-GA remote sensing campaign provides evidence of the great potential of hyperspectral remote sensing techniques for wetland classification and monitoring of their resources. In particular, attention has to be paid to data calibration and validation for the complex heterogeneity of the observed ground surface.

6. Conclusion

Data collected by different aerospace optical sensors, operating in the visible and infrared spectral ranges, have been processed to analyse wetland characteristics and land coverage, and to assess many biogeochemical parameters in the San Rossore Natural Park. The results indicate the need for data acquired with high spatial and spectral resolution and good radiometric accuracy.

Next generation satellites with spatial resolution better than 10 m and spectral resolution of 5 nm would provide useful data to contribute to the management of wet areas in the coastal zones heavily influenced by anthropogenic activities.

High spectral resolution sensors allow an accurate determination not only of vegetation indices, but also a direct retrieval of many biogeochemical parameters through the use of physical characteristics like surface spectral reflectance.

In particular a multi temporal analysis performed by these sensors could monitor seasonal changes in the coastal zone wetland ecosystems of small pools and marshes which are important but fragile habitats.

Acknowledgements

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References


