Sleep cycle of a fin whale based on reprocessing of old satellite observations

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Abstract

Reprocessing of old data from the Argos satellite tracking of a fin whale during 42 days in 1991 allowed us to show the significance of loops previously observed on its path. Originally, five loops on five consecutive days had been detected. The reprocessed data reveals at least 21 loops, plus many other phases of inertia, together with additional information on the whale's position at the surface during these phases of inertia. Based on these new interpretations, we deduce a sleep cycle for this animal.

Résumé en français

Mise en évidence à partir d'un suivi satellitaire d'une phase de sommeil quotidienne chez un baleinoptère.

La fixation d'une balise Argos sur un rorqual (*Balaenoptera physalus*) a donné lieu à un suivi satellitaire de septembre à novembre 1991. Cette expérience de suivi d'un Baleinoptère visait à démontrer notre hypothèse sur leurs déplacements migratoires. Notre suivi n'a pas été assez long pour déterminer si le baleinoptère marqué sortait de Méditerranée mais il a permis de mettre en évidence quelques phases d'inertie (5 boucles en 5 jours consécutifs) dans la vie de la baleine, identiques aux boucles d'inertie observées dans les trajectoires de bouées dérivantes utilisées en océanographie physique.

Avec de nouveaux moyens informatiques, nous avons repris ces anci-

ennes données. Outre la mise en évidence de l'adéquation de la trajectoire et du comportement de l'animal avec les caractéristiques hydrologiques et trophiques de chaque localisation, cela a permis de détecter un grand nombre de phases d'inertie dans la trajectoire de la baleine et de les apparenter à des phases de sommeil. Pour cela il fallait démontrer qu'elles se répétaient chaque jour.

Keywords: cetaceans, Argos tracking, sleep cycle, data mining

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1. Introduction

In the late 1980s, the Argos technology provided for the first time efficient means of tracking cetaceans at scales suited in space and time to their migrations, their positions being transmitted by satellite. The first successful 'tagging' of a whale concerned an animal caught in a fishing net; the device fixed on its flank provided 100 hours of data. Similar tracking attempts had involved explosive anchors penetrating under the skin. For ethical scientific reasons we rejected such approaches.

The initial conception of our "Argocet" tracking program dates from 1986. Its development phase, from 1988 to 1991, led to the development of a dedicated Argos platform transmitter (Argos PTT). This small device, powered by lithium batteries, was designed to last 3 months. Attached to a fin whale (*Balaenoptera physalus* Linnaeus, 1758 (*Balaenopteridae, Mysticeta*), abbreviated "Bp" hereafter), it provided tracking data from 22 September to 2 November, 1991. The PTT was not in contact with the whale's body: a 12 m line tied to the dorsal fin of the (approx. 20 m long) animal dragged the Argos device.

In the following years, Watkins *et al.*(1996) [1] tracked a fin whale near Iceland, and Kingsley *et al.*(1996) [2] tracked belugas in the St Laurent estuary, but only for a few days. With more recent and miniaturized technology, tracking techniques have evolved and remain highly relevant : a programme to track megapterans is under way in South Africa.

Our tracking programme was intended to demonstrate our hypothesis on the migratory course of fin whales. Bp are present during winter and summer in the Mediterranean sea (Disciara *et al.* 1993; Forcada *et al.* 1996; Gannier 1997) [3][4][5], but these two populations are probably different (Viale 1985) [6]: one, present in winter, migrates in summer towards the North Atlantic

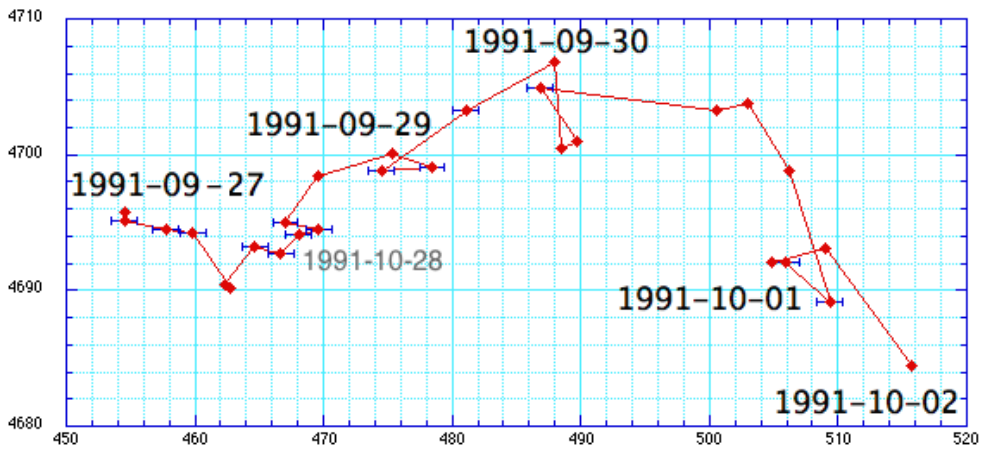

Figure 1: Part of the whale's track, showing three of the five loops initially detected in 1991. Vertical axis: km from the equator; horizontal axis: km from the Greenwich meridian.

as identified by Jonsgärd (1966) [7], whereas the other, more abundant in summer, migrates to the South Atlantic according to our hypothesis.

The tracking record did not last long enough to determine whether 'our' whale eventually left the Mediterranean, but the loops in its recorded track revealed inertial phases in its life cycle (Viale *et al.* 1992; 1995, Pichod Viale, Deleplancke & Millot 1993)[8][9][10].

These loops of variable size (a few km) are similar as those observed for drifting buoys used in oceanography (Millot & Crépon 1981; Millot 1987)[11][12]. However, linking these loops to sleep phases requires observation of a repeated occurrence over many days, and only five loops during five consecutive days had been detected in the initial study (fig.1).

We recently reprocessed these old data with modern means. This led to the detection of at least 21 loops in the whale's track, in addition to many other phases of inertia, and allowed correlations to be made with the hydrological, trophic and meteorological conditions at the different points.

2. Equipment and Methods

When the whale tracking data was originally collected, D. Viale and collaborators only had the old Argos technology available. Now, the new Argos

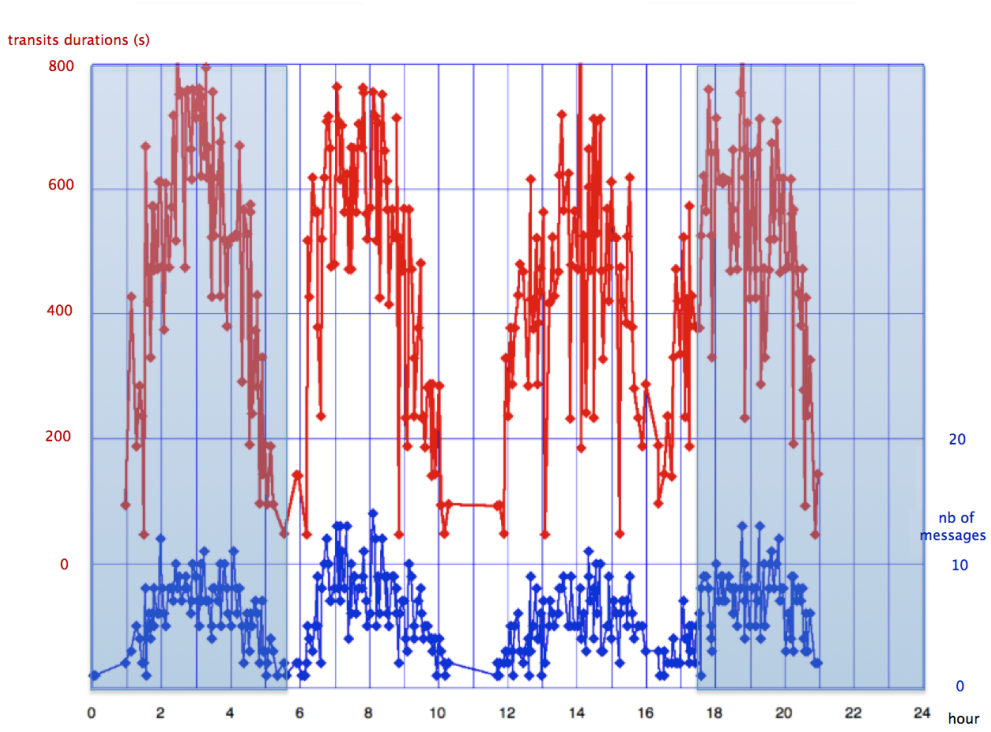

Figure 2: Graphs as a function of local time. In red: transit durations of the Argos satellites above the horizon (20 to 800 seconds); in blue: cumulated number of passages for a given hour. The fin whale was not covered by the satellite tracks during the following intervals each day: 20h50-01h30; 05h00-06h00; 10h00-12h00; 15h50-16h30.

system and the global network satellite system (GNSS) are much more powerful. However, reprocessing these old data reveals useful information.

The Argos buoy used for this survey, conceived in Nice by J.J. Pesando, withstands speeds up to 23 knot speeds and depths to 600 m. This transmitting platform (PTT) consists of a carbon fibre container, housing the CEIS-Espace emitter, is covered with polyurethane. It also contains lithium batteries, a short helicoidal antenna, a manometer and low density stuffing for flotation. Miniaturization allowed the mass to be reduced from 12 to 3.5 kg. The antenna is efficient against waves and the manometer stops emissions during dives, restoring it a few meters below the surface (i.e. a few seconds before the Bp surfaces). Previous observations of Bp in the Mediterranean had shown that they often take very short surface breaks between dives, too short to complete an Argos emission cycle.

The two Argos satellites, NOAA 'H' and 'D', received signals from the buoy when two conditions were met: satellites high enough above the horizon and whale at surface. These signals are series of 4 s 'emissions' separated by 15 s of 'silence'. Argos could locate the Bp if its satellites received three or more consecutive signals.

The attachment system between the Bp and the PTT had been designed to respect the animal's physiology. If fixed to its flank, the fragile skin would not have supported a 3.5 kg buoy, which would have caused a wound. To avoid that, the attachment setup described by Viale *et al.* and Mouillot & Viale in [8][13], used a 12 m long Kevlar line between the dorsal fin and the Argos buoy.

Finding a Bp in natural conditions, approaching the animal and attaching the Kevlar line to its dorsal fin, all in a limited time because the ship (operated by Centre National de la Recherche Scientifique: CNRS) had to return to harbour every evening, required three years of training and trials. It was finally achieved by Carli Viale on 22 September 1991.

The Argos buoy transmitted its position data to the satellites several times a day (fig.2). The lithium battery for the transmitter was designed to last three months. Unfortunately it ran out after only 42 days, due to incorrect parametrization by the subcontractor.

3. Data Mining and Analysis

Modern computer and geolocalisation resources (e.g. Google Earth) allow a new look at the old data. The digital records from 1991 were irrecoverable

or lost, but the paper printouts are still available. These were scanned and redigitized using optical character recognition (OCR), and then checked for transcription errors.

Several track points were erroneous and have been removed. We used two criteria to identify errors: the Signal/Noise ratio given by CLS-Argos for each point, and unfavourable positions of the Argos satellites. The precision given by the Argos Doppler tracking is poor when the satellite-to-whale distance passes through a minimum (satellite at zenith for example) and, for different reasons, when the satellite is low above the horizon. In both cases these imprecise points would have added bogus spikes and high speed segments.

Argos yields geographical coordinates (longitude, latitude), which we translated into distances (in km) from the equator and from the Greenwich meridian, yielding one point (two coordinates) on the map. Then, using pairs of points, we derived segments (four coordinates) and their average speed, and from each couple of segments (i.e. three consecutive points or six coordinates) we derived a signed angle in the trajectory. We integrated these angles to detect loops in the trajectory.

To each segment we associated the local times of sunrise and sunset, in order to study the effect of the daily cycle on the animal's behaviour. We also investigated the causes of non reception of signals from the whale by the satellites: satellite not high enough above the local horizon, or whale submerged.

4. Results

The whale trajectory from 1991-09-22_08:58 to 1991-11-02_04:12 has a cumulated segments length of 1317 km. The actual trajectory of the Bp is longer, being fractal and undersampled (Mouillot, Frontier & Viale, 1999)[14].

The satellites received between 2 and 15 Argos 'messages' per day during the tracking. A fraction of the messages were not sufficiently complete to provide a localization. Their high number per day was a surprise, as the Argos buoy cannot send messages when the Bp is submerged: it appears that this Bp was more often near surface when left alone than when in the vicinity of human observers.

The transit duration of an Argos satellite above the whale's horizon lasted from 20 to 800 s. Our prior observations in the Mediterranean showed Bp dives lasting from 240 to 900 s, most frequently 450 to 500 s. Our expectations were pessimistic.

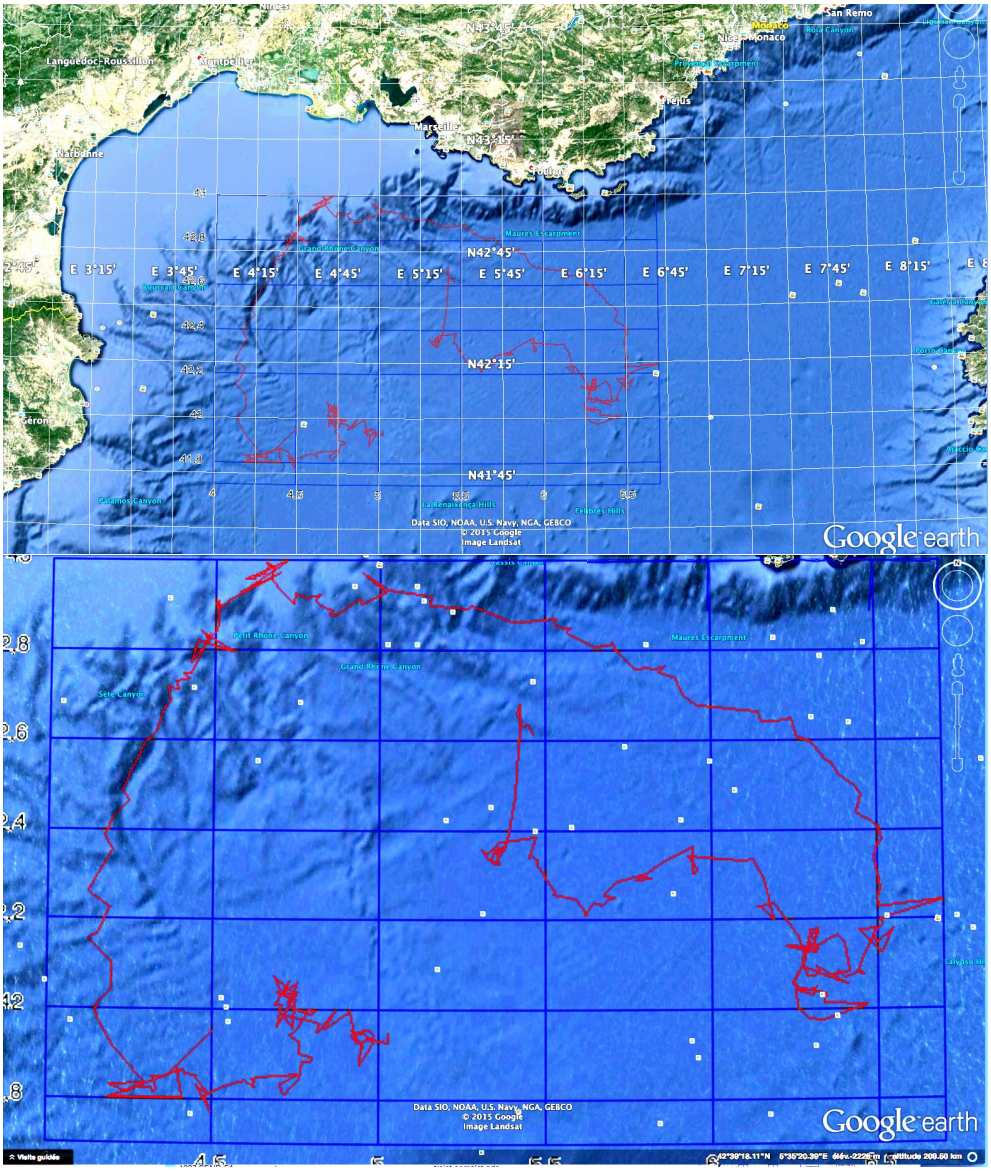

Figure 3: Track of the fin whale superimposed onto the corresponding Google Earth map of the north-western Mediterranean Sea (Corsican coast at right; French coast, Toulon, Marseilles, at top; Spanish coast, Girona at left). The bottom figure is an enlargement, better showing correlations between the whale's track and submarine canyons or cliffs. Note the evident match of the track to the underlying submarine topography, the marine circulation, and sources of food, such as the upwelling zone south of the Gulf of Lion. The whale spent four days in that area, three of which in the Sète and Grand Rhône canyons, before continuing into the Catalan stream. This track reveals additional biomass-rich zones, which are little known, in a central area separate from the general Mediterranean circulation.

Fig.2 displays the number of messages received and the duration of satellite transits over the Bp as a function of time (modulo 24h). Because there were only two satellites, the Argos coverage is variable and incomplete. From our revised study of the:
– satellite schedules;
– message lengths and transit durations;
– positions of the Bp;
– local times of sunrise and sunset.
We have deduced some aspects of the whale's behaviour while it was tracked. These are synthesized in fig.3, which shows the track superimposed on a Google Earth© map of the area.

Unlike that of a drifting buoy, the whale track shows active adaptation to the marine environment. The plankton and krill are not distributed randomly, being concentrated in areas where the joint action of marine circulation, winds, temperature and submarine topography enrich the sea in nutritive salts (Viale 1991,1995; Mouillot *et al.* 2001)[15][9][13].

The Bp adapts to the distribution (dubbed 'contagious') of the food resources it detects (Viale & Frontier 1994; Viale *et al.* 1996)[16][17]. This indicates a strong interaction between the Bp and its environment (Mouillot & Viale, 2001)[13]. In addition, its track suggests several other biomass-rich zones in the Mediterranean.

The track superimposed on the Google Earth map fig.3 shows the activity of the Bp; its speed varies as a function of hydrology, food availability, and sea currents related to winds. These data on the Mediterranean ecosystem had been collected previously by participating in the international oceanographic mission "Western Mediterranean Circulation Experiment" (Viale & Pistek 1988; Viale & Frontier 1994)[18][16]; here they explain the Bp speed modulations observed: fast through food-sparse zones (e.g. in the Catalan stream from 18-21 Oct. 1991) or on the contrary slow in non-circulating water masses (22 Oct. to early November 1991), where long chains for biomass production have time to develop from phytoplankton: → phytophagous zooplankton → phyto- and zoophagous zooplankton → macroplankton, such as Euphausiacea, forming swarms hunted by the Bp.

5. Discussion

A few clockwise loops in the Bp track had been detected during the initial study, such as those around 1 Oct. 1991 in fig.5, and identified as inertial

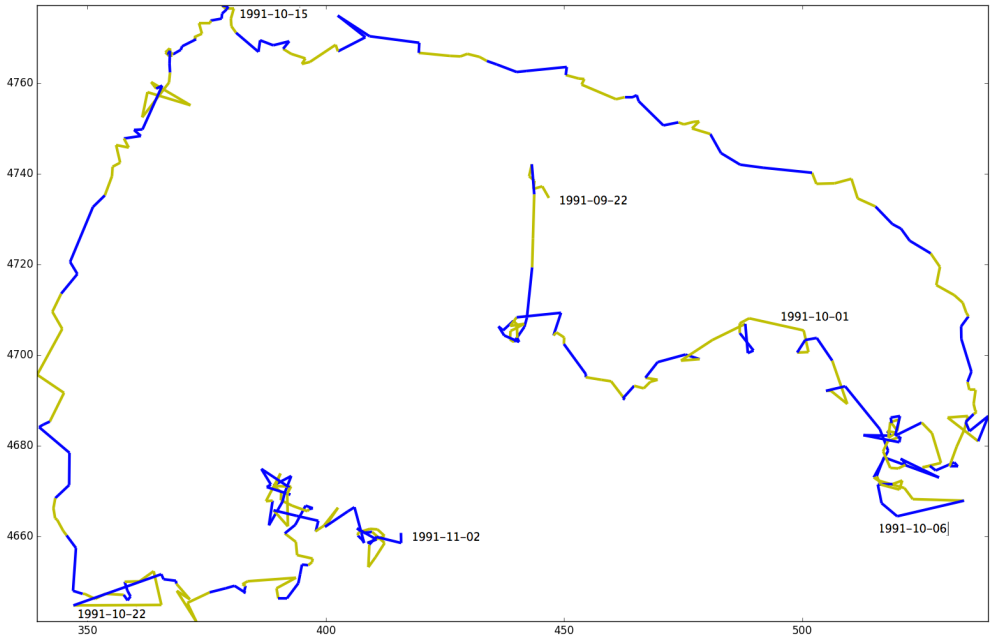

Figure 4: Day-night alternation of the Bp between consecutive localization points, colour-coded: in blue are the track segments starting during nighttime, and in olive during daytime. Scales in km: vertically from the equator; horizontally from the Greenwich meridian.

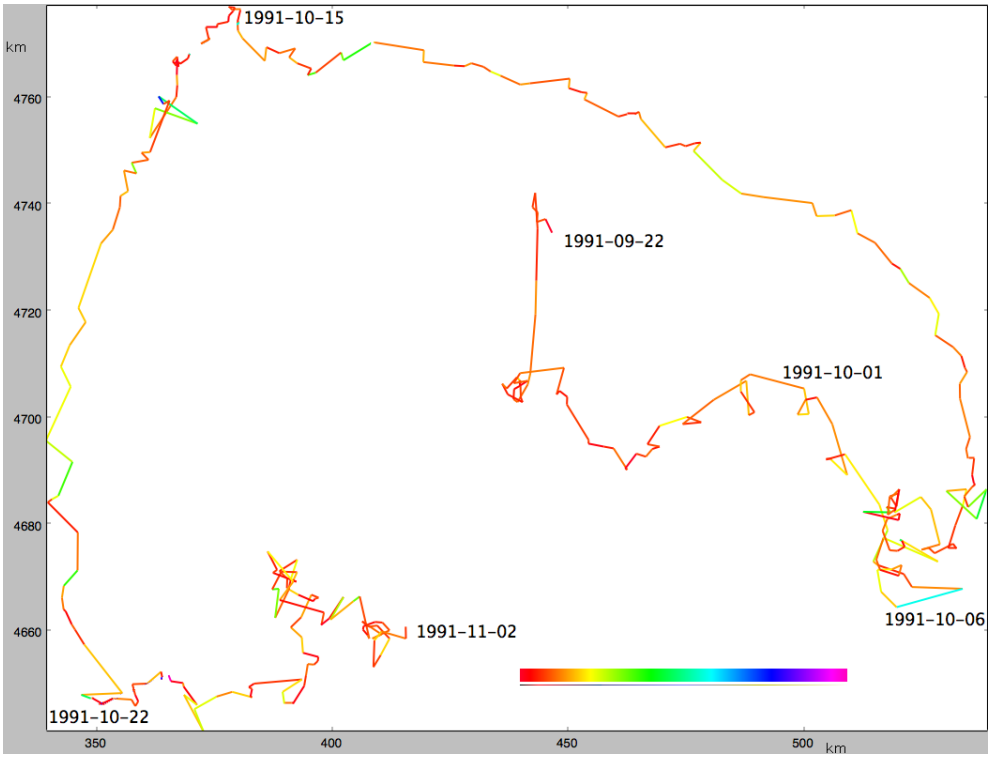

Figure 5: Average speed of the Bp between consecutive localization points, colour-coded from red: $\simeq$ 0.3km/h to blue: $\simeq$ 3km/h. Scales in km: vertically from the equator; horizontally from the Greenwich meridian. The speed is high, for example, when the animal is in the Catalan stream (descending on the left side of the plot). The animal is taking advantage of, rather than being subjected to, this circulation: on 22 Oct. 1991 it leaves it and moves towards rich zones, probably guided by vocalizations of other animals already feeding there.

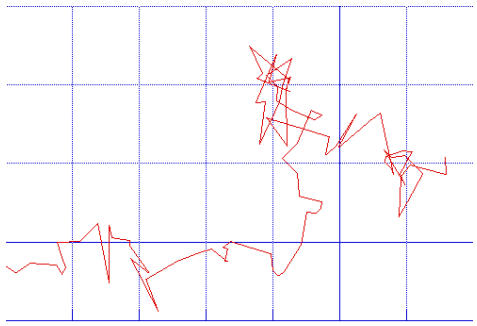

Figure 6: Last part of the whale's track (from 22 Oct. to 2 Nov.1991) before the end of transmissions; its shape suggests feeding behaviour.

fluctuations similar to those of drifting oceanographic buoys (Pichod-Viale, Deleplancque, & Millot 1993)[10]. Those five loops seen in five days (*ibid.* ; Mouillot & Viale 2001)[13] suggest a daily sleep period. P. Deleplancque had found additional loops towards the end of the track (fig.4).

These inertial fluctuations correspond to an oceanological phenomenon due to Coriolis force, observed with the drifting buoys used to study superficial circulations (Tomosada 1989; Millot & Crépon 1981))[19][11]; they reveal rotations of sea-water masses, within which the buoy (or whale in our case) is 'inert'. These loops would not cause a displacement of a whale relative to a surveillance boat, both drifting in the same water mass.

We interpret the 'inertial floating' periods during which the whale shows no autonomous mobility, being due to the animal being at muscular rest, a state that is usually called sleep.

Our reprocessing of the Argos data revealed 21 clockwise α-shaped loops in the whale's track, similar but less visible than those in figs.4 and 5. To detect these 21 loops we integrated the angles obtained between consecutive segments of the trajectory. The resulting curve is plotted in fig.7. This graph shows the number of loops as a function of time in the whale's track. They add up (i.e. they all correspond to a clockwise rotation) except in the central part of the graph where the whale was in the main Mediterranean circulation, from 6 to 21 Oct. 1991. Fourteen loops are detected by the "integrated angles procedure" in the first part of the track between 22 Sept. and 05 Oct. 1991, and six in the last part between 25 and 31 Oct., although not easily visible from the track in fig.4.

The central part of fig.7 is quasi constant (no loops) from 6 to 15 Oct.

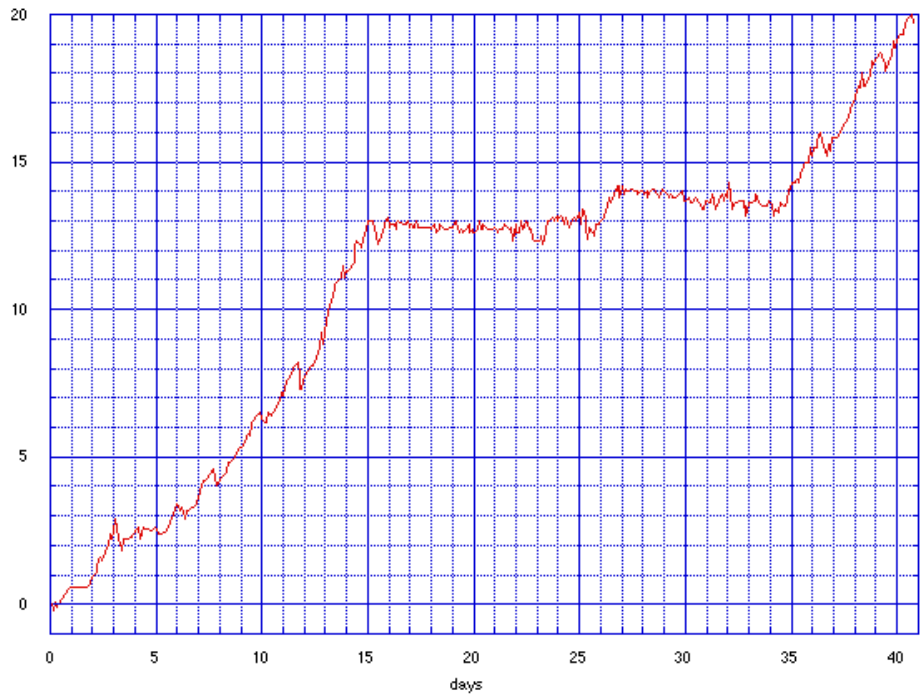

Figure 7: Graph showing the number of loops as a function of time in the whale's track. Ordinate: cumulated angles between consecutive track segments (number of loops since origin). Abscissa: time (in days) since first day of tracking. It can be seen that the angles are additive, except in the central part of the graph, where the whale is in the main Mediterranean circulation (from 6 to 21 Oct. 1991). Although they do not appear clearly to the eye (e.g. in fig.4), 21 loops are detected in the Bp track by the integrated angles procedure.

1991 and from 18 to 22 Oct. 1991. It corresponds to the track of the whale in a circulating water mass: the strength of sea circulation prevent the Coriolis loops from closing, which results into a loopless cycloid trajectory. The undersampling of the Argos coverage turns it into a 'sawtooth' shape.

However, from 15 to 18 Oct. 1991 there is a short 'loopy' phase, which comprises the most northern part of the track on 15 Oct. 1991, with a loop on 15 Oct. 1991 cancelled by a southwards 'U-turn' of the Bp.

During this phase the whale is above the Bourcart canyon. It is localized at a quasi-constant position: 10 times on 16 Oct. 1991 and 10 times again on 17 Oct. 1991 in the same 8 x 8 km area (a total of 105 Argos messages in 35 hours). In figs.5, the track on 17 Oct. 1991 and adjacent nights reveals two small concentric circles that are also visible on fig.3, causing the increment in the loop count.

The 105 messages in 35 hours provide information on the whale's behaviour: 15 messages during daytime on 1991-10-17 and 90 messages, by clusters of 6 or 7 during the adjacent nights. The last message clusters received before these mornings are at 1991-10-17–03:54 and at 1991-10-18–02:03; by the time of the following satellite coverage the whale had resumed its activity. As a consequence, there were three times more messages when the whale was surfacing in inertia at night than during its daytime activity.

From 1991-10-22 to 25, the most south-western part of the track (in figs.4 and 5) is relatively intricate and although three additional loops can be deduced visually, they cancel out in the graph fig.7, which remains constant at these dates, because the contribution of the loops is neutralized by opposite left turns of the Bp heading west.

The six inertial loops (plus one night in circulating water) in the last part of the track are hard to see, but their presence is confirmed by the integrated angles procedure (fig.7), accounting for six turns, and corresponding to the 'complex' end of the track in figs.4 from 1991-10-26 to the last recorded position 1991-11-02 at 04:12. Overall, we detected 14 inertial loops in 14 consecutive days, followed by twice three loops in three consecutive days, and then six loops in the last six days. These 26 phases of inertia are periodic with a 24h period, and seem to represent sleep.

To ascertain the link between repeated inertial loops and daily sleep phases, it has to be shown that they occur every night. These loops are conspicuous only in the parts of the trajectory that are drawn in slow water masses (see fig.5), such as near 1991-10-01, away from the northwestern Mediterranean circulation.

They do not show up in areas with circulating water masses, where, like drifting buoys, the Bp trajectory presents broken line segments (Millot & Crepon 1981, Tomosada 1989)[11][19], for example from 1991-10-11 to 15, in the 'Provençal current' and from 1991-10-18 to 22 in the 'Catalan current', whose speeds are well defined. We have evidenced elsewhere that the speed of the Bp at night between 20h30 and 01h50 appears to be precisely in correspondance with the current, whereas during daytime the Bp is tracked at speeds twice faster than the current. This allows to distinguish 'inertial' phases at night in the current from 'active' phases during the day (D.Viale *et al.* 2018) [25].

In the right part of the track leading North-West, during 1991-10-06 to 14, (fig.3) the Bp is located in a region where intermittent currents due to cold North winds (e.g. mistral), which cause the colder, denser surface water to sink. This in turn causes an upwelling of 'intermediate water', rich in nutriments, into the euphotic layer.

Such local turbulences are sources of nutriment enrichment, leading to a possible increase in biomass production, including krill. This food supply in turn would be taken advantage of by the wale, as suggested by the wiggles (variable segment lengths, speed and direction) in this part of its track (fig.5). The speed varies because the whale travels faster through food-poor regions. One can see (fig.4) that night-time segments are quasi similar, varying only with the stream speeds. Short day-time segments indicate a diving activity that ceased one hour before sunset, and/or a direction of swim northwards, opposite to the current.

The part of the track from 1991-10-22 to 25 remains in an area interpreted as being rich in trophic resources because the Bp track becomes complex and slow (fig.4). The track points are numerous and frequent: the Bp emitter is more often detectable as the animal probably dives to feed and rests longer on the sea surface.

The track features 26 inertial loops plus 15 inertial phases in circulating waters during the 42 days and 41 nights it covers (the first day and last night were not covered entirely). It appears that our Bp had a sleep phase every night.

On fig.4, the majority of the loops and related segments occur between two hours after sunset and the middle of the night. These daily periods after sunset, when the Bp is inactive, correspond to the rise and dispersion of plankton over the sea surface. Our previous work had shown that Bps dive for feeding only into concentrated biomass volumes: swarms formed

during vertical nycthemeral migrations of the krill. These krill swarms remain developed at 50-75 m depths, between one and one and a half an hour before sunset. Then they disperse over the euphotic layer, where they consume the plankton matured during the day (Viale & Frontier 1994; Viale *et al.* 1996)[16][17] and present no interest to the Bp, which stops diving one hour before sunset. The descent of the krill begins one hour before sunrise; in the following hour biomass accumulates at the usual depths and the whales start diving again.

The inertial loops have allowed us to estimate the duration and time of sleep phases: around 6 to 8 hours, starting after sunset, whereas feeding activity stops one hour before. These are estimated with limited precision, as allowed by the two satellites of the Argos system, which did not have a 24-hour coverage, see fig.2.

6. Conclusion

The Argos tracking of the whale in 1991 had originally allowed the detection of periods of activity followed by rest: five cycles in five consecutive days. The hypothesis of a sleep phase was suggested, but only for a few days in the 42-day tracking record.

Rest periods were revealed by the α-shaped loops of the whale track. Assimilated to the inertial loops of drifting buoys used to study marine currents, they can be assumed to be sleep phases. These loops are all in a clockwise direction: such a pattern can be explained by the motion (due to Coriolis force) of a sea-mass in the northern hemisphere, relative to which the whale remained motionless. In addition, the Argos tracking indicated that the animal was at the sea surface (not diving) during those periods. A cetacean's sleep implies two conditions: ability to breathe, hence at or close to the surface, and no displacement relative to the surrounding water (Siegel 2005)[20].

In the present work we retrieved and reprocessed the 25 year-old data with new algorithms. We superimposed the track onto a Google Earth map (fig.3), on which the path of our tagged fin whale appears coherent with its marine environment.

For each segment of the track we calculated an average speed (fig.5) and correlated this with the local times of sunrise and sunset to study the affect of day/night cycles on the whale's behaviour. The length and speed of the track segments recorded during day-time vary as a consequence of diving for

food and its availability, whereas night-time segments are more constant in length, varying in accordance with the speed of the stream in which the Bp is swimming (or floating when in a phase of inertia).

Fig.7 displays the number of loops as a function of time. This graph is completely different from one that would be obtained from a random trajectory; it reveals a large number of loops: one in the Bp track every night, except when currents prevent them from closing.

The 20 m long whale that we tracked behaved like a ship without a harbour: it did not need to stop over for food or fresh water. We have shown (Viale 1979, and Viale & Masson-Viale 2009)[21][22], that a Bp desalinates its internal medium by means of a pleated surface of the germinal epidermal layer and the dermis in contact with a vast layer of blood capillaries of the hypodermis. It 'sweats' salt crystals by regularly peeling off its superficial epidermal layer.

This 'ship' had another problem to solve: sleep. Sleep in cetaceans has been shown to be uni-hemispheric (Rattenborg, Amlaner, Lima, 2000)[23], here we simply deduce a sleep cycle for Bp from our data on its behaviour, we make no further assertions regarding its cerebral sleep mechanisms. Anecdotal accounts exist of fin whales seen 'asleep', observed (or even harpooned) by ships (e.g. Viale, Koechlin, Martoja, 1973)[24]. But were these animals were asleep, or sick, or dead? This harbourless whale has indeed places to rest in the marine environment: moored to its water, six to ten hours each night, after sunset.

Here we establish that our Bp, tracked for 42 days by satellite, follows a path comprising 26 inertial loops, which correspond to 26 phases of total inertia, every night for 26 consecutive nights. Furthermore, during 15 other days when the Bp was in sea currents, we know by comparison with the behaviour of drifting buoys used for studying ocean dynamics, that inertial loops can be masked and modified into cycloid-like paths that no longer include closed loops. These cycloid-like paths, once (under)sampled by the Argos satellite system appear as broken line paths.

The measured speeds of the Bp during these nighttime segments, when in circulating waters and when they are identical to the water current, indicate that inertial phases are present.

Such phases of total inertia, with the absence of autonomous movement, usually start one or two hours after sunset. They correspond to a 'rest' of the cerebral commands for motion and at least partly accomplish the functions of sleep. This indicates the regular sleep cycle of a whale lasting approximately

from 6 to 8 hours each night.

7. Acknowledgements

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