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Identification of Bed Forms Through ERS SAR Images in San Matías Gulf, Argentina

Domingo A. Gagliardini†, Salvador Aliotta‡, Ana I. Dogliotti†, and Pablo Clemente-Colón§

†Instituto de Astronomía y Física del Espacio (CONICET)
Pabellón IAFE
CC.67, Suc. 28 (1428)
Buenos Aires, Argentina
agaglia@iafe.uba.ar,
adogliotti@iafe.uba.ar

‡Instituto Argentino de Oceanografía (CONICET-UNS)
Complejo CRIBABB
C.C. 804, (8000)
Bahía Blanca, Argentina
gmaliott@criba.edu.ar

§U.S. Department of Commerce
NOAA/NESDIS
NOAA Science Center
5200 Auth Road
Camp Springs, MD 20746, U.S.A.
Pablo.Clemente-Colon@noaa.gov

ABSTRACT

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The European Space Agency (ESA) funded two projects in 1991 and 1994 concerning the observation of the Argentine coastal environment with synthetic aperture radar (SAR). Studies were carried out for the periods 1992–1994 and 1994–1997. Several ERS-1/2 satellite SAR images were acquired over the San Matías Gulf in the Patagonian coast during these two periods. SAR is a side-looking imaging radar that operates from either a satellite or an aircraft. The instrument emits a series microwave pulses toward the earth in a direction perpendicular to the flight path. Imagery is constructed from the strength and time delay of the returned signals, which depend primarily on the roughness and dielectric properties of the surface under observation and the distance from the radar.

Ocean surface roughness wave-like patterns, imaged as a series of bright and dark linear features by SAR, are persistently observed over the San Matías Gulf mouth region. A total of thirty-three (33) ERS-1/2 SAR images (100 km × 100 km) from 15 different orbits from 1992 to 2000 were analyzed. This series of observations has allowed for a detailed examination of the location, persistence, and the conditions involved in the imaging of the observed wave-like patterns. Very strong tidal currents of the order of 2 m/s characterize the gulf region. The characteristics of recurrent surface patterns in the SAR images indicate that they are caused by the interaction of the tidal currents with bed forms in the bottom topography of the gulf. The location of these bed forms is poorly documented in the available bathymetric charts of the region. The SAR images show the significant potential that satellite radar observations have as a tool for detecting unmapped coastal ocean bottom features, particularly, where bathymetric mapping activities can be extremely difficult, dangerous, or costly.

ADDITIONAL INDEX WORDS: *Bed forms, synthetic aperture radar, satellite remote sensing.*

INTRODUCTION

Most geomorphologic studies of the sea bottom are based on ship sounding methods that make use of seismic-acoustic systems (lateral "multi-beam") scanning sonar. Since the information from the sea bottom is restricted to the proximity of the surveying ship, a large number of transects are usually required to provide the desired coverage and detail. This in turn represents an increase in the already high costs of operating an oceanographic ship. The observations provided by the Seasat-A satellite, launched in June 1978 by NASA, showed that the synthetic aperture radar (SAR) sensor could also serve as an efficient tool for detecting various types of sea bottom irregularities in the coastal zone (KASISCHKE et at., 1983). Since then, many investigators have demonstrated this capability and have tried to apply it quantitatively to shallow water bathymetry as well as current measurements with different levels of success. Some of these works include VAN DER KOOIJ *et al.* (1995), DONATO *et al.* (1997), HESSELMAN et al. (1997), VOGELZANG (1997), and JOHANNESSEN (2000). Although bathymetric measurements obtained from SAR has not demonstrated the same level of accuracy as those derived from acoustic methods, the experience gained have shown that active microwave remote sensing can be used to provide a systematic and synoptic view of the bottom topography that may be used to complement classical sounding observations.

In 1991, the European Space Agency (ESA) approved a project entitled Integral Study of the Argentine Coastal Environment, which was carried out for the period 1992–1994. Its purpose was to begin the design and development of a SAR information database for the main coastal environments in Argentina, including the Valdés Peninsula in the Patagonian coast (Figure 1). ERS-1 satellite SAR images for this study were acquired at the O'Higgins ground receiving station in the Antarctic. Images of the Valdés Peninsula taken on July 9, 1992 were used in the first SAR geomorphological study of

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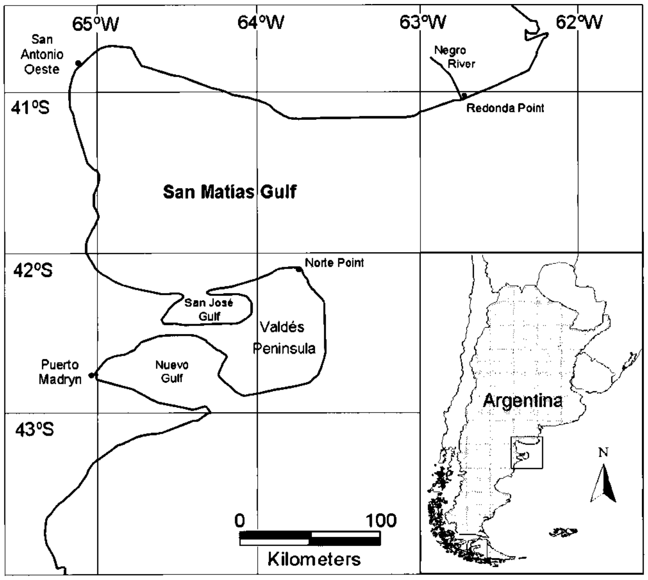

Figure 1. Map of the San Matías Gulf and the Valdés Peninsula study area.

this peninsula (GAGLIARDINI *et al.,* 1994). In 1994, the European Space Agency approved a second project entitled Integral Study of Patagonian Coastal Deserts. It was carried out for the period 1994–1997 and its main objective was to enhance coastal research activities started in the previous period. The authors noticed the persistence of a series of bright and dark linear features over the waters near the mouth of the San Matías Gulf, located north of the peninsula, in the data from both periods. The recurrence of these linear features in most of the available images of the Valdés Peninsula as well as the presence of similar patterns in other parts of the gulf was clearly evident. In 1997, the Argentine Agency for Space Activities (Comisión Nacional de Actividades Espaciales—CONAE) started receiving ERS SAR data in its Córdoba ground receiving station. A substantial number of additional images from the 1997–2000 period became available and provided an opportunity for detailed examination of the distribution and conditions involved in the imaging of the above-mentioned patterns of interest. This study presents SAR images of the San Matías Gulf mouth from 1992 to 2000 that demonstrate the identified signatures to be associated with bed forms in the region.

STUDY AREA

The San Matías Gulf is located between 40° 47′ S and 42° 13′ S on the Atlantic coast of South America. It covers an area of approximately 17000 km^2 being the second largest gulf in Argentina. One of the most remarkable characteristics of this gulf is the presence of two large depressions exceeding 160 meters in depth in the middle of the gulf (PIERCE *et al.,* 1969). The sea bottom and sub-bottom in this region are made of fine-texture sediments unevenly deposited on the mid-upper Tertiary rock basement (ALIOTTA *et al.,* 2000). On the eastern side, the continental shelf forms an open basin with a depth of about 60 meters at the entrance. Approximately 55% of the total gulf area exceeds 100 meters in depth (PIOLA and SCASSO, 1988).

The mouth of the Negro River is found to the northeast.

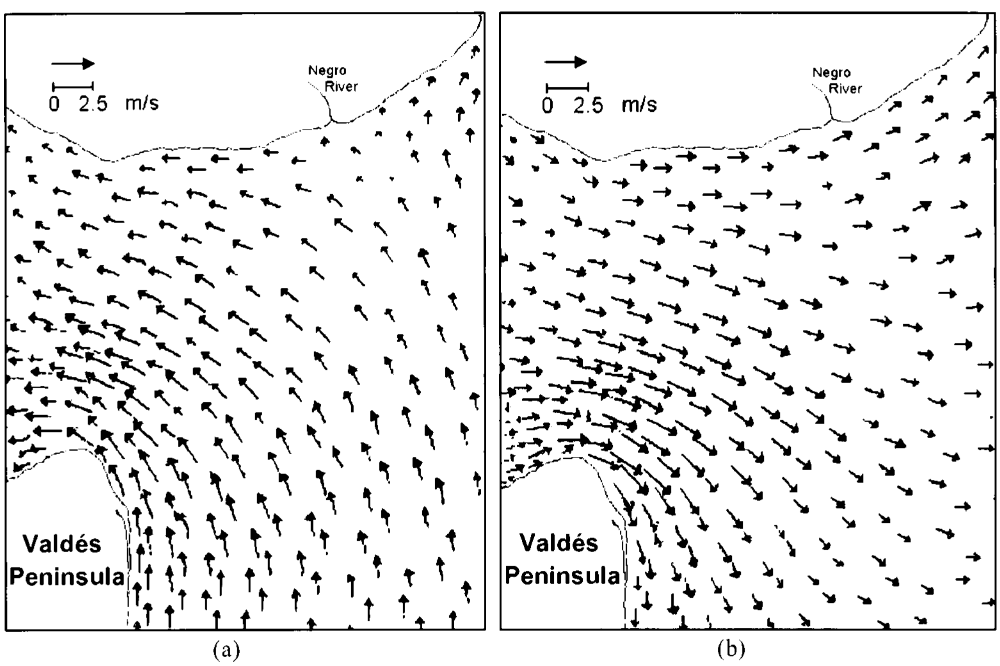

Figure 2. Tidal current vectors during (a) maximum flood and (b) maximum ebb flow conditions at the entrance of the San Matías Gulf.

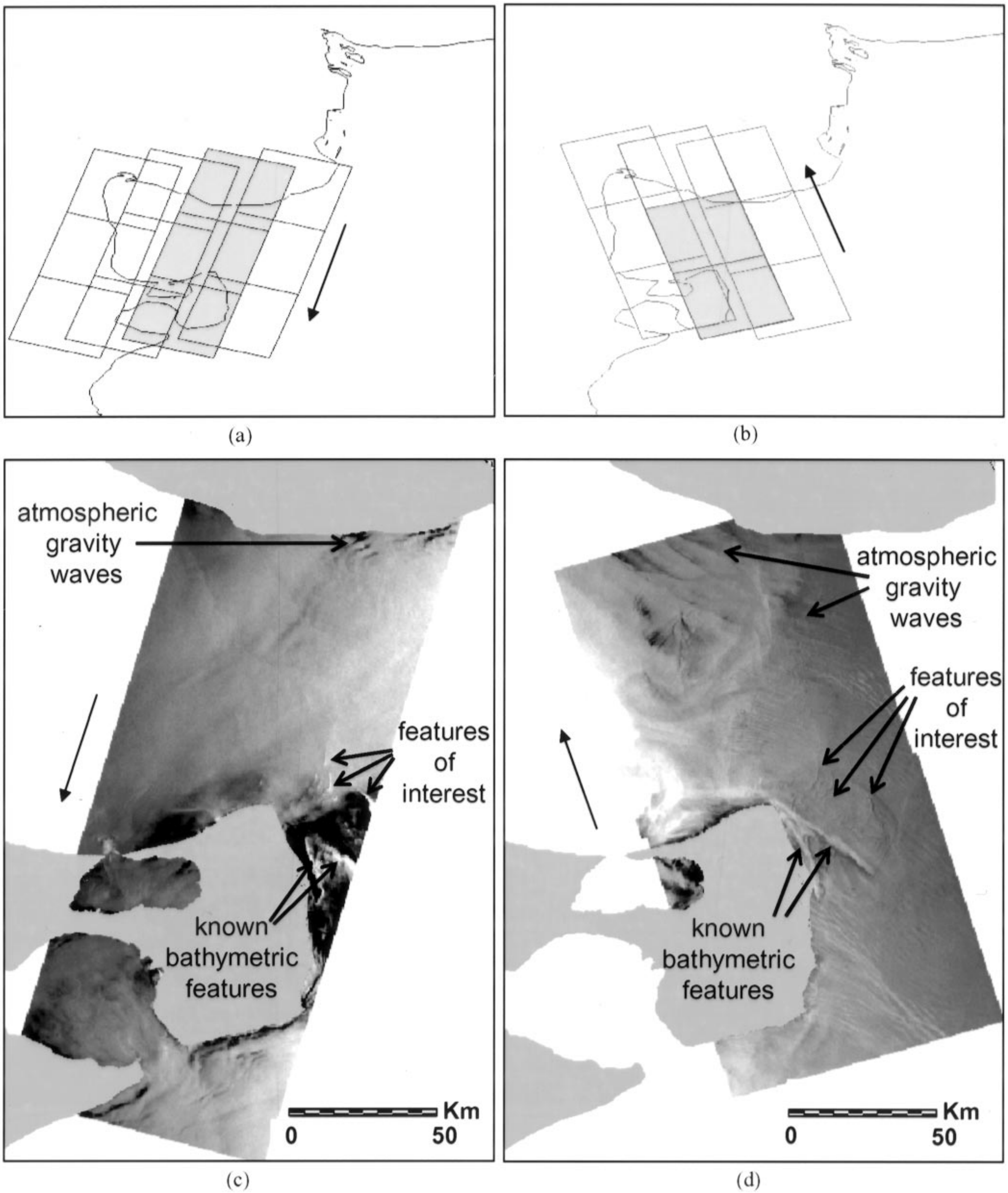

Figure 3. SAR frame coverage of the study area during (a) descending and (b) ascending orbits with shaded zones corresponding to mosaics of the San Matías Gulf entrance on (c) July 9, 1992 and (d) February 6, 1996. The arrows alongside the frames indicate the direction of the orbits.

Table 1. *ERS SAR images used in the study.*

Date	Orbit Number	Orbit Direction	Frame Numbers	Tidal Stage (At Norte Point)
July 9, 1992	5136	Descending	4437 4455 4473	Ebb tide
February 25, 1996	24125	Ascending	6345 6327	Flood tide
February 26, 1996	4452	Ascending	6345 6327	Flood tide
October 5, 1997	12861	Descending	4437 4455	Flood tide
February 22, 1998	14865	Descending	4437 4455	Ebb tide
March 2, 1998	14973	Ascending	6345 6327	Flood tide
January 11, 1999	19482	Ascending	6345 6327	Ebb tide
March 30, 1999	20605	Descending	4437	Flood tide
September 5, 1999	22881	Descending	4437 4455 4473	Ebb tide
November 30, 1999	24112	Descending	4437 4455 4473	Ebb tide
January 4, 2000	24613	Descending	4437	Flood tide
January 23, 2000	24885	Descending	4437 4455 4473	Flood tide
March 14, 2000	25615	Descending	4437 4455 4473	Ebb tide
April 26, 2000	26224	Ascending	6327 6345	Flood tide
August 20, 2000	27891	Descending	4437 4455	Flood tide

The river carries a substantial amount of fine sandy sediments to the coast, which are further carried eastward by littoral drift (ALIOTTA, 1983). At the gulf entrance, off the northeast coast of Valdés Peninsula, the bottom material is largely sandy. Large sand waves and broad undulations reported there (ACHILLI and ALIOTTA, 1992), added to the seismic configurations of the substratum (ALIOTTA *et al.,* 2000), indicate intensive deposit-erosion processes and high sedimentary dynamics.

Semidiurnal tides govern the circulation inside the gulf. There are remarkable differences in tidal height amplitude along the coast. The mean height is 3 m at the mouth of the Negro River (gulf entrance) while it reaches 6 m in the inner region. Although current measurements are scarce, maximum tidal current values of the order of 2 m/s have been reported (SERVICIO DE HIDROGRAFÍA NAVAL ARGENTINO, 1995). A tidal model developed by PALMA (1984) indicates currents in the San Matías Gulf of the same order. Figure 2 shows tidal current vectors during maximum flood and maximum ebb flow conditions. Monthly wind speed averages are of the order of 5 m/s in the coastal regions and 7 m/s in oceanic regions (PIOLA and SCASSO, 1988).

METHODS

SAR is a side-looking imaging radar operating from a moving platform (either satellite or aircraft). The SAR instrument emits a series microwave pulses toward the earth in a direction perpendicular to the flight path. Imagery is constructed from the strength and time delay of the returned signals, which depend primarily on the roughness and dielectric properties of the surface under observation and the distance from the radar. SAR images represent the spatial pattern of the intensity of the electromagnetic energy backscattered by the illuminated area. Over the ocean, SAR responds for the most to the surface roughness imposed by wind-generated capillary waves and small surface gravity waves (of the order of the radar wavelength, *i.e.* centimeters). Thus, a SAR image of the ocean represents, to a first approximation, sea surface roughness conditions given by the spatial distribution of the wind-generated waves (VALENZUELA, 1978). It follows that most SAR imaging of the ocean surface depends directly on atmospheric processes that sustain or modify surface winds. Ocean processes readily captured by SAR may include upper ocean circulation features such as fronts, eddies, and internal waves. In addition, it is well documented that the presence of irregularities at the ocean bottom, particularly in shallow waters, can modify indirectly the distribution of Bragg waves through the interaction of the bottom topography with the ocean currents above.

Thirty-three (33) ERS SAR 100 km × 100 km frames from 15 different orbits (5 ascending and 10 descending) from 1992 to 2000 were collected as part of this study (Table 1). ESA ERS satellites have a Sun-synchronous, near polar, quasi-circular orbit with a mean altitude of 785 km and an inclination of 98.5°. The ERS SAR is a C-band instrument (5.3 GHz) that illuminates the ground with a 100 km wide swath from which 100 km × 100 km frames or images with a resolution of approximately 25 m are produced. This right-looking radar collects data in ascending and descending orbits and has a repeat cycle period of 37 days.

The area covered by the available ERS SAR frames is shown in Figure 3a (descending orbits) and 3b (ascending orbits). The frames where combined into mosaics in order to examine the overall area covered by each orbit. All mosaics were co-registered using coastal land control points and georeferenced to the regional topographical charts. Overlapping mosaics were compared side-by-side or combined into red-green-blue (RGB) composite images in order to study recurring signatures. Two sample mosaics corresponding to descending and ascending orbits are shown in Figures 3c and 3d, respectively.

Tidal records at Norte Point and Redonda Point (Figure 1) were obtained. Table 1 shows the tidal current stage at Norte Point, the most relevant location for this work. The local tide model indicates that tidal current vector directions into and out of the gulf are highly correlated with the flood and ebb tidal stages, respectively (PALMA, 1984). Meteorological observations for the region were only available at the Puerto Madryn airport, 120 km away from Norte Point. Unfortunately, wind speed and direction data acquired at Puerto Madryn are not necessarily representative of conditions over the critical features analyzed here because of the distance and large area under study.

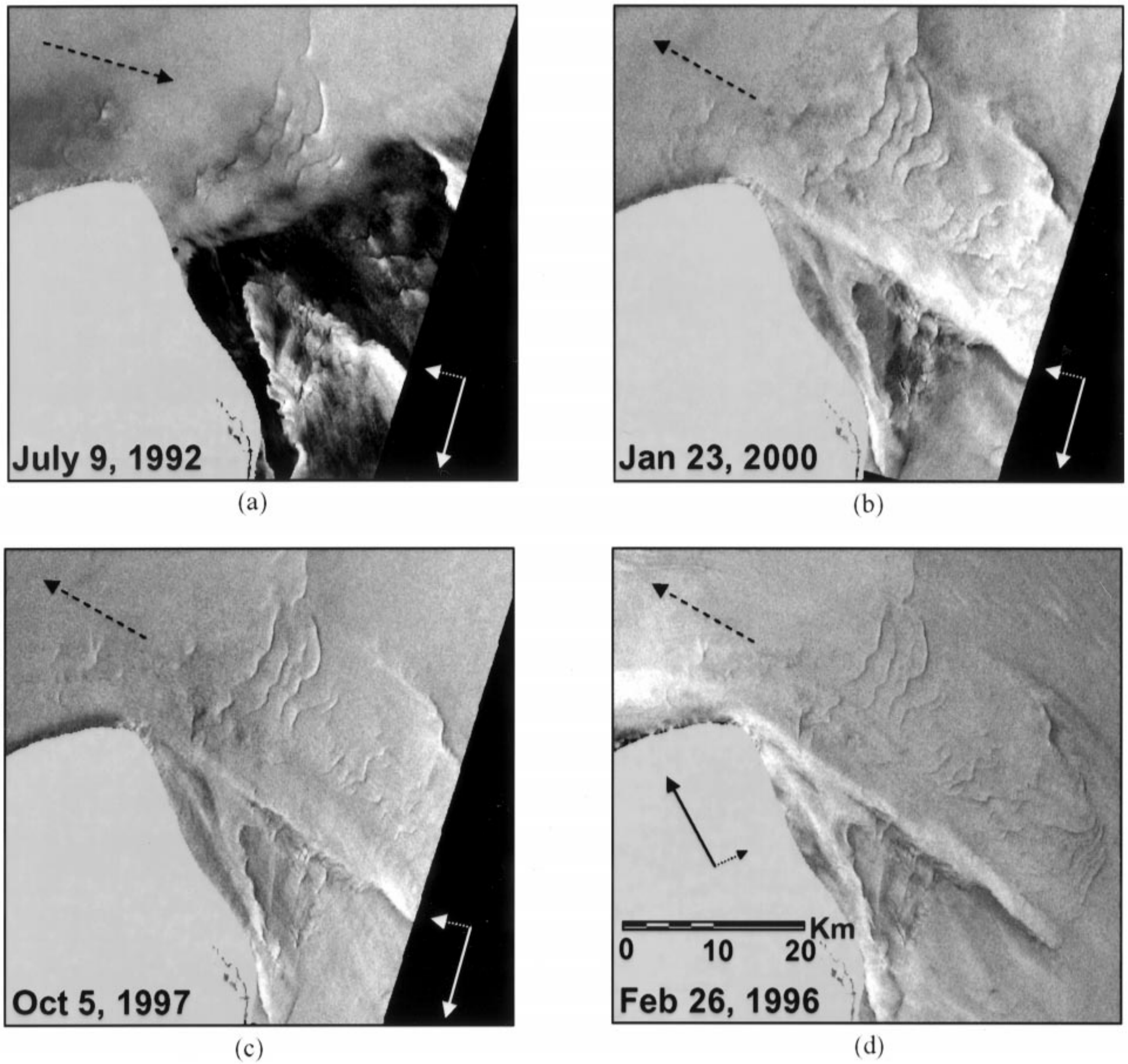

Figure 4. Close-up of linear features observed in the southern area of the San Matías Gulf entrance, near Norte Point, during four days with different combinations of tidal flow and radar look directions.

IMAGERY ANALYSIS

Land-masked mosaic images were formed from consecutive frames acquired during each orbit. A mosaic of the first ERS-1 SAR frames taken over the study region on July 9, 1992 is shown in Figure 3c. The descending orbit image covers the Valdés Peninsula and the entrance of the San Matías Gulf. Figure 3d shows the mosaic resulting from ascending frames collected on February 6, 1996 over the San Matías Gulf entrance. Extended areas of bright and dark backscatter observed in the images are probably due to the spatial variability of the wind conditions. For example, indications of atmospheric gravity wave activity are clear to the north of the gulf entrance in both cases. Several bright linear features observed in the mosaics off the Valdés Peninsula are imaged over known bathymetric features as documented in the Argentine Navy Hydrography Service standard nautical charts. Conversely, a series of additional wave-like patterns formed by narrower bright and dark linear features in both cases are not documented in the bathymetric charts.

Images of the area near Norte Point corresponding to several combinations of radar look and tidal flow directions are shown in Figures 4a, b, c and d. In each case, the narrower bright and dark linear features of interest are clearly seen. The orbit and radar look directions are indicated with two perpendicular arrows. The direction of the tidal flow at the entrance of the gulf (middle point), inferred from the tidal

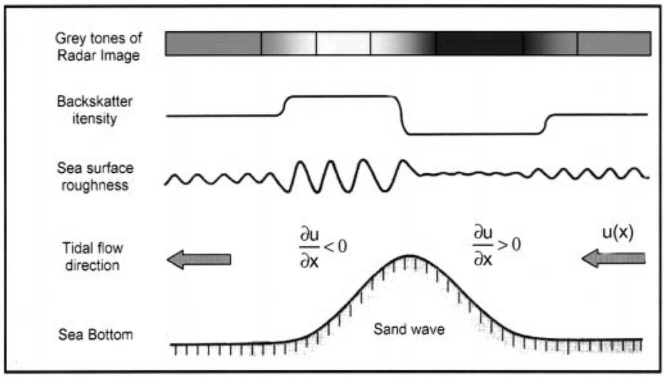

Figure 5. Modulations generated when tidal currents encounter an obstacle. [Adapted from Kasischke (1983)].

charts, is also indicated. Noticeably, a brighter and a darker side relative to the surrounding waters characterize all these features. Although corresponding to different seasons and years, these images provide a similar view of the distribution of the features. An inverted sequence of the bright and dark patterns can be observed in Figure 4a relative to Figures 4b, 4c, and 4d. In the first image, the bright side is located to the right of the dark side, whereas in the other images the order is reversed. In all cases analyzed, it was found that the bright-dark direction always followed the direction of the tidal current independently of the radar look direction (ascending or descending orbit) as seen in Figure 4.

Many authors, including DE LOOR (1981), MCLEISH *et al.* (1981), KASISCHKE *et al.* (1983), SHUCHMAN *et al.* (1985), and DONATO *et al.* (1997), have identified similar SAR features as corresponding to bathymetric signatures. In most of these cases, their interpretation of the features as bed forms, either sand banks or sand waves, has been based on comparisons of the SAR observations with available bathymetric maps that show the geological features at the same locations as the features imaged by SAR. It is well accepted that the characteristic bright and dark pattern is the result of changes in speed of the current flowing across the bottom features as shown in Figure 5. An increase in speed over the right side of the bottom feature in the figure generates divergence and a decrease in amplitude of the Bragg waves, whereas a decrease in speed on the lee side has the opposite effect. A change in the direction of the current will also produce an inversion of the bright and dark pattern in the corresponding SAR image. In any case, a component of the current perpendicular to the bed form is required. For protruding features such as sand waves the dark side will always occur first on the side of the

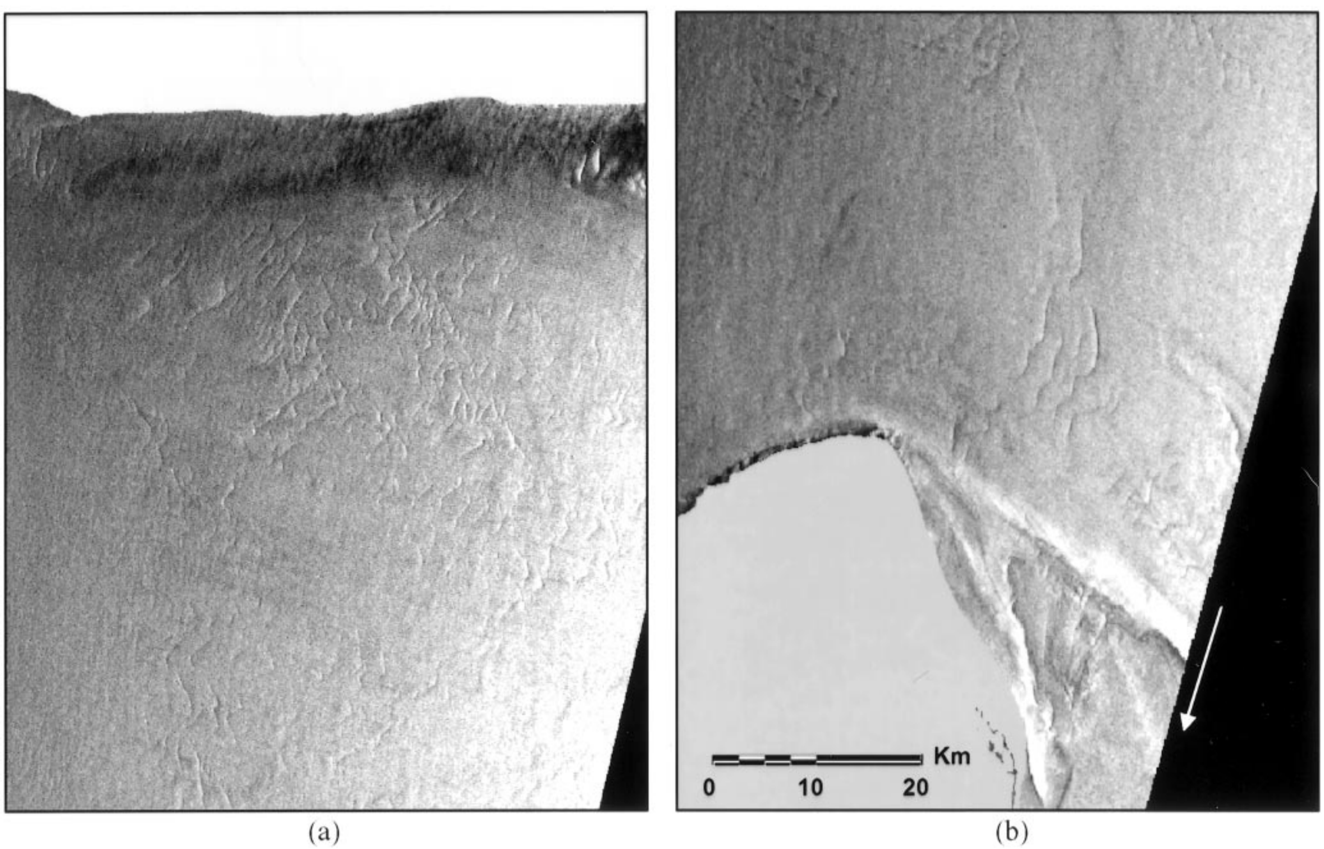

Figure 6. Linear features observed in the (a) northern and (b) southern areas of the San Matías Gulf entrance on August 20, 2000.

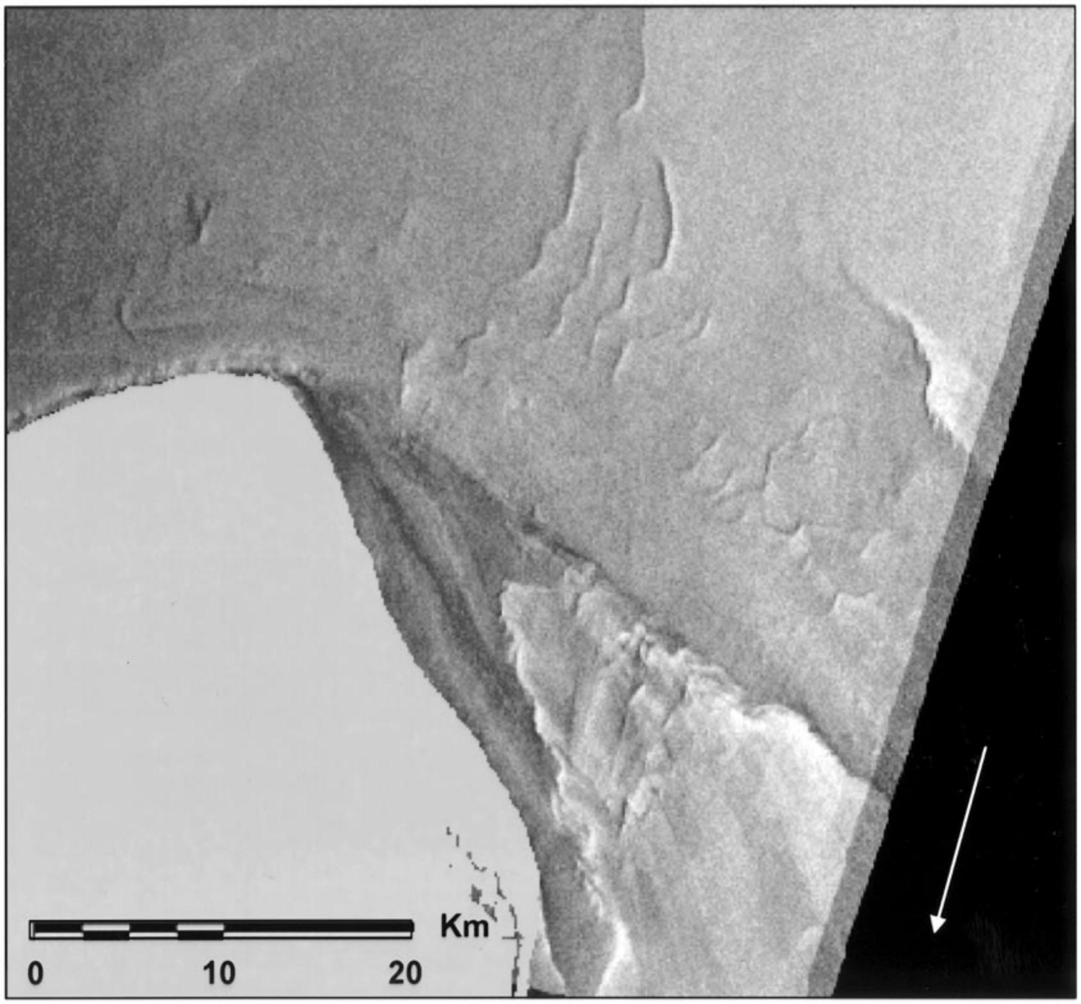

Figure 7. Multitemporal black and white rendition of an RGB composite image obtained from SAR observations on July 9, 1992, February 22, 1998, and September 5, 1999.

incoming current and independently of the radar look direction. The opposite effect will be observed for depression features. The present observations are consistent with the interpretation of protruding features in the sea bottom.

Figures 6a and 6b show additional examples of these features detected in both the northern and southern areas of the gulf entrance on August 20, 2000. Typically, the patterns observed to the south, off Norte Point, are much more strongly defined than those found to the north. In particular, the southern features are observed over a region characterized by an irregular bottom associated with rock outcrops that could correspond to an ancient abrasion shelf formed during the last marine transgression. Some of these shoaling outcrops can be observed on the inshore side off Norte Point (MONTI, 1997). The available SAR data sets show more variability in the observations of features to the north than in those to the south. In fact, a supposition of the better-delineated and persistent features in the southern region indicates no detectable change in shape nor drift within the precision of the observations throughout the time interval covered by the available images. This is demonstrated by the multiyear RGB composite image shown in black and white in Figure 7. The sharpness of this image is indicative of the apparent stability of these features over the years, which likely results from a combination of strong tidal dynamics between the flood and ebb stages and the nature of the bottom sediments, i.e., characterized by sandy gravel in this region (SERVICIO DE HIDROGRAFÍA NAVAL, 1974).

An overlay with the location of the most persistent features detected in the region was carefully drawn. Figure 8 shows the features found off Norte Point overlaid on the standard chart of the Naval Hydrography Service, where zones designated as turbulent and dangerous are indicated. The observed collocation of the SAR features and these danger zones is remarkable. A map of the full distribution of identified features in the analyzed imagery is shown in Figure 9. The features were mostly found off the gulf entrance. From the available bathymetry, it appears that about 60% of them occur

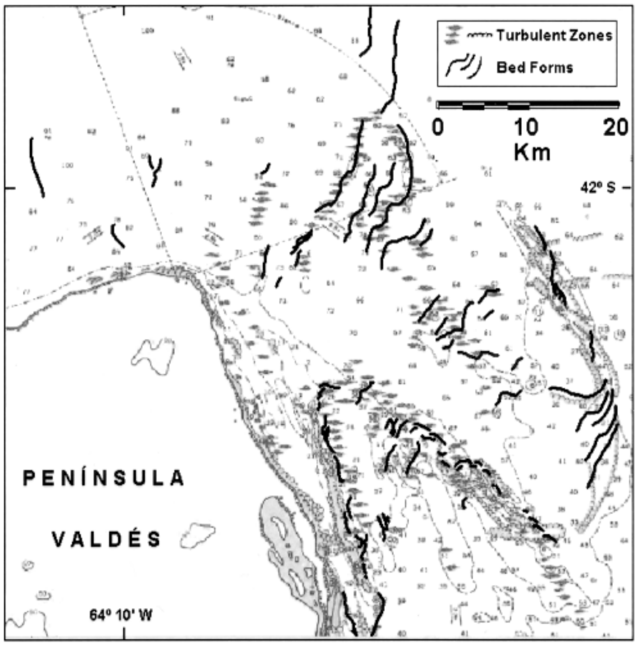

Figure 8. SAR major linear features detected over the southern area of the San Matías Gulf entrance overlaid on the Argentine Navy Hydrography Service standard nautical chart. The location of many of these features corresponds with zones identified in the chart as turbulent and dangerous for navigation.

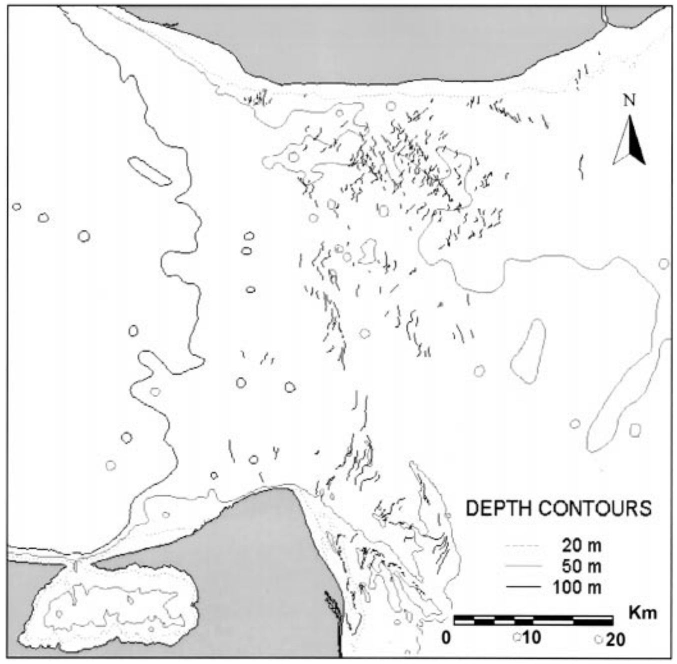

Figure 9. Map of the San Matías Gulf entrance bathymetry overlaid with the full distribution of features interpreted as sand waves in the 1992–2000 analyzed SAR data.

between 20 m and 50 m depth and another 38% between 50 m and 60 m depth.

DISCUSSION

While navigation charts indicate areas of whitecaps or turbulence off the Valdés Peninsula, present bathymetric maps of the San Matías Gulf region do not particularly identify the apparent abundance of bed forms. On the other hand, several researchers (Servicio De Hidrografía Naval Argentino, 1961; Pierce *et al.,* 1969; So *et al.,* 1974; Urien and Ewing, 1974) have indicated the presence of large sand waves at the gulf entrance. The Naval Hydrography Service first observed the presence of these bed forms in July 1959. Sand waves were detected through acoustic records at approximately 80 m with an approximate height of 10 m and a length of 600 m. Because of these dimensions they were referred to as giants. Using acoustic soundings, Pierce *et al.* (1969) found a series of large sand waves as high as 17 m and as long as 680 m at the entrance of the San Matías Gulf at a depth of less than 90 m. Achilli and Aliotta (1992) carried out a detailed study of bed forms over the northern area of the gulf entrance. These authors defined the morphological characteristics of such bed forms using similar acoustic technology. Southwest of the Negro River mouth, at depths of 20 m and 45 m, they found large isolated sand waves separated by several kilometers, mostly between 7 m and 11 m in height, and 80 m to 240 m in length. These features, formed by coarse-medium sand, can in some cases be as high as 16 m and up to 400 m in length. Achilli and Aliotta (1992) also observed an asymmetric profile with the larger slope of the sand wave toward the east. This characteristic appears to be consistent with the model developed by Palma (1984), which indicates slightly larger maximum velocities during flood than during ebb.

According to the literature, bottom topography is usually expressed in the SAR when a number of conditions are met, namely, (1) the height of the irregularities is significant with respect to the depth, (2) current speeds are above 0.4–0.5 m/s, and (3) wind speeds conditions are optimum, i.e., between 3 and 10–12 m/s (McLeish *et al.,* 1981; Vogelzand *et al.,* 1992; Shuchman *et al.,* 1985; Donato *et al.,* 1997). All these conditions are typically met to some degree at the entrance of San Matías Gulf, which allows for some observation of sand waves in practically each SAR image available. In fact, tidal currents are usually above the required level in most cases. The tidal model developed by Palma (1984) describes currents in the San Matías Gulf as nearly normal to the detected bed forms during maximum flood and ebb conditions (Figure 2). This perpendicular alignment is consistent with the theory on the generation and development of transversal sand waves (Allen, 1968) as well as supports strong SAR imaging of the sand waves during flood and ebb conditions.

Shuchman *et al.* (1985) has reported detecting bed forms as deep as 50 meters in Seasat-A satellite SAR images. In the case of San Matías Gulf, most of the identified bed forms are located between 20 m and 50 m deep, although a considerable number of them lie between 50 m and 60 m (Figure 7). In the northern gulf entrance, the significant height of sand waves was found to vary between 4 m and 15 m (ACHILLI and ALIOTTA, 1992). Unfortunately, no bathymetric data are available on the height of the bed forms observed off Norte Point. In this area, tidal currents reach their maximum speed, which suggests the development of even higher sand waves compared to the north. The presence of sharper signatures off Punta Norte in all the analyzed images probably reflects a combination of higher speeds and sand wave heights. As mentioned before, this region coincides with an area of turbulence in the nautical charts.

Still, sand waves were not consistently captured over the gulf entrance region in all the available images, particularly to the north. This may have been in part due to the variability of the wind field over the extensive area covered by the observations. Wind velocities should not be expected to be necessarily uniform over the entire region and at times may reach values outside the optimum interval needed to image the features. In addition, tidal currents can have uneven velocities over the gulf entrance and will depend on the tidal stage at the time of the observation.

CONCLUSIONS

The bright and dark linear features observed throughout the entrance of San Matías Gulf in the radar images analyzed have been associated to large sand wave bed forms superimposed to the known submarine topography. These sand waves appear to reach their maximum height at the southern side of the gulf entrance, where tidal currents also reach their highest velocities. This combination may account for the substantial turbulence and wave breaking action typically observed in the region which poses extreme danger to navigation. The information provided by SAR can be especially useful as a complement to classical acoustic morphological studies of the ocean bottom carried out through echo sounding or side-scanning techniques, that are generally more restrictive with respect to the size of the area under study. The data show the significant potential of radar as a tool for the observation of ocean bottom morphology in coastal areas, especially where bathymetric charts indicate sparse information on submarine topography and do not provide detail record on bed forms. In particular, these observations point toward a possible use of SAR for chart updating along the Argentine coast that could supply new and valuable information related to coastal processes of interest to the scientific, government, commercial, and recreational communities.

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