Near real time satellite tracking of striped marlin (Kajikia audax) movements in the Pacific Ocean

Article *in* Marine Biology · February 2009

DOI: 10.1007/s00227-008-1104-y

John C. Holdsworth
Blue Water Marine Research

Tim J. Sippel
Washington Department of Fish & Wildlife

Barbara A Block
Stanford University

Mar Biol
DOI 10.1007/s00227-008-1104-y

ORIGINAL PAPER

Near real time satellite tracking of striped marlin (*Kajikia audax*) movements in the Pacific Ocean

John C. Holdsworth · Tim J. Sippel · Barbara A. Block

Received: 14 March 2008 / Accepted: 28 November 2008

Abstract High-resolution satellite locations were obtained from striped marlin using Argos transmitters attached to the upper lobe of the caudal fin. Twenty-six striped marlin were tagged off New Zealand (2005–2007) and tracked as far as the central Pacific Ocean. Caudal fin mounted Argos tags generated 1,524 locations during a total of 659 tracking days [mean 25 (±21.24) days per fish and 2.3 (±2.30) locations per day]. 38% of locations have an estimated accuracy of ±1 km or better. Displacement rates from high quality locations ranged from 2.9 to 170.8 km in a 24 h period, with a mode at 20–30 km and a mean of 45 km/day. The caudal fin attachment methodology and antenna configuration was adjusted each season to improve transmission life and data quality, with the best results obtained in the last year of deployments (2007). The longest track duration was 102 days, with a total displacement of 4,959 km and a total track distance from all locations received of 6,850 km. Tag shedding and antenna failure appear to have limited the duration of tracks from SPOT tags. The high temporal and spatial resolution data revealed behaviours not previously observed in striped marlin, including associations to subsurface bathymetric features. High resolution location data such as these are useful inputs for statistical models used to investigate habitat selection and switching between different behavioural modes. The geolocations calculated using ukfsst estimates from PAT tag data had RMS errors of 1.01° latitude and 0.59° longitude when compared with SPOT tag Argos locations.

Communicated by M.I. Taylor.

J. C. Holdsworth (✉) · T. J. Sippel
Blue Water Marine Research,
PO Box 402081, Tutukaka, New Zealand
e-mail: John@bluewatermarine.co.nz

T. J. Sippel
School of Biological Sciences, University of Auckland,
Private Bag 92019, Auckland, New Zealand

B. A. Block
Tuna Research and Conservation Center, Hopkins Marine Station,
Stanford University, Pacific Grove, CA 93950, USA

Introduction

Striped marlin (*Kajikia audax*, Family Istiophoridae) (Collette et al. 2006) are a wide ranging pelagic fish found in the Indo-Pacific Ocean. They are a high profile recreational species in some countries such as New Zealand, and are also an important commercial species elsewhere in their range. Historically, movements of highly migratory species (HMS) including striped marlin were inferred from seasonal shifts in commercial catch per unit effort (CPUE) data (Kume and Joseph 1969; Squire and Suzuki 1990) and from conventional mark and recapture techniques (Ortiz et al. 2003). These methods rely on an overlap between fishing activity and striped marlin distribution so are fisheries dependent. Striped marlin have a wide latitudinal distribution occurring from 45°N to 45°S latitude mainly in tropical or subtropical waters and penetrating to higher latitudes in local warm seasons (Nakamura 1985).

Electronic tags have revealed much about HMS movements, habitat preferences and behaviours at much finer spatial and temporal scales. Pop-up satellite archival transmitting (PAT) tags have recorded striped marlin movements and behaviour over extended temporal (up to 9 months) and spatial scales (thousands of kilometres) within the Pacific Ocean (Domeier 2006; Sippel et al. 2007). Current generations of PATs measure and archive

Published online: 19 December 2008

water temperature, pressure, and ambient light level intensity data which can be used collectively to estimate the location of tagged animals up to twice per day (Nielsen and Sibert 2007). Methods of geolocating animals by modeling environmental data such as sunlight and sea surface temperature from archival tags are rapidly evolving (Musyl et al. 2001; Sibert et al. 2003; Teo et al. 2004; Domeier et al. 2005; Nielsen and Sibert 2007; Lam et al. 2008) and range in positional error from 0.2 to 0.5° of longitude and up to 2° of latitude. Assessing how these models perform in different situations is important for understanding at what spatio-temporal scales they are capable of resolving animal behaviours.

Satellite linked radio telemetry (SLRT) has proven to be a powerful high resolution method of tracking marine animals that surface regularly. Early uses of SLRT and the Argos system enabled tracking of marine animals including testudines (Stoneburner 1982; Timko and Kolz 1982), elasmobranchs (Priede 1984), pinnepeds (Stewart et al. 1989), and cetaceans (Mate et al. 1994). Attempts to telemeter movements of blue marlin using Argos PTT's tethered to tow bodies had limited success in the 1990's, yielding only a few positions post deployment (B. Block, personal communication). The mass and drag of PTT's and their tow bodies probably contributed to high shedding rates.

Five striped marlin tagged in New Zealand waters in 2003 carried PAT tags for 22–60 days. Their general movement patterns were described and archival data from a recovered PAT tag revealed detailed diving behaviour in the shelf and pelagic waters surrounding the North Island (Sippel et al. 2007). The tracked striped marlin spent 72% of their time in the upper 5 m of the water column during an austral summer and autumn. The high proportion of time that the electronic tags documented the striped marlin near the ocean's surface, coupled with reductions in the size and weight of PTTs, provided the opportunity to develop a new method for attaching transmitters directly to the body of striped marlin to obtain higher resolution spatial temporal data sets. During 2005, 2006 and 2007 Argos PTT transmitters were attached to the upper caudal fin lobe of 26 striped marlin, providing satellite telemetry data in the southwest Pacific Ocean (20–40°S latitude and 165°E–135°W longitude). These deployments provided the first satellite linked radio telemetry data from a pelagic teleost, and revealed new details about the movements of striped marlin. A PAT tag was also attached to 22 of the caudal fin tagged striped marlin to concurrently gather additional environmental data.

The primary objective of this paper is to describe the new method used to track striped marlin with satellite linked radio telemetry and describe the quality of data obtained. SLRT data are also compared with geolocations estimated by modelling environmental data recorded by PAT tags on the same fish.

Materials and methods

Tag configuration

For these experiments the AM-S216B smart position or temperature (SPOT) tags (SPOT 4.0 and SPOT 5.0) manufactured by Wildlife Computers (Redmond, WA, USA) were used with the M1 battery configuration and an antenna 20° offset from vertical. The tags measured 80 × 19.5 × 10.5 mm weighing 32 g in air and the manufacturer rated their operational depth to 500 m. Twenty-two marlin were also tagged with pop-up archival transmitting tags (PAT4, Wildlife Computers), using procedures previously described (Sippel et al. 2007).

Conductivity changes associated with exposure of the tag to air triggers radio transmissions to the satellite which are repeated at a prescribed rate while the tag remains exposed to air. Several transmissions must be received during a single Argos satellite pass before a location can be calculated using Doppler shift. In 2005, tags had a fast transmission repetition rate of 20 s when dry and slow repetition rate of 90 s, after 20 successive dry transmissions with a maximum of 1,000 transmission over a 24 h period. In 2005 and 2006 tags were limited to a maximum of 200 transmissions per day and some were duty cycled to coincide with the periods of highest satellite coverage in the region (Table 1). Multiple antenna configurations were used over the 3 years, and some were reinforced at the base with Tygon tubing and silicon filler (Table 1).

Tag attachment

In 2005 five SPOT tags were bonded to Lurethane plates (Ludowici Plastics, Auckland, New Zealand). The plates were attached to the anterior upper lobe of the caudal fin using a modified pneumatic stapler (Paslode International). The stapler was modified with a clinching arm that positioned a striking plate to fold the staples over after penetrating the caudal fin and plates.

In 2006 PVC cloth sleeves were used to hold the tag. These were placed over the dorsal tip of the tail (a slotted envelope approach) and attached with two or more galvanized steel staples placed near the leading edge (Fig. 1). In addition a 6 mm stainless steel bolt passed through a tab on the tag and a hole drilled in the caudal fin. This was fastened with a flat washer and self locking nut.

The tag sleeve was constructed from side curtain PVC coated polyester fabric (900 g/m^2). This was folded twice and then glued and stitched together to fit a striped marlin caudal fin. The tag was held in a pocket on the side of the sleeve with epoxy glue. The tapered shape of the sleeve allowed it to be slid over the upper caudal lobe so that it would stop 10–15 cm down from the tip (Fig. 1). The

Table 1 Tag deployment and set up parameters including model of Wildlife Computers tag and antenna configuration, transmission limits and attachment method used

Fish ID	Date tagged	Archival tag	Radio tag	Antenna configuration	Programmed to transmit (GMT 12 h)	Max. trans/day	Tag attachment
STM05_01	21/02/2005	PAT4	SPOT4	SSWire	24 h	1,000	Plates and staples
STM05_02	25/02/2005	PAT4	SPOT4	SSWire	24 h	1,000	Plates and staples
STM05_03	26/02/2005	PAT4	SPOT4	SSWire	24 h	1,000	Plates and staples
STM05_04	18/03/2005	PAT4	SPOT4	SSWire	24 h	1,000	Plates and staples
STM05_05	23/03/2005	PAT4	SPOT4	SSWire	24 h	1,000	Plates and staples
STM06_01	10/01/2006	PAT4	SPOT5	BM	24 h	200	Sleeve and bolt
STM06_02	11/01/2006	PAT4	SPOT5	BM	24 h	200	Sleeve and bolt
STM06_03	12/01/2006	PAT4	SPOT5	BM	24 h	200	Sleeve and bolt
STM06_04	13/01/2006	PAT4	SPOT5	BM	24 h	200	Sleeve and bolt
STM06_05	04/02/2006	PAT4	SPOT5	BM	24 h	200	Sleeve and bolt
STM06_06	20/02/2006	PAT4	SPOT5	BM reinforced	24 h	200	Sleeve and bolt
STM06_07	01/03/2006	PAT4	SPOT5	BM reinforced	24 h	200	Sleeve and bolt
STM06_08	31/03/2006	PAT4	SPOT5	BM	0400–0900, 1600–2100 hours	200	Sleeve and bolt
STM06_09	13/02/2006	PAT4	SPOT5	BM	24 h	200	Sleeve and bolt
STM06_10	31/03/2006	PAT4	SPOT5	BM reinforced	0400–0900, 1600–2100 hours	200	Sleeve and bolt
STM06_11	31/03/2006	PAT4	SPOT5	BM reinforced	0400–0900, 1600–2100 hours	200	Sleeve and bolt
STM06_12	02/04/2006	PAT4	SPOT5	BM reinforced	0400–0900, 1600–2100 hours	200	Sleeve and bolt
STM06_13	03/04/2006	PAT4	SPOT5	BM reinforced	24 h	200	Sleeve and staples
STM06_14	03/04/2006	PAT4	SPOT5	BM reinforced	24 h	200	Sleeve and bolt
STM06_15	04/04/2006	PAT4	SPOT5	BM reinforced	24 h	200	Sleeve and bolt
STM07_01	19/02/2007	None	SPOT5	BM reinforced cured	0300–2200 hours	200	Sleeve and staples
STM07_02	19/02/2007	None	SPOT5	Memory metal	0300–2200 hours	200	Sleeve and staples
STM07_03	20/02/2007	None	SPOT5	Memory metal	0300–2200 hours	200	Sleeve and staples
STM07_04	20/02/2007	PAT4	SPOT5	Memory metal	0300–2200 hours	200	Sleeve and staples
STM07_05	21/02/2007	None	SPOT5	BM reinforced cured	0300–2200 hours	200	Sleeve and staples
STM07_06	22/02/2007	PAT4	SPOT5	BM reinforced cured	0300–2200 hours	200	Sleeve and staples

Antenna codes: *SS* stainless steel, *BM* braided metal

sleeve was modelled on a tail of a 100 kg striped marlin, which is a typical size in New Zealand (Kopf et al. 2005). In 2007 six SPOT tags were attached to marlin using the folded PVC sleeve and staples but no bolts were used.

Fish handling

All fish were caught by recreational fishers on rod and reel using lures. Only fish deemed to be in good condition at the boat were tagged. In 2005 fish were held in the water across the stern of the tagging boat and tags attached from the swim step.

The configuration of the tagging vessel in 2006 made it difficult to tag the fish in the water. A fish ramp constructed out of 60 mm stainless steel pipe was used to pull marlin aboard through the stern door and onto a padded vinyl mat on the deck. The fish were irrigated with seawater and their exposed eyes were covered with a damp cloth. After tagging was complete they were returned to the water tail first, then held by the bill and towed behind the boat until they were actively swimming (1–5 min).

In 2007 marlin where tagged while the fish remained in the water along side an eight meter trailer boat.

Location accuracy and displacement distance

Argos satellites are polar orbiting and at 30°S latitude (similar to deployment latitudes) a satellite pass lasts up to 16 min and are often about 100 min apart but with occasional gaps of several hours. Satellite coverage varies with time of day and latitude. There are seven location classes provided by Argos (coded LC = 3, 2, 1, 0, A, B, Z). Argos estimates that 66% of locations from LC classes 3, 2, and 1 are accurate to <150, 150–350, and <1,000 m, respectively, LC = 0 > 1,000 m and LC = A and B are of unknown accuracy (Argos 2007). However, some researchers have found LC = A accuracy to be comparable to LC = 1 (Hays et al. 2001; Vincent et al. 2002).

Fig. 1 Attachment technique for SPOT tagged marlin. A PVC cloth tag sleeve with a SPOT tag glued into the side pocket was positioned high on a striped marlin tail. This tag has the braided metal antenna and a bolt positioned near the centre. Note: sleeves were painted with *black* antifouling prior to deployment

Displacement distances and mean displacement rates for each fish day over 24 h periods were calculated from LC = 1, 2 or 3 locations that were between 18 and 30 h apart. These distances were then standardized using the fraction of 24 h between the time at the two locations. Preference was given to start or finish locations that were of higher quality (LC = 2 or 3). The length of time tags remained operational is defined as the number of days between deployment and the last transmission received by the satellite.

Geolocation assessment

Transmitted data from six PAT tags and archival data from two recovered PAT tags attached to striped marlin concurrently carrying SPOT tags were used for geolocation accuracy assessments. Light level geolocations were estimated using the tag manufacturer's geolocation algorithm based on Hill and Braun (2001). Light level geolocation estimates and sea surface temperatures (SST) reported by the PAT tags were used as inputs into ukfsst, a Kalman filter developed by Lam et al. (2008). AVHRR-GAC 8-day composite SST data at $0.1° \times 0.1°$ spatial resolution were used for SST cross referencing within the model. The model's performance was tested using default parameter settings, except for SST bias estimation (bsst.active) which was deactivated. Geolocation estimates were paired with Argos locations from SPOT tags on the same day and the root mean squared (RMS) error was calculated for ukfsst geolocations, but excluding deployment and pop-off locations.

Results

Days of data and transmissions received

SPOT tags were attached to the caudal fins of striped marlin estimated to weigh 60–110 kg providing a total of 659 tracking days from 26 fish (Table 2). Tags remained operational for up to 101.6 days, with an overall mean of 25.3 ± 21.24 (SD) days per tag. A total of 1,524 locations of were calculated from transmissions received by Argos satellites with overall means of 58.6 ± 57.33 (SD) locations per tag and 2.31 ± 2.284 (SD) per day (Table 2). The mean straight line distance recorded across all SPOT tag tracks was 921 ± 264 km/fish and 32.2 ± 13.81 km/day.

The relative performance of tags from each year is summarised in Table 3. This table excludes the two SPOT tags that failed to transmit due to fish mortality shortly after release according to PAT records from these fish. The mean number of days that tags remained operational tags increased from 13.3 ± 11.05 days/tag in 2005 to 52.9 ± 31.67 days/tag in 2007. The number of locations received per operational tag increased from a mean of 58.7 ± 51.52 in 2005 to 118.4 ± 76.16 in 2007 (Table 3), largely as a function of longer deployment times. The mean number of locations per day declined over the same period (Table 3) as transmission rate was restricted to 200 per day in 2006 and 2007 in an effort to increase longevity of the track.

Locations with a known accuracy of ±1 km or better (LC = 1, 2, or 3) usually require four transmissions or

Table 2 Sizes of striped marlin estimated on capture, number of days SPOT tags remained operational, total transmissions made, locations received and straight line distances between release and final SPOT location

ID number	Year	Est. Wt (kg)	LJFL (cm)	Days of SPOT data	Number of transmissions	Number of locations	Mean locations/day	Total displacement (km)	Mean displacement/day (km)
STM05_01	2005	95		0	0	0	NA	NA	NA
STM05_02	2005	85		9.3	1,024	8	0.86	467	50.2
STM05_03	2005	100		18.7	6,656	57	3.05	893	47.7
STM05_04	2005	70		25.3	17,664	111	4.39	795	31.4
STM05_05	2005	90		0	0	0	NA	NA	NA
STM06_01	2006	74	236	25.2	6,400	122	4.84	327	13.0
STM06_02	2006	80	248	0.5	256	5	10	31	62.8
STM06_03	2006	80	248	20.6	8,704	145	7.04	312	15.1
STM06_04	2006	66	234	28.4	2,560	50	1.76	1,198	42.1
STM06_05	2006	110	250	21.2	3,584	58	2.74	927	43.8
STM06_06	2006	66	229	22.8	NA	61	2.68	642	28.2
STM06_07	2006	66	227	43.2	4,864	76	1.76	877	20.3
STM06_08	2006	65	218	28.2	2,816	20	0.71	1,287	45.6
STM06_09	2006	80	240	17.3	256	5	0.29	249	14.4
STM06_10	2006	75	234	35.8	1,536	23	0.64	781	21.8
STM06_11	2006	95	235	25.1	3,328	69	2.75	672	26.8
STM06_12	2006	80	232	16.5	1,024	16	0.97	414	25.1
STM06_13	2006	90	237	15.1	3,072	34	2.25	701	46.3
STM06_14	2006	80	228	26.3	4,608	64	2.44	1,025	39.0
STM06_15	2006	76	228	18.0	1,024	8	0.45	523	29.1
STM07_01	2007	85		101.6	9,216	208	2.05	4,959	48.8
STM07_02	2007	60		58.3	1,536	26	0.45	860	14.7
STM07_03	2007	75		50.5	7,168	175	3.47	1,564	31.0
STM07_04	2007	100		32.5	5,376	123	3.78	1,272	39.1
STM07_05	2007	80		18.4	3,072	60	3.27	419	22.8
STM07_06	2007	95		0	0	0	NA	NA	NA
Total				659	48,896	1,524		21,193	
Mean		81.5		25.3	3,830	58.6	2.31	921	32.2
SD		12.62		21.24	3,988.3	57.33	2.284	264.0	13.81

Est. Wt estimated weight, *LJFL* lower jaw fork length

Table 3 The number of locations received from SPOT tags by tag and season and the mean number of locations received per day

Year	Number of tags	Total locations	Min. locations/tag	Max. locations/tag	Mean locations/tag	SD	Mean locations/day	SD
2005	4	176	0	111	44.0	51.28	3.30	2.006
2006	15	756	5	145	50.4	41.82	2.20	2.684
2007	5	592	26	208	118.4	76.16	2.24	1.377
All	24	1,524	0	208	63.5	57.00	2.30	2.302

more during a single satellite pass. 38% (578) of locations estimated by Argos were coded LC $\geq$ 1. Most operational tags (61%) did not transmit at all during the first 2 days following release. Nineteen tags (79%) did not transmit a location of LC1 or better during the 48 h following release. In 2005, when up to 1,000 transmissions per day were allowed, locations were received on 86% of days while the tags remained operational. In all years some tags ended transmission abruptly while others gradually faded with gaps of several days between messages. All tags stopped transmitting before reaching the limit of their expected battery life.

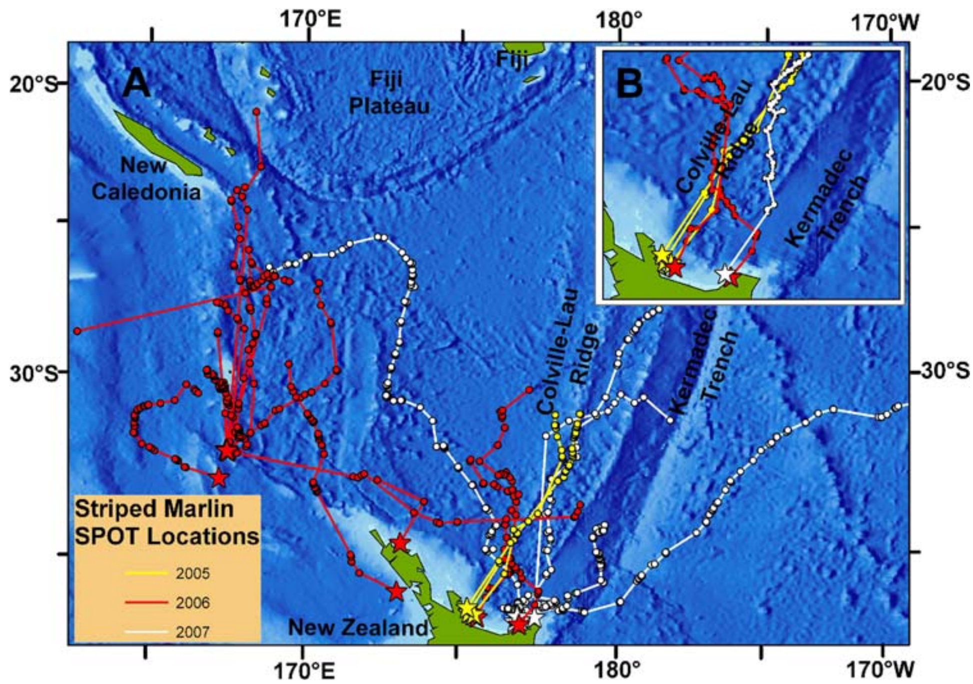

Fig. 2 **a** Distribution of SPOT tagged striped marlin released in New Zealand waters. Striped marlin SPOT tag data (*circles*) with known location quality (LC ≥ 1) during three consecutive seasons (2005–2007) in the southwest Pacific Ocean. Deployment locations (*star*). **b** Close-up of striped marlin movements along the Colville-Lau Ridge from the Bay of Plenty

Fish movements

The location data collected from these tags revealed detailed near real time movements of striped marlin around New Zealand of higher accuracy than had previously been obtained (Sippel et al. 2007). All marlin tagged on the New Zealand coast moved offshore following release, usually to the north or northeast (Fig. 2).

A trend of striped marlin moving away from tagging locations upon release was observed in all years. In 2005 three fish tagged over a 21 day period all moved from the Bay of Plenty onto the Colville-Lau Ridge. Two fish tagged in the Bay of Plenty 9 days and 125 km apart in 2006 moved onto the Colville Ridge for a few days and then moved north along similar tracks (Fig. 2b). Fish tagged offshore at the Wanganella Banks in the Tasman Sea mainly moved north, parallel with the Norfolk Ridge. One fish tagged in mid January 2006 moved 1,200 km to the southeast but did not enter New Zealand coastal waters. The five fish that provided tracks in 2007 were tagged over a 4 day period in the northeastern Bay of Plenty. They appear to have moved in different directions with only one fish confirmed to track along or parallel to the Colville Ridge. The longest distance recorded came from a fish that initially spent 14 days in an area about 40 km north of its tagging location. This fish then moved to the east before turning to the northeast and increasing speed, travelling a straight line distance of 4,597 km in the next 76.4 days (Fig. 3).

Displacement distance and rate

The maximum daily displacement rate observed, calculated from LC ≥ 1 locations, was 7.1 km/h for a total distance of 128.2 km in 18.0 h which extrapolates to 170.1 km over 24 h. This fish was estimated to be 227 cm (LJFL) so the maximum displacement equates to a mean of 0.87 body lengths per second. At the time this fish was moving between New Zealand and French Polynesia during April and was recording high daily displacement rates. Over a period of 20.6 days this fish moved 1,461 km at a mean rate of 70.9 km/day. The tag on this striped marlin provided the longest track in this study of 102 days, with a total displacement distance of 4,959 km and a total track distance from all locations received of 6,850 km (Fig. 3).

The distribution of daily (18–30 h) displacement distances from all fish adjusted to 24 h is plotted in Fig. 4. Most (74%) were between 10 and 69 km with a few over 120 km/day. The mean displacement over 24 h was 45 ± 27.6 km with a median distance of 40 km/day.

Assessment of geolocation model performance

Of the 347 days of ukfsst geolocations available from the double tagged marlin, a total of 84 geolocations were available for comparison with paired SPOT locations on the same day (Fig. 5). RMS error estimates of the difference between ukfsst latitude estimates and SPOT latitudes over the latitudinal range of 20–40°S during the months of January through June. When compared to all SPOT locations

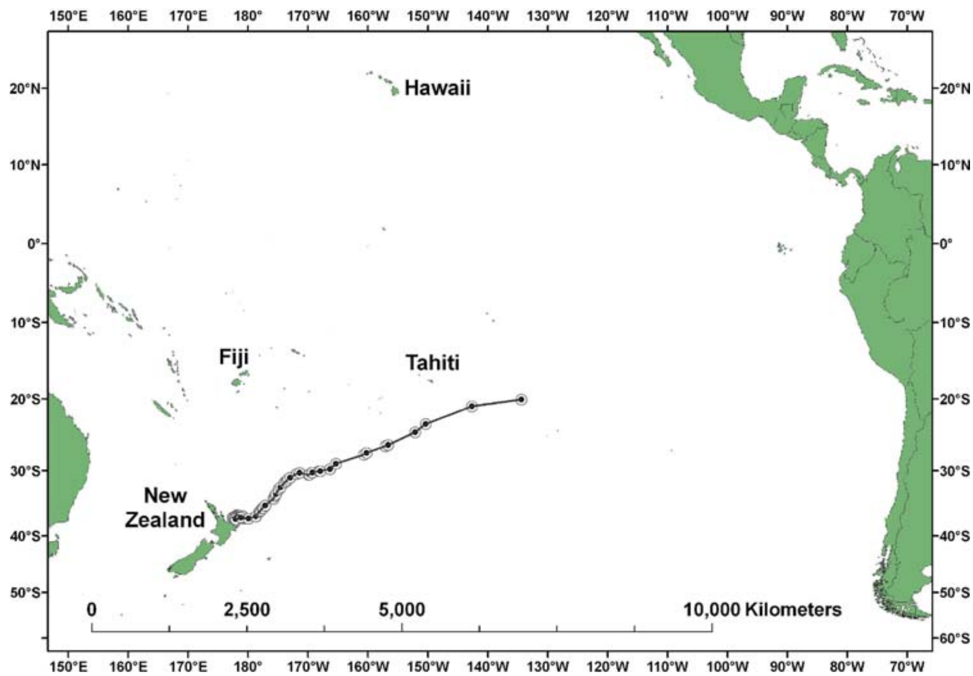

Fig. 3 Striped marlin SPOT tag data of 102 days duration recorded from a fish tagged in 2007

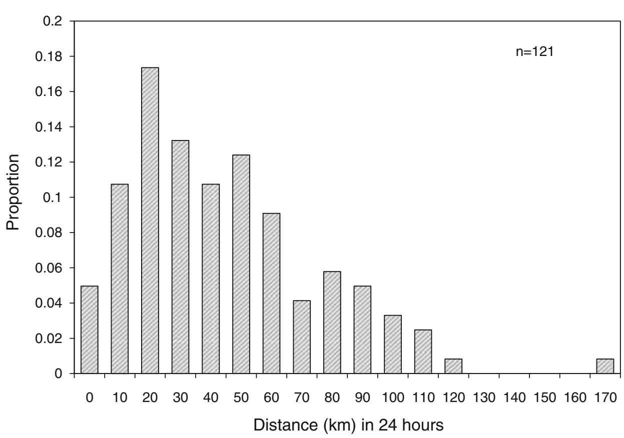

Fig. 4 Striped marlin 24 h displacement distances calculated from SPOT tag locations on consecutive days

RMS error was 1.01° latitude. RMS error was significantly less for latitude estimates from recovered PAT tag archival data were (0.560°) than from PAT tag transmitted data (1.25°). One transmitted dataset (light blue in Fig. 5) contributed a significant northerly bias (RMS 0.445°) to the overall error. This illustrates that while there is significant robustness in the geolocation algorithms as reported previously, geolocation biases occur. Likewise the RMS error for longitude from the ukfsst estimates was 0.588° when compared with SPOT locations on the same day.

Discussion

Striped marlin spend sufficient time cruising at the ocean's surface for SLRT to be a viable method of tracking their movements with high temporal and spatial resolution. The location data obtained from tail mounted SPOT satellite transmitters were of higher accuracy and precision than can be obtained using current methods of satellite tagging using estimation of position with light level and sea surface temperature based geolocation.

In all Istiophorids the caudal fin is a robust structure with strong bony fin rays allowing a secure tag attachment. The caudal fin is a high stress location for attachment of an electronic tag due to the continuous acceleration and deceleration associated with the tailbeat cycle. In 2005 we hypothesize that attachment failure reduced the operational life of the SPOT tags. Only 9 days of SPOT location data were received from STM05_02 but it the fish was recaptured by a surface longline vessel 32 days after transmission stopped. The crew returned the tether from the PAT tag but did not see anything attached to the tail of the fish, indicative of SPOT attachment failure. The introduction of the vinyl sleeve tail mount technique in 2006 and 2007 increased attachment lifespan significantly. Securing tags and sleeves to the tail with a bolt in 2006 did not result in additional transmission longevity compared to unbolted sleeves in 2007. An advantage of using only staples to fasten the sleeve is that they will eventually corrode; allowing the tag sleeve to be shed. In 2007 marlin were not removed from the water and the attachment took only about 60–90 s to complete, followed by fish revival time (1–3 min) and release.

In these experiments, we document an evolving series of tag attachment techniques and antenna configurations that we hypothesize improved strain relief issues. This in turn, enabled longer durations of successful tag attachment

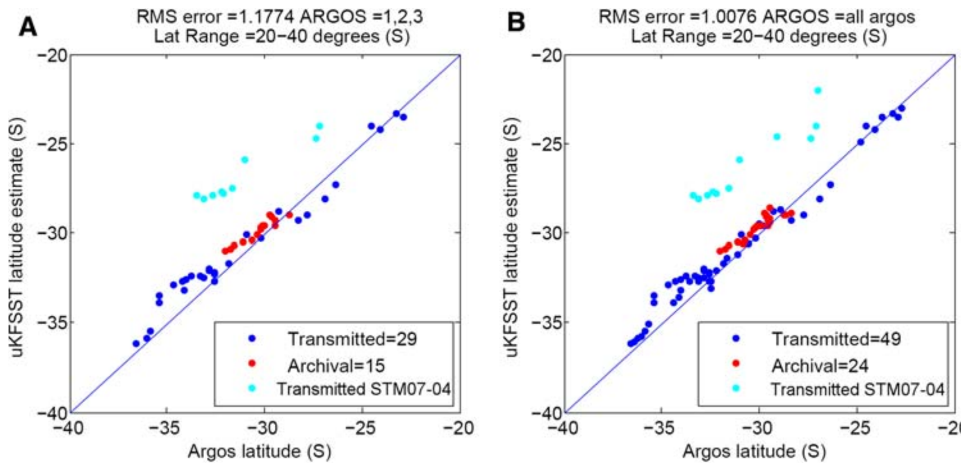

Fig. 5 RMS error estimates of ukfsst latitude estimates which paired with SPOT locations on the same day. **a** RMS error from ukfsst latitudes which paired with Argos SPOT locations of LC = 1, 2, or 3. **b** RMS error from latitudes which paired with any Argos SPOT location

strategies and increased transmissions in each successive deployment year. In addition, and perhaps most notably, the transition to flexible memory wire antennas used in 2007, also contributed we think to improving performance as this most likely allows for reversible deformations during accelerations and decelerations of the tail. Importantly, to date, the longest track was obtained from a tag with an antenna reinforced with a Tygon sleeve bonded with water proof cement at the base of the antenna and filled with silicon sealant which had cured for a year. Failure of the antenna due to biofouling or the constant stresses associated with the strain of the tailbeat cycle of the caudal attachment site may be a factor in reduced transmission longevity.

Twenty-two of the 26 marlin in the study were doubled tagged with SPOT and PAT tags. Three SPOT tags did not transmit at all, but PAT data provided additional insights into the behaviour and fate of these non-reporting fish. PAT data shows that the first striped marlin tagged in 2005 survived the tag and release event, and behaved similarly to others in this study. The SPOT tag probably did not transmit because the attachment failed immediately. Two additional fish died within 24 h of release according to transmitted PAT data. SPOT tag data also shows four fish with non-reporting PAT tags survived catch and release as their SPOT tags transmitted for 17–28 days suggesting some failure in the PAT performance.

A caudal fin mounted tag may have an effect on swimming performance and behaviour of the marlin carrying the tag. Given the size of marlin and the relatively stream lined shape and mass of the combined tag and sleeve (weight 62 g) the additional drag is not considered a significant burden for such large fish. The sleeve and tag may reduce the flexibility of the upper lobe of the caudal fin but also increases its surface area. Displacement rates for fish with caudal fin mounted SPOT tags are similar to those observed from fish carrying other tags. Average displacement rates for striped marlin double tagged with PAT and SPOT tags (32.2 ± 13.81 km/day) are similar to PAT tagged only striped marlin (22.2 ± 25.49 km/day, release to popup locations) (Sippel et al. 2007). The maximum displacement rates for individual fish are also similar (63 km/day this study, 65 km/day in 2003). A conventionally tagged striped marlin from New Zealand travelled 1,854 km in 33 days, or a displacement rate of 56 km/day (unpublished data held at the Ministry of Fisheries, Wellington, New Zealand). The SPOT tagged striped marlin showed modal displacement rates of 20–30 km/day. However, at times different behavioural modes with displacement at consistently higher rates of 50–120 km/day were recorded. These results do not suggest a significant negative effect of the SPOT tag on displacement rates.

Prior electronic tagging data indicates that there is often a recovery period required after a tagging event that can range from a 24 to 48 h following capture and tagging, to a week or more in the case of surgical implantation of tags (Block et al. 1992; Gunn and Block 2001). It took 2 days or longer for SPOT transmissions to be received from most striped marlin following tag and release which is comparable to the post-stress recovery periods seen with blue marlin carrying acoustic tags (Block et al. 1992). After this period, transmissions were usually received regularly, suggesting fish where at the surface long enough to reliably provide 3–10 high-quality locations (±1 km) each day.

The spatial and temporal resolution of location estimates from SPOT tagged striped marlin was generally sampled at a similar resolution or higher level to some remotely sensed environmental data products available such as sea surface temperature, sea surface height and chlorophyll concentrations. This match between position and environmental data allows confident assessments of habitat utilization for striped marlin when available. Furthermore, data of this quality are ideal inputs in behavioural switching models which provide a robust framework for estimating different behavioural modes (Jonsen et al. 2003, 2005, 2006). These SLRT tracks revealed some striped marlin moved from the

Colville and Kermadec Ridges as they left their Bay of Plenty release locations. Movements along these ridge systems by multiple fish over consecutive years indicates that part of this ridge system is an important movement corridor for striped marlin as they leave the Bay of Plenty (Fig. 2b). In this area there are a series of seamounts, some with peaks rising to within 250–500 m of the ocean's surface (Rowden et al. 2005). Similar associations to the Norfolk Ridge system (longitude ~167°E, latitude ~25–32°S) were also observed in 2006. It is unknown if striped marlin movements are associated to features of subsurface structure (i.e. bathymetry itself or geomagnetic fields), the current deformations or upwelling of water, or if these associations are indirectly related via foraging on prey which are themselves associated with subsurface features.

The assessment of PAT geolocations estimated by ukfsst demonstrates that light level geolocation when compared to SLRT generated positions via ARGOS are reasonable predictions from the current model data. Overall, ukfsst provides reliable geolocation estimates with confidence limits that correctly bounded the RMS error estimates shown here. These estimates provide useful guidelines for what spatial scales remotely sensed data products might be binned when investigating habitat selection with these data. Striped marlin are ideal subjects for geolocation comparisons with SLRT data, as they spend a high proportion of time near the surface, are often found at mid latitudes where satellite coverage is frequent. Striped marlin tagged in New Zealand also travelled long distances across a large latitudinal region with a relatively consistent temperature gradient. Marine animals with deeper depth preferences, or behaviours that make comparisons difficult (e.g. diving at sunrise and sunset) or animals that show associations to shallower SST gradients characteristic of low latitudes might not produce geolocations of comparable accuracy results.

Recent developments in fast acquisition GPS technologies have enabled even better geoposition estimates to be made from tagged animals using single satellite uplinks lasting less than a second. However, to date, the GPS tags are heavier and bulkier than SPOT tags used here and require a specific orientation when placed on an animal to assure quality satellite transmission. There are multiple trade-offs when considering which tagging technology is most appropriate for a given study. Many teleost species (and species from other groups) do not spend enough time at the ocean's surface for successful satellite uplinks to occur or are not anatomically amenable to certain tag attachments, meaning radio telemetry of any form is unlikely to be useful, leaving archival and acoustic technologies as the only suitable approaches for tracking movements. Continued experimentation with the satellite platforms coupled with miniaturization of the technology will assure that near real time tracking of marlin and other billfishes will expand in use as the tag size and technology facilitates more permanent attachments.

Acknowledgments We thank the trustees of the New Zealand Marine Research Foundation who initiated this research and provided primary funding for this study. The Tagging of Pacific Pelagics provided support for this study through grants from the Gordon and Betty Moore Foundation and the Packard Foundation. The New Zealand Big Game Fishing Council and many of their affiliated clubs have been consistent contributors. Professor P.S. Davie instigated satellite tagging of striped marlin in New Zealand and has been a mentor throughout. Enterprise Motor Group provided significant support to make the 2006 tagging possible. The contribution of the owners and captains of the primary tagging boats B. Marshall, F. Lewis, T. Francis, C. Fraser, and P. Saul is much appreciated. We thank P. Kim of Stanford University for assistance with the geolocation and satellite telemetry assessment. This research complies with the laws of New Zealand and has University of Auckland ethical approval, number AEC/11/2005/R43

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