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PROGRESS REPORT--MAY 1983 TO SEPTEMBER 1983

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Prepared for
Alaska Outer continental Shelf Program Office
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under
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BACKGROUND

A gray whale was tagged in February 1979 with a 148.6 MHz radio tag that used two subdermal attachments (Mate et al. 1983). The tagged whale was relocated 5 times by radio as it travel led over a 94 day period, from central Baja, Mexico, to Unimak Pass at the base of the Aleutian Islands, Alaska (at least 6,200 km). The same animal was subsequently observed 27 months after tagging with the tag still attached. The success of keeping a radio attached for such a long period initiated a feasibility assessment of tracking whales by satellite.

ARGOS is the only satellite system available to civilians to calculate locations of platform transmitter terminals (PTT's). The ARGOS system is administered by Service ARGOS, a branch of the French Centre National D' Etudes Spatiales (CNES) in cooperation with the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautic and Space Administration (NASA). ARGOS receivers are on board polar-orbiting, sun-synchronous NOAA weather satellites (currently NOAA 7 and NOAA 8). The system receives encoded data from special PTT's and, when certain criteria are met, can determine the PTT location by aria"lysis of the transmitter's doppler shift. For Service ARGOS to determine the PTT location, the satellite receiver must receive at least 5 signal:s from the PTT, at least 40 seconds apart and covering a period of at least 7 minutes during a single satellite orbit, or 3 signals on each of two consecutive orbits. The satellites pass over different geographic areas on each successive orbit. When the satellites are above the horizon, they are "in view" and able to receive a PTT signal for up to 15 minutes (depending upon the relative elevation and range of the satellite to the PTT). This occurs several times each day with more frequent coverage of northern latitudes. Thus, each satellite passes over a location at 20″N latitude 8 to 10 times each day and over 60″N latitude 14 to 16 times daily.

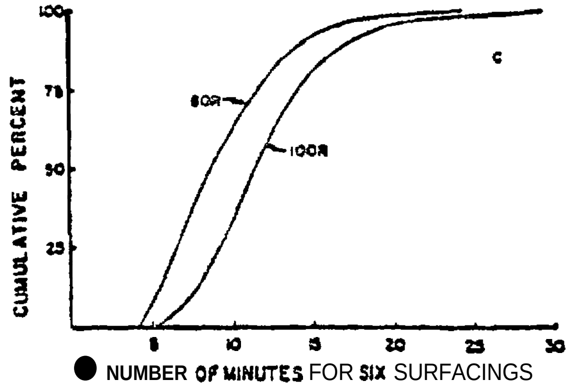
Surfacing patterns of gray whales (Mate et al. 1983), humpback whales (Goodyear, unpub. data) and bowhead whales (unpubl. data from D. Rugh, B. Krogman, B. Wuersig, M. Fraker, J. Richardson, and D. Ljungblad were analyzed by Mate and Harvey (1982). The probability of each whale species surfacing sufficiently to result in 5 or more messages to a satellite from an attached PTT during orbits of varying elevation and hence time in view was predicted (Fig. 1). These probabilities were compounded with the numbers and durations of orbits daily at various latitudes to predict the number of whale location determinations each day over the species range (Table. 1). These analyses predicted that location determination by satellite was feasible and would be most successful with humpback whales.

A collaborative effort in PTT design, construction, and implementation by the National Center for Atmospheric Research (NCAR), Oregon State University (OSU) and Telonics resulted in a satellite whale tag (SWT) built by Telonics (Mesa, AZ) and deployed by OSU on a humpback whale off the northeast coast of Newfoundland in July, 1983. This report provides an evaluation of the first data ever collected by satellite from a free-ranging cetacean.

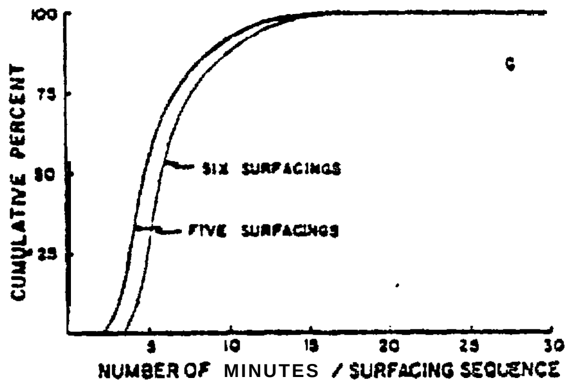
METHODS

The SWT was housed in an aluminum cylinder 14 cm in diameter, 7.6 cm long and weighing 3.52 kg. One end of the cylinder was attached to a flat

GRAY WHALES



HUMPBACK WHALE



BOWHEAD WHALES

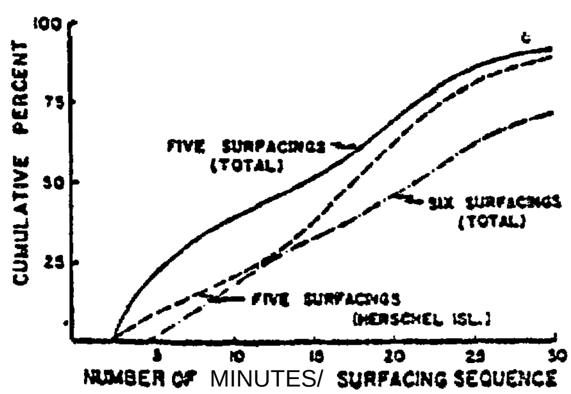


Figure 1." The probability of five and/or six sequential surfacings separated by at least 45 seconds from one another for gray whales, humpback whales and bowhead whales as calculated from data from Mate and Harvey, (unpub. data), Goodyear (unpub. data), Rugh, Fraker and Wursig, Richardson, and Krogman (unpub. data).

Table 1. A three-day sampling of satellite passes acheiving azimuths of >2.5° and >5.0° for various locations (° latitude), summarizing their average duration and the expected number of locations fixes for various species of whale likely per day.

Location	Date	Total Passes >2.5°	Total Passes >5.0°	Avg. Duration(min.) >2.5°	Avg. Duration(min.) >5.0°	Gray >2.5°	Gray >5.0°	Humpback >2.5°	Humpback >5.0°	Bowhead >2.5°	Bowhead >5.0°
Baja Calif.	7-8-82	8	8	11.4	10.8	3.65	3.24	7.14	6.96		
Sur--26.83°N	7-9-82	9	8	10.3	10.2	3.83	2.81	7.17	6.69		
113.17°W	7-10-82	10	10	10.0	7.7	3.31	2.25	7.64	5.80		
Newport, OR	7-8-82	12	10	10.3	9.9	4.84	3.23	9.13	8.21		
44.62°N	7-9-82	12	11	10.4	9.3	4.62	3.17	9.45	8.02		
124.04°W	7-10-82	12	11	10.6	9.4	4.88	3.41	9.39	8.30		
Newfoundland	7-8-82	15	15	9.8	9.3			11.10	9.54		
47.00°N	7-9-82	14	14	9.6	7.8			9.91	8.94		
53.00° W	7-10-82	13	13	9.8	8.7			9.98	8.94		
St. Matthews	7-8-82	20	19	10.4	9.0	7.73	4.99	16.35	13.07	3.46	2.30
Isl. 60°N	7-9-82	21	21	10.7	8.8	8.13	5.38	17.51	14.05	3.65	2.06
173°W	7-10-82	20	20	10.4	8.7	7.27	5.18	16.3	12.85	3.35	2.14
Tuktoyaktuk	7-8-82	23	21	11.2	10.5					4.54	3.20
70°N	7-9-82	24	23	11.2	9.9					4.82	3.35
133°W	7-10-82	23	22	11.3	10.2					4.68	3.39

30 mm thick stainless steel base plate 29 cm long, and 14.5 cm wide, which tapered at each end (Figure 2). The other end of the SWT's cylindrical housing was capped with a lid using an O-ring seal. A truncated helix antenna (8.9 cm in height and 63 mm in diameter) was mounted on the lid, as was a saltwater switch contact electrically isolated from the lid by an O-ring sealed electrical feed-through and stiffened by a machined Delrin cone which also promoted water drainage. The top of the entire lid was cast in high density orange polyurethane at an angle to facilitate water run off and provide mechanical rigidity to the base of the otherwise flexible antenna.

A 4.5 m Zodiac inflatable boat, equipped with a special mast and boom to counter-balance the application equipment, was used to approach whales. The tag in its applicator was suspended at the end of a 4.8 m fiberglass pole supported at its center by a rope from the boom of the boat which was counter-balanced by a movable weight inside the mast.

Six slots in a circular pattern were cut into each end of the base plate through which umbrella anchors fastened the tag to the whale’s back (Mate and Harvey, 1982). An umbrella anchor consisted of a piston with six curved wire tynes. When these tynes penetrate the whale’s skin, they spread out laterally. The anchors were applied by a specially designed applicator using electrically actuated pressure cartridges (Holex model 6300 or 6301).

Because whales are usually at the surface for just a few seconds, the SWT transmitted twice during a single surfacing. A different identification (ID) code was used for each of the two transmissions to avoid difficulties with the Service ARGOS requirements demanding

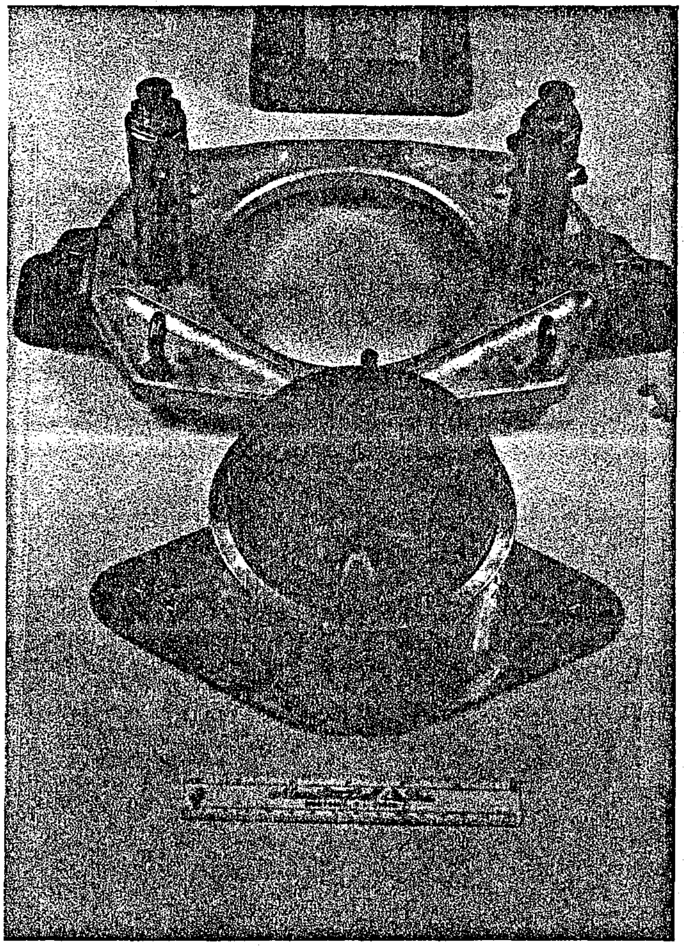


FIGURE 2.. Telonics satellite whale tag (foreground) with salt water switch (forward) and truncated helix antenna (rear) of colored polyurethane top. Deployment module is shown in the background.

separation of at least 45 seconds between transmissions of the same code. Two sensors were utilized in the SWT: one for transmitter temperature to perform frequency calibration and drift experiments (to be reported at a later date), and a second to measure dive duration. The latter measured the time from immersion of the saltwater switch to surfacing by interrogating the saltwater switch every 80 ms to determine the resistance between the electrically isolated probe in the SWT's lid and its metal case.

The typical dive and transmission cycle was thus: submergence of the whale resulted in saltwater switch closure and initiated the clock measuring the dive; upon surfacing the clock stopped; after a brief delay, an undulated carrier was transmitted followed by the first ID code, temperature and dive duration data from the dive prior to the most recent dive; a 500 ms pause, unmodulated carrier, second ID code, current temperature and dive data from most recent dive. Two ID codes were used because we were not sure whether water would drain from the antenna fast enough for a good first transmission, and a short surfacing might result in the antenna being underwater before completion of the second transmission. Thus, if both ID codes were received by the satellite during a single surfacing, data from two dives would be obtained. A comparison of both ID codes was used to determine the frequency of undetected surfacings.

The ARGOS receiver stores data during its orbits and periodically transmits the data to ground stations for forwarding to Service ARGOS in Toulouse, France. Service ARGOS attempts to determine locations using doppler data. Updated locations and the last data received by Service

ARGOS are made available to users by interrogating a computer in Suitland, MD referred to as the NOAA/NESDIS (National Environmental Satellite Department of Information Services) concentrator. A full printout of all data was made available once a month from Service ARGOS with approximately a 6 week delay.

R. Kutz, C. Hoisington, and S. McBroom, NASA, monitored the NASA local user terminal (LUT): 1) during terrestrial tests when the satellite was in mutual view of the SWT in Oregon or Arizona and their LUT in Greenbelt, MD (necessarily orbits with <15° elevation due to the long distances involved), and 2) to provide some back-up data collection during the Newfoundland experiment, as the satellites were in mutual view of the NASA facility and the whale tagging area during a portion of many orbits. They also calculated locations during some orbits when the acquired data did not meet Service ARGOS requirements (see Appendix).

Terrestrial tests of the SWT to determine location accuracy occurred fromSan Ignacio Lagoon, Baja Mexico (27°N) to Pt. Barrow, Alaska (72°N). Simulated diving and surfacing sequences were carried out in a seawater holding pond at the OSU Marine Science Center, Newport, Oregon (44°N).

Field studies were conducted in Newfoundland, Canada during June and July, 1983. Humpback whales have become entangled in gillnets and cod-trap nets during summer months along the Newfoundland coast for many years (Lien and Merdsoy, 1979; Perkins and Beamish, 1979). We chose to work in Newfoundland because we could get close to these live whales and radio tag them during the process of their release. We worked with the Whale Research Group at Memorial University of Newfoundland and Ceta-Research to obtain such opportunities.

Operation of the SWT was confirmed on 27 June through both the concentrator and NASA/Goddard. During the next 5 weeks, only one logistitally feasible opportunity to work on a live humpback was obtained. On the morning of 14 July, a young humpback whale approximately 9.7 m long became entangled in a gillnet 1.1 km northwest of Cape Bonavista (48° 707'N, 53°095'W) in water 12 m deep. We arrived just before dusk and examined the animal with Peter Beamish. We found the whale in good health. Our operations began at sunrise (0600) the next morning. The whale was entangled by the 1.3 cm diameter polypropylene head rope of a well-anchored gill net. The rope passed through the baleen and formed a bridle limiting the animal's movements to a circle of approximately 15 m radius.

The tagging boat, manned by Bruce Mate and Mary Lou Mate, was tied on to the headrope approximately 10 m from the whale. Attempts to tag were limited to times when the whale surfaced near the boat. A second 4.5m inflatable boat manned by Beamish and Tom Goodwin was tied to the tagging boat approximately 5m farther from the whale as a safety backup. Seas reflected Beaufort 4 winds with swells of 1.0 to 1.5 m. The sea state made it difficult to coordinate movements of the whale, its surfacing, proper positioning of the boat and handling the tagging pole. As a result, it took 3 hours to apply the SWT. Throughout the pre-tagging, tagging, and post-tagging periods, Beamish made hydrophore recordings of the entrapped humpback's numerous underwater vocalizations.

The SWT was attached 1.5 meters behind the whale's blowhole along the mid-dorsal line (Figure 3). Poor performance of the usually dependable Holex pressure cartridges resulted in incomplete deployment of the

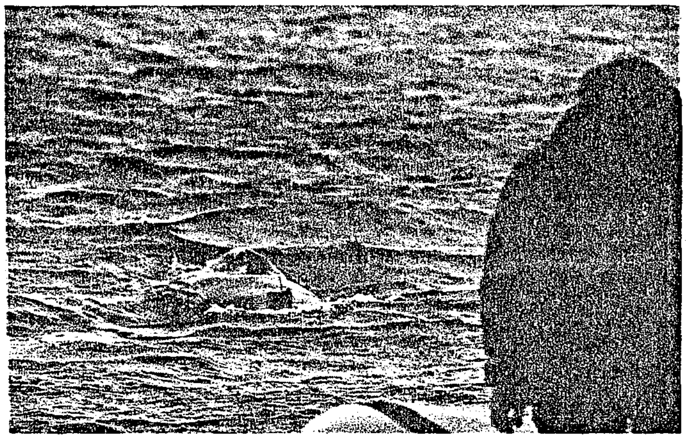


FIGURE 3. A humpback whale tagged with a Telonics SkIT.

subdermal umbrella anchors. The audible report of the cartridge firing was noticeably weak. The power of the Holex cartridges was so reduced from normal that the piston body of the umbrella anchor did not hit the transmitter base plate sufficiently hard to break one of the two nylon screws holding it to the applicator. Fortunately, the humpback whale had no visible reaction to the tagging process and stayed at the surface where the nylon screw was ultimately cut with a knife. Mate and Harvey (1981) previously estimated that 70% of the holding power of these attachments was generated in the last 30% of their deployment, during which the tynes are spread laterally (bending at their insertion into the piston body). As the attachments failed to deploy the last 30%, they probably only developed 30% of their potential holding power. Further, the loose attachment allowed the transmitter to wobble, thus subjecting it to considerably more hydrodynamic drag than a fully deployed tag.

During 1980, a female gray whale with an incompletely attached umbrella radio tag lost its tag after 12 days during which it spent most of its time with it's calf in a shallow Mexican lagoon (Mate and Harvey, op.cit.). We were concerned how long the loosely attached tag might stay on the humpback whale. Removal of the tag was contemplated. However, concern for the whale's reaction, its possible further entanglement, and the safety of the tagging crew precluded such attempts.

A conventional umbrella radio tag (148.6 MHz) with a one meter long white streamer was applied 38 minutes after the SWT and deployed completely. The sound from the pressure cartridges was normal and there was no visible reaction from the whale. The transmitter's power output was less than 10 mwatts and limited to line of sight reception. It's function was confirmed by a cliff-based monitoring crew using a Telonics TR-2 receiver with a 2-element hand-held Yagi antenna. Goodwin took underwater photographs for 20 minutes prior to cutting the headrope "bridle" in two places approximately4m from the mouth, which did not release the entrapped whale. Beamish and Goodwin, using surface techniques, were then able to cut the headrope approximately 3 m from the other side of the . . . . mouth, which released the entrapped whale. Twenty minutes later, they were able to pull the remaining rope out of the freed whale's mouth.

RESULTS

Service ARGOS only guarantees locations from certified platforms to be within 7 km. In terrestrial trials Service ARGOS located the SWT within 7 km consistently, usually within 1.5 km, and often less than 1 km in temperatures varying from 25° to -8°C. The saltwater simulation dive sequences demonstrated good surface sensing by the saltwater switch and accurately measured temperatures and dive durations.

Tests were conducted in a saltwater pond to determine the reliability of data collection and location in a saltwater environment. In one such experiment the SWT was brought to the surface once every minute throughout the pass (Table 2). The test demonstrated consistent data gathering capability (dive times and temperatures) but did not always result in a location determination. When achieved, locations were within a 1 km radius of the actual experiment site. Orbits of 21°, 23°, and 41° elevation resulted in a calculated location of the SWT, while a pass of 44° did not. The latter pass resulted in 7 messages but they were not all acceptable to Service ARGOS so there was no location determination made. It was not surprising that low passes did not always result in location determinations, as our saltwater test facility had obstructions as high as 10° in some quadrants. The SWT's performance was deemed sufficient to warrant a live whale experiment.

During pre-application tests, there were times when we were not able to get new information from the NESDIS/Suitland concentrator, despite apparently proper transmitter function. This difficulty caused considerable delay until we confirmed the operation of the SWT with the

TABLE 2. “ARGOS summary data for 29-30 May, 1983.

DAY	TIME	NOAA SATELLITE	MAX. PASS ELEVATION	LOCATION	DATA
5/29	5:54	7	410	x	x
5/29	8:27	6	210	X	X
5/29	14:00	7	12°		x
5/29	19:42	6	440		x
5/29	21:26	6	23°	x	x
5/30	11:21	6	14°		x

(LUT) at NASA/Goddard.

Following the double tagging of the humpback whale off Cape Bonavista at approximately 10:00, the 148.6 MHz transmitter was monitored intermittently from the cliff until 16:45 when only weak signals could still be heard. The first two satellite orbits following application apparently did not receive messages from the SWT, however an orbit at 17:21 did result in new data. Table 3 summarizes the print out data we obtained from Service ARGOS and the subsequent calculated locations. Data were acquired for 144 hours and it is likely that the loose tag attachment allowed the tag to fall off after that time.

Figure 4 shows the distribution of the 72 satellite orbits (>5°) from the time of tagging to the last orbit with data. We obtained new data from 59 orbits (82%), containing 121 complete messages. Fifty-four messages from 40 orbits (56%) were documented during aperiodic interrogations of the Suitland concentrator. The concentrator only maintains a record of the most recent data. Thus, if data were not documented by interrogation of the concentrator before new information replaced it, we had no record of it until the complete data printout came from Service ARGOS. The concentrator did not show any new data for a 33 hour period (apparently due to technical problems at Service ARGOS) beginning on the afternoon of 20 July. Except for this period of difficulty, our interrogation of the concentrator showed 50 to 83% of all passes >5° obtained new data each day (for an overall average of 62%). Some data for 21 July became available after the concentrator service was restored. Orbits acquiring new data varied in pass height from 4° to 87°, while those without new data varied from 7° to 57°.

A complete transmission sequence included two ID codes and

TABLE 3. ARGOS satellite collected data on a humpback whale radio-tagged on 15 July, 1983 at Cape Bonavista, Newfoundland, Canada (48° 707'N, 53° 095'W). Satellite-elevation is divided into the maximum (MAX.) and the elevation at acquisition (AQUIS.). Arrows indicate ascending "or descending aspect of-the--satellite.

ID	JULIAN DAY	ZULU TIME	NFLD. TIME	TEMP. °C	DIVE TIME (MIN.)	SAT. ELEV. MAX/AQUIS.	SAT . NOAA # LOCATION	SIGNAL
842	196	1756	1526	10.91	1.68	84°/<5°↑	7 °	-140.0
842	196	1758	1528	10.84	2.83	84°/ 7°↑	48. °718 N	-134.6
843 ∞	196	1758	1528	10.98	2.22	84°/ 7°↑	52. 984°W	-136.4
842	196	1806	1536	10.80	1.39	84°/60°↓		-131.0
842	196	1940	1710	10.29	1.87	14°/<5°↑	7	-138.0
842	196	1941	1711	9.76	4.46	14°/<7°↑	48 .801°N	-139.1
843	196	1941	1711	9.35	11.95*	14°/<7°↑	53 .234°W	-138.4
842	196	1943	1713	9.35	1.31	14°/ 9°↑		-135.9
843	196	1943	1713	8.99	2.21	14"/ 9°↑		-137.5
843	196	1944	1714	8.87	0.95	14°/12°↑		-138.2
		inferred	dive(s)		2.05			
842	196	1946	1716	8.87	0.95	14°/140		-132.4
843	196	1948	1718	8.75	1.40	14°/12°↓		-135.1
843 h	196	1953	1723	9.15	3.51	7°/ 7°	8	-137.3
843	196	1955	1725	8.93	1..82	7°/ 5°		-136.8
843"	196	2133	1903	10.30	1.45	38°/380	**8	-- .
		inferred	dive(s)		4.04			
842	196	2137	1907	10.30	1.45	38°/14°↓		
842	196	23?1	2041	11.5	2.1	35°/27°↓	**8	
843	196	2311	2041	9.9	6.04	35°/27°↓		
843	197 "	0618	0348	11.86	7.17	31°/14°↑	7	-129.2.
		inferred	dive(s)		3.75			
842	197	0622	0352	11.86	7.17	31°/310		-132.9
√843 ∞	197	0758	0528	-37.9*	5.07	46°/11°↑	7	-132.1
842	197	0803	0533	4.30	2.30	46°/460		-135.7
√842	197	0939	0709	9.24	1.74	10°/ 6°↑	7	-137.3
842	197	1119	0849	9.96	4.27	69°/12°↑	8	-139.6
√842	197	1125	0855	10.25	1.95	69°/560	48.687°N	134.1
843	197	1125	0855	9.67	6.27	69°/560	51.948%!	.130.1
843	197	1301	1031	8.96	2.32	24°/15°↑	8	-133.9
843	197	1303	1033	9.43	1.86	24°/230	48.780°N	-135.5
√843	197	1306	1036	10.04	3.29	24°/19°↓	52.543°14	-137.0
843	197	1609	1339	9.34	6.30	16°/11°↑	7	-136.0
√843	197	1755	1525	9.50	3.22	79°/28°↑	7	-138.4
4843	197	1933	1703	8.66	1.91	18°/17°↑	7	-138.0
√843	197	2113	1843	10.77	5.69	26°/18°↓	8	-133.6
843	197	0607	0337	11.63	4.54	25°/20°↑	7	-135.1
843	197	0671	0341	11.52	4.63	25°/21°↓		-132.4
843	197	0748	0518	10.48	5.05	57°/37°↑	7	-135.9
√842	198	0920	0650	10.68	4.44	5°/ 4°↓	8	-136.6
843	198	0920	0650	11.24	4.59	5°/ 4°↓		-138.9
√843	198	1102	0832	9.62	7.24	42°/38°↓	8	-.133.6
4842	198	1242	1012	9.86	4.22	34°/ 3°↑	8	-136.0
√843	198	1242	1012	9.12	9.04	34°/ 3°↑		-131.8
843	198	1554	1324	7.81	8.19	13°/<5°↑	7	-138.9
4842	198	1735	1505	9.11	3.56	64°/12°↑	7	-132.7
√843	198	1740	1510	7.71	4.93	64°/640		-134.4
√843	198	1918	1648	10..06	4.39	22°/15°↑	7	-133,.3

ID	JULIAN DAY	ZULU TIME	NFLD. TIME	TEMP. 'C	DIVE TIME (MIN.)	SAT. ELEV. MAX/AQUIS.	SAT. NOAA # LOCATION	SIGNAL
842	198	2048	1818	4.40	7.10	18°/18°↑	8	-130.6
843	198	2048	1818	5.52	5.77	18°/18°↑	47.989°N	-135.5
√842	198	2051	1821	5.52	5.77	18°/15°↓	51.054°W	-136.4
√843	198	2051	1821	6.52	2.71	18°/15°↓		-137.9
842	198	2223	1953	7.66	5.85	85°/12 ↑	8	-135.6
√843	198	2223	1953	8.40	53.68*	85°/12°↑		-136.0
		inferred dive(s)			3.04			
√842	198	2226	1956	8.40	4.87	85°/12°↑		-130.5
√843	199	0005	2135	6.87	1.98	13°/ 6°↑	8	-140.0
843	199	0008	2138	7.38	1.98	13°/13°↓	47.785°N	-138.2
		inferred dive(s)			1.26		50.538°W	
842	199	0009	2139	7.38	1.98	13°/13°↓	(LUT)▽	-137.9
√842	199	0011	2141	7.57	.96	13°/11°↓		-138.9
843	199	0011	2141	7.81	1.25	13°/11°↓		-138.3
843	199	0012	2142	8.09	1.40	13°/ 9°↓		-136.0
843	199	0551	0321	11.76	9.34	20°/<4°↑	7	-137.5
843	199	0738	0508	8.85	8.54	71°/710	7	-132.8
√843	199	0740	0510	8.81	2.38	71°/41°↓		-133.8
843	199	0917	0647	5.27	7.57	14°/140	7	-137.1
√843	199	0918	0648	4.97	.98	14°/140		-137.3
842	199	1045	0815	4.10	9.90	29°/13°↓	8	-133.0
√842 a	199	1048	0818	4.01	.86	29°/<4°↓		-137.6
√843	199	1224	0954	-1.92	74. 49*	48°/24°↓	8	-131.2
843	199	1228	0958	5.66	30.98*	48°/<4°↓		-139.8
√842	199	1550	1320	9.39	5.53	11°/10°↓	7	-136.9
842	199	1719	1449	9.24	.90	52°/<4°↑	7	-137.6
842	199	1723	1453	7.94	8.63	52°/12°↑	47.163 'N	-130.0
√842	199	1730	1500	9.02	4.80	52°/34°↓	50.533 °W	-140.0
√843	199	1730	1500	10.22	6.16	52°/34°↓		-139.7
√842	199	1909	1639	11.32	.85	27°/270	7	-137.6
√84 3	199	2025	1755	6.69	10.45	13°/ 9°↑	8	-133.4
4842	199	2203	1933	10.93	.71	66°/18°↑	8	-132.3
4843	199	2203	1933	7.93	9.97	66°/18°↑		-132.3
842	200	0540	0310	12.71	14.67	16°/ 5°↑	7	-135.2
842 b	200	0543	0313	9.49	9.59	16°/14°↑		-134.8
843	200	0722	0452	7.43	8.27	86°/20°↑	7	-137.1
		inferred dive(s)			3.26			
842	200	0725	0455	7.43	8.34	86°/61°↑		-133.6
843	200	1018	0748	11.12	3.03	1°/18°↑	8	-139.7
842 c	200	1019	0749	11.12	5.68	19°/190		-130.5
842	200	1156	0926	12.25	3.48	71°/27°↑	8	-133.6
842 d	200	1205	0935	10.54	0.91	71°/ 7°↓		-138.3
843	200	1340	1110	8.10	10.12	14°/13°↓	8	-137.9
843 ∞	200	1849	1619	10.00	9.24	34°/<4°↑	7	-136.5
842	200	1855	1625	11.11	4.59	34°/260+	46.084°N LUT▽	-133.4
843	200	1855	1625	11.39	0.83	34°/26°↑	51.127°W	-132.5
842	200	2006	1736	3.91	9.41	9°/ 9°↑	8	-134.8
842	200	2142	1912	11.52	3.62	45°/23°↑	8	-131.5
843	200	2328	2058	8.74	8.30	30°/18°↓	8	-139.3

ID		JULIAN DAY	ZULU TIME	NFLD. TIME	TEMP. 'C	DIVE TIME (MIN.)	SAT. ELEV. MAX/AQUIS.	SAT. NOAA # LOCATION	SIGNAL
843		201	0533	0303	16.31	2.92	13°/12°↓	7	-135.0
842		201	0707	0437	13.29	5.30	77°/<4°↑	45.847 °N	-138.2
√842		201	0708	0438	14.63	7.50	77°/ 8°↑	..52,341 °W	-138.3
843	e	201	0708	0438	14.75	0.88	77°/ 8°↑		-137.1
√843		201	0717	0447	13.65	0.95	77°/29°↓		-137.8
√S42		207	0851	0621	12.03	3.37	21°/14°↑	7	-135.0
843		201	0851	0621	13.19	59.16*	21°/14°↑		-135.0
√843		201	0852	0622	13.42	.91	21°/17°↑		-133.4
843		201	1139	0909	11..83	8.24	80°/61°↓	8	-137.9
√842		201	1143	0913	11.83	8.24	80°/12°↓	'45.078 °N	-135.5
√843		201	1143	0913	12.44	3.60	80°/12°↓	53.406 °W	-135.3
842		201	1318	1048	9.51	1.12	20°/19°↓	8	-137.8
842	f	201	1322	1052	8.99	8.68	20°/ 6°↓		-136.2
842		201	1659	1429	13.26	3.43	35°/10°↑	7	-133.7
843		201	1703	1433	11.34	3.39	35°/32°↑		-135.3
842		201	1836	1606	13.53	1.03	42°/<4°↑	7	-134.7
842	g	201	1837	1607	8.62	8.72	42°/<4°↑		-134.3
842		201	1947	1717	6.51	2.99	6°/ 4°↓	8	-139.4
842		201	2025	1755	6.15	1.27	<4°/<4°	7	-138.3
'842		201	2127	1857	8.99	0.93	32°/18°↓	8	-132.4
842	.	201	2128	1858	8.14	10.01	32°/13°↓		-133.9
842	"'	201	2129	1859	8.40	1.15	32°/ 9°↓		-136.6
843		201	2129	1859	9.02	1.25	32°/ 9°↓		-137.6
843		201	2300	2030	11.18	.89	45°/16°↑	8	-134.3
842		202	0522	0252	17.46	3.68	9°/ 8°↓	7	-139.2
843		202	0701	0431	12.91	20.55*	62°/53°↑	7	-137.1
			inferred	dive(s)		3.67			
√842		202	0705	0435	12.91	9.63	62°/28°↓		-138.8
843		202	0837	0607	16.50	2.34	25°/ 8°↑	7	-137.6
4843		202	1116	0846	11.76	10.85	54°/540	8	-135.7
4843		202	1256	1026	11.28	11.30	27°/270	8	-138.4

* Encoding, transmission, or processing error
** Data available from concentrator only
√ Data available on concentrator
∞ One or more surfacings without message
a Inferred "dive(s) lasting ≤ 3.24 min.
b " " " 3.51 min.
c " " " 1.01 min.
d " " " 9.72 min.
e " " " 8.31 min.
f " " " 4.07 min.
g " " " 1.00 min.
h " " " 0.83 min.
v LUT = Local User Terminal,

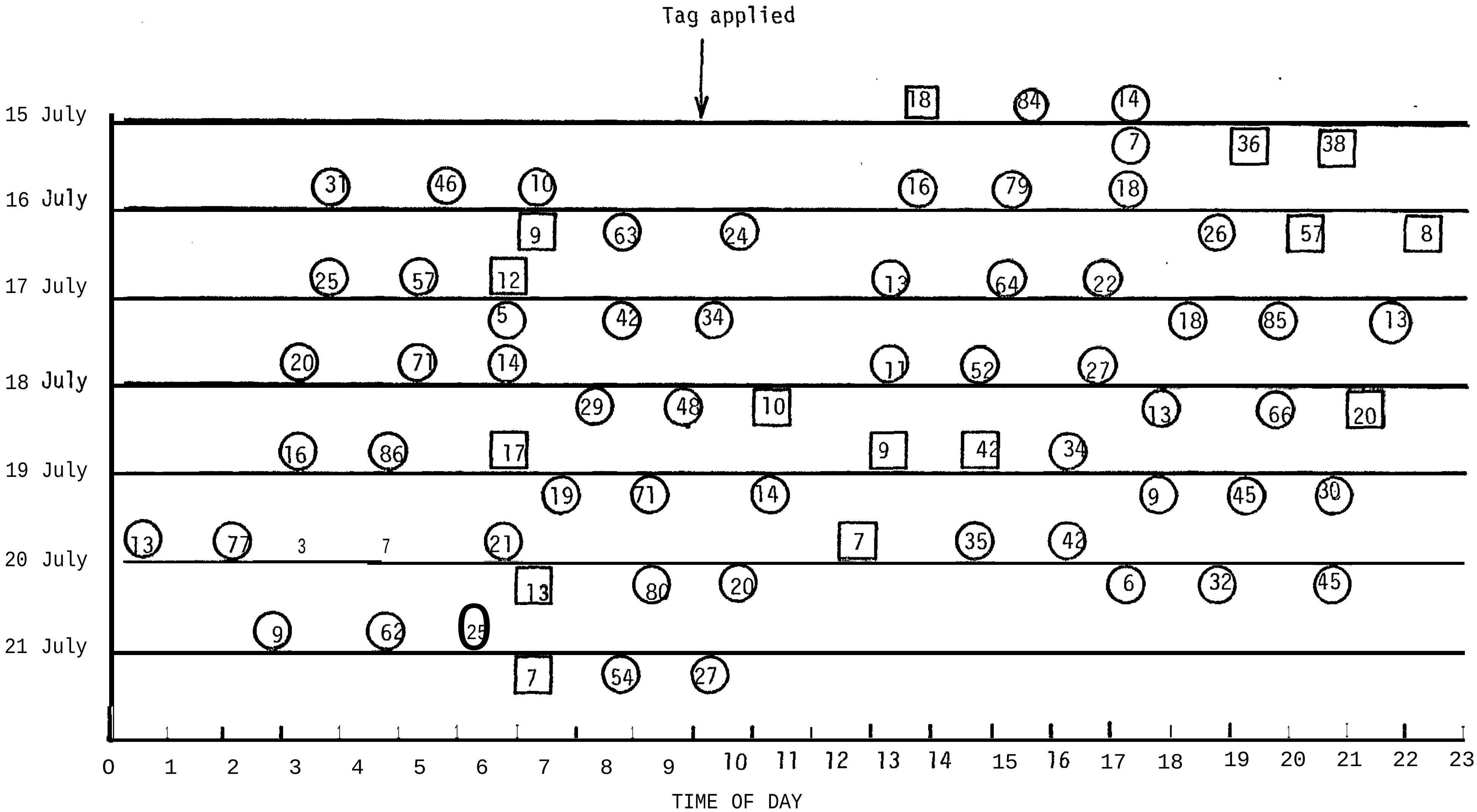
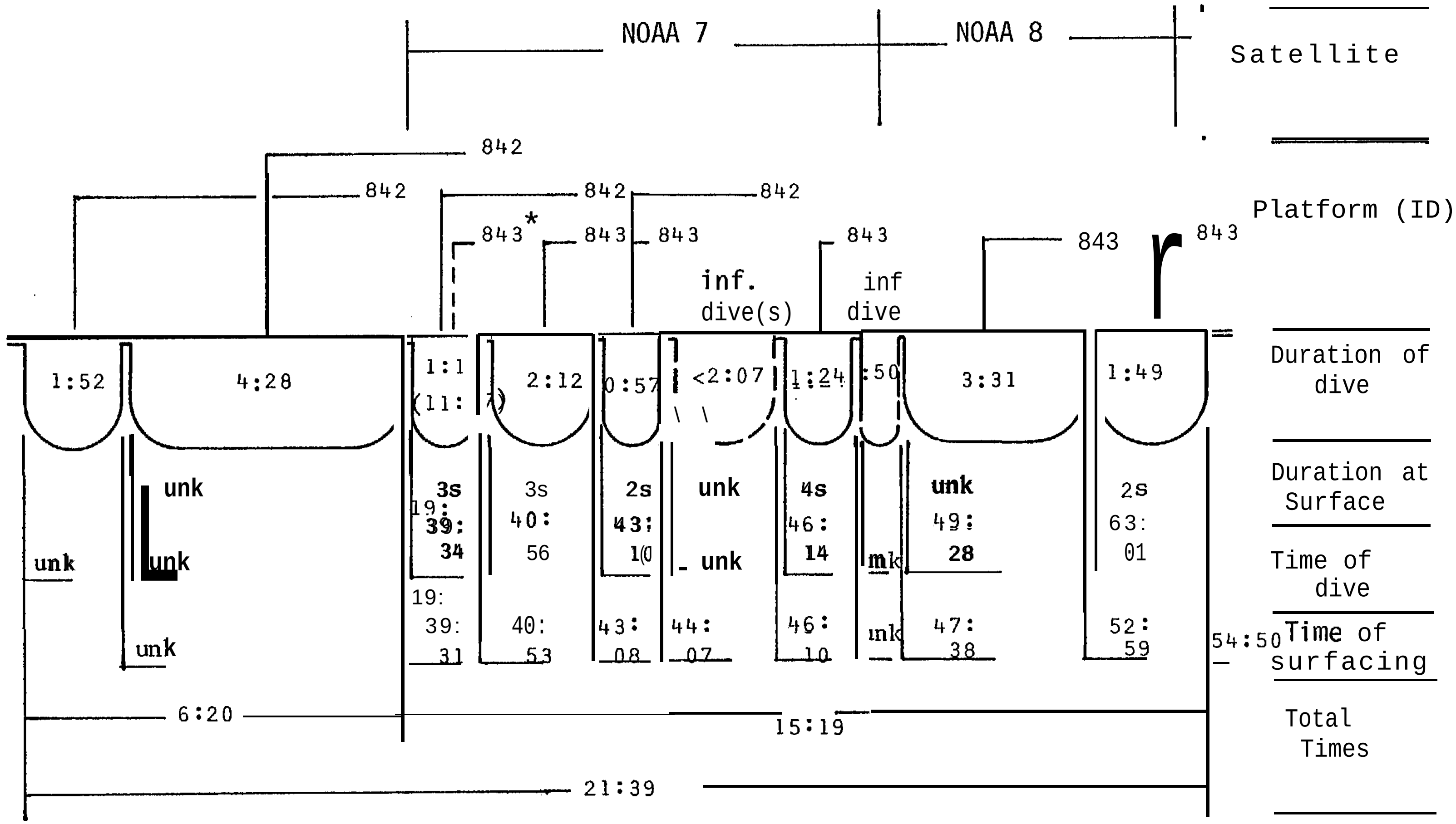


FIGURE 4. A summarization of orbits >5° throughout the 6 day experimental period. Circles depict orbits successfully acquiring new data? . . . . squares-indicate orbits without new data. Numbers indicate satellite maximum elevation. NOAA 7 (above line) and NOAA 8 (below line). ",'

information for two dives. An example of this can be seen for the surfacing at 196/1758 (Table 3). The first ID (842) indicated the dive before the most recent dive was 2.83 minutes in duration and the transmitter temperature then was 10.84″C. The second ID (843) shows that the most recent dive was 2.22 minutes in duration, and the temperature had risen to 10.98″C. The sequence of received data also allows some dives to be inferred such as from the surfacings at 197/0618 and 197/0622. In this instance the dive data associated with ID 843 at 197/0618 was for the most recent dive and the dive associated with ID 842 at 197/0622 was a repeat of that dive data, assuring that there were no intervening surfacings and that the time in between these transmissions represented a dive for which there was no recorded data. Thus, 8 interpreted dives have been added to Table 3.

Figure 5 illustrates the interpretation of signals from 196/1940 to 196/1955. This sequence of surfacings is actually the result of two satellites whose orbits nearly overlapped. The first 6 messages were received by NOAA 7 and the last two were received by NOAA 8. The 8 messages represent 8 separate surfacings which define at least 7 dives. Two additional dives prior to the first surfacing (1940) were identified by ID code 842 on the first and second surfacings (1940 and 1941). Two different values for the duration of the third dive were encoded in transmission from ID code 843 at 1941, and ID code 842 at 1943. The latter value of 1.31 min. was confirmed by subtracting the time of surfacing at 1940 from the 1941 surfacing. Note-that the dive time of the fifth dive was confirmed by both ID codes although from separate surfacings (1944 and 1946). However, the time between those two surfacings represents one or more dives lasting a total of 2.07 min. and was not defined any other way.



* Probable data error in this record as dive time for platform 843 = 11:57, while 842 = 1:19. The latter matches the time of surfacing and diving.

FIGURE 5. An example of whale diving and surfacing deduced from ARGOS satellite data. Data from two ID codes are shown. Some dives are inferred. Periods of unknown time are abbreviated unk.

Although information was received from both satellites over a period of only 15 minutes and 19 seconds, the 8 messages gave information on at least 10 dives covering a period of 21 minutes and 39 seconds. At least one dive was certainly missed between 1947 and 1949.

Location determinations were never achieved by Service ARGOS because: 1) most often an insufficient number of messages were received during a single orbit; 2) when sufficient messages were recieved, they were not sufficiently spread out (>420 seconds). However, subsequent analysis using our own algorithm with less stringent criteria (and hence somewhat less accurate locations) than that used by Service ARGOS we were able to make 10 location determinations (see Appendix). Figure 6 shows the original tagging site at Cape Bonavista, the 10 subsequent locations, and sea surface temperatures around Newfoundland for 18 to 20 July (Canadian Forces METOC Centre). The influence of the Labrador Current can be seen as its cold southward moving waters encounter the warmer Gulf Stream and split into two branches (Petrie and Anderson, 1983). The tagged whale moved offshore and then south in the same direction as the Labrador Current. Movements of humpbacks between inshore and offshore locations have previously been documented by the use of fluke photographs (Whitehead and Lien, 1983). Overall, the whale moved at least 707 km in 119.45 hrs for an average speed of 5.92 km/hr. Table 4 shows the distances traveled between locations (6 to 139 km) and average segment speeds (1 to 22 km/hr). These speeds are conservative estimates as the whale likely wandered from the straight line paths shown in Figure 6. Humpbacks spend most of their summer feeding or in search of food (Whitehead et al, 1982). One location of the SWT-tagged whale was along the southeast edge of the Grand Banks, close to where a concentration of humpback whales had

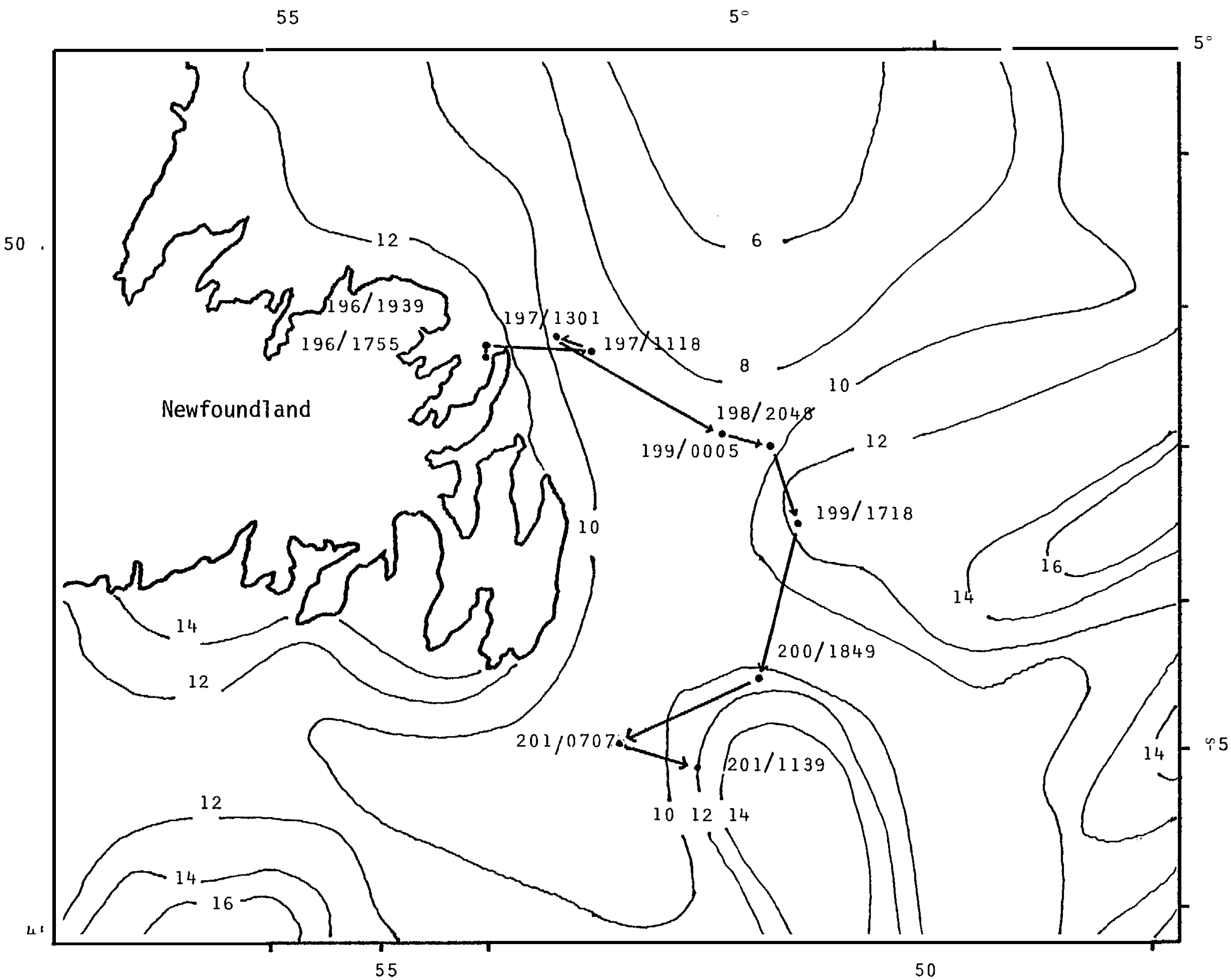


FIGURE 6. Surface temperatures for 18 to 20 July 1983 (Canadian METOC Centre) with locations of tagging and subsequent location determinations calculated from ARGOS satellite data for a free-ranging humpback whale.

TABLE 4. Distance and speed of travel for a SkIT-tagged humpback whale, 15-20 July, 1983.

		TIME (HR)		DISTANCE (KM)		SPEED (KM/HR)	
DATE	TIME	ABS*	SUM**	ABS	SUM	ABS	SUM
196	1230						
		5.42	5.42	8.25	8.25	1.52	1.52
196	1755						
		1.73	7.15	13.57	21.82	7.84	3.05
196	1939						
		15.95	23.10	96.40	118.22	6.05	5.12
197	1118						
		1.72	24.82	45.41	163.63	26.40	6.59
197	1301						
		31.78	56.60	140.73	304.36	4.43	5.38
198	2048						
		3.28	59.88	44.43	348.79	13.55	5.83
199	0005						
		17.22	77.10	68.31	417.10	3.97	5.41
199	1718"						
		25.52	102.62	126.46	543.56	4.96	5.30
200	1849						
		12.30	114.92	94.04	637.60	7.65	5.55
201	0707						
		4.53	119.45	55.91	693.51	12.34	5.81
201	1139						

*ABS = Absolute (Time or distance between locations).
**SUM = Summary (Total time or distance since tagging).

been observed feeding one week earlier (H. Whitehead, pers. comm.). The Labrador current moves south at a maximum speed of 2.8 km/hr along the eastern edge of the Grand Banks (Figure 7 and Table 5). Generally, its mean velocity is 0.54 km/hr nearshore to 1.3 km/hr 300 km offshore (Petrie and Anderson, 1983).

The waters off Newfoundland generally get colder with depth and in some areas one or more distinct thermoclines exist (Lynch, 1983). Sub-surface water temperatures as low as -1.50° were measured during early July by Whitehead (pers. comm.). Thus, temperatures from dives may provide some interpretation of dive depth and activity. Temperature measurements were accurate to the nearest 0.030C, but because the temperature sensor was inside the transmitter, there was a considerable time delay in changing the temperature of such a large thermal mass. Inside the SWT, air insulated the temperature sensor even further from its housing. The temperature of the transmitter was therefore a somewhat vague and amorphous average of the “recent” water temperatures encountered by the whale. Thus, the temperatures reported for dives more accurately reflect the history of previous dives. Short dives near the surface in warm water may follow longer dives into cooler waters. Long dives may not necessarily be deep dives. In fact, long dives near the surface would warm the transmitter after deeper dives (long or short) into cooler water. Therefore, the temperature trend (up or down) reported for consecutive dives may be of greater value in evaluating the whale’s diving behavior than analysis of individual dives in isolation. For example, the dive sequence from 196/1940 to 1955 shows a general trend toward lower temperatures,starting at 10.29”C and ending at 8.93°C which may indicate a period of more diving to deeper colder waters than before the sequence

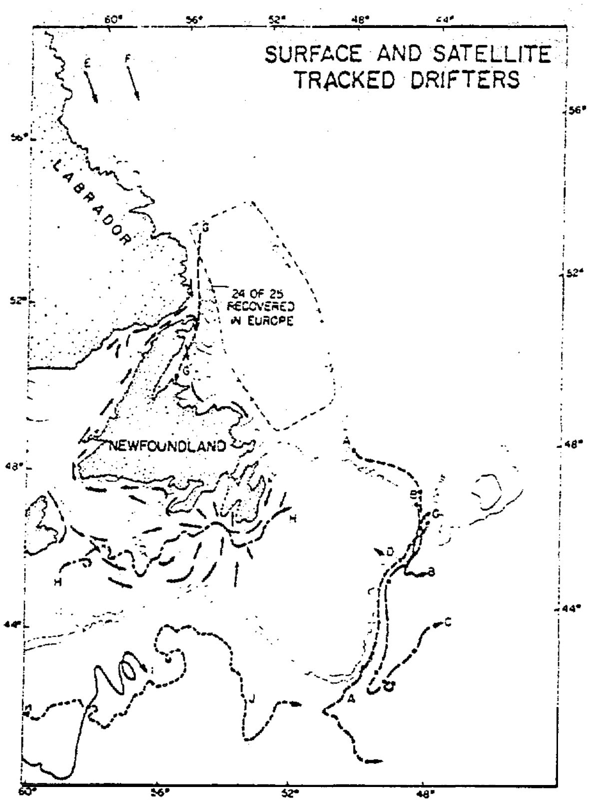


FIGURE 7. Map of the surface circulation on the Newfoundland Shelf based on surface and satellite-tracked drifters. Short arrows represent an interpretation of the flow based on surface drifters for which *only* release recovery times and locations are ktiown. The longer, lettered lines (see Table 1b as well) represent the paths taken by satellite-tracked buoys. (Petrie & Anders on, 1983) .

TABLE 5" . Statistics of satellite-tracked surface drifters

Track	Mean Speed (in s⁻¹)	Direction (°T)	Maximum Speed (in s⁻¹)	Time Period of Track
A-A	0.30	Slope, offshore Lab. Current	0.70	April–May 1978
B-B	0.22	Lab. Current	0.80	April 1977
C-C	0.37	Lab. Current	0.70	April 1976
D-D*	0.02	300°T	—	August 1971
E-E	0.20	Shelf, inshore	—	September 1977
	0.11	Lab. Current	—	October 1977
F-F	0.43	Slope, offshore	—	September 1977
	0.54	Lab. Current	—	October 1977
G-G†	0.20	Shelf, inshore Lab. Current	—	November 1980
H-H	0.15	76°T	0.43	June-July 1979
1-I	0.08	75-T	—	July- .August I 979
J-J	0.10	80°T	—	September–December 1979

*Tracked by ship.
†Mooring, recovered two weeks after release. **(Petrie & Anderson, 1983)**

started (especially as the starting temperature is close to the surface temperature in that area). Thus, it is not surprising that dive duration does not correlate well with temperature data (Figure 8). One reason why duration of dive may have little affect on temperature is a selection of a temperature stratum by whales. Bredin (1983) has reported that feeding humpback whales concentrate their activities in waters bounded by one or more thermoclines which contain capelin, but this activity shows considerable variability relative to surface temperature (Whitehead et al, 1982). Fish exhibit temperature preferences. Off Newfoundland cod prefer OOto 4°C, capelin prefer 6°to 12°C and basking sharks prefer 8°to 12°C. As humpbacks are feeding primarily on capelin, SWT temperatures of 6°to 12°C would be expected and in fact comprise 79% of all reported temperatures (8% were <6°C and 13% were >12°C).

There is generally good correspondence between the SWT- and METOC-derived temperatures in as much as the SWT -reported temperatures_ higher than immediately adjacent waters only once. Higher temperatures are obviously hard to rationalize although without ground truthing the temperature isotherms are unreliable for small scale measurements. Lower SWT temperatures likely reflect subsurface temperatures and do not help corroborate location determinations. The temperature contours supplied by the METOC Center are crude three day averages. Thermal gradients can be quite dynamic, changing constantly with localized eddies requiring high resolution techniques for adequate description. We have examined the resolution of the sea surface infrared scanners on NOAA 7 and 8 during the experiment. Although sensitive to differences of 0.50C, the data lack adequate ground truth measurements for proper calibration.

Figure 9 depicts the frequency distribution of all dives in 30 second

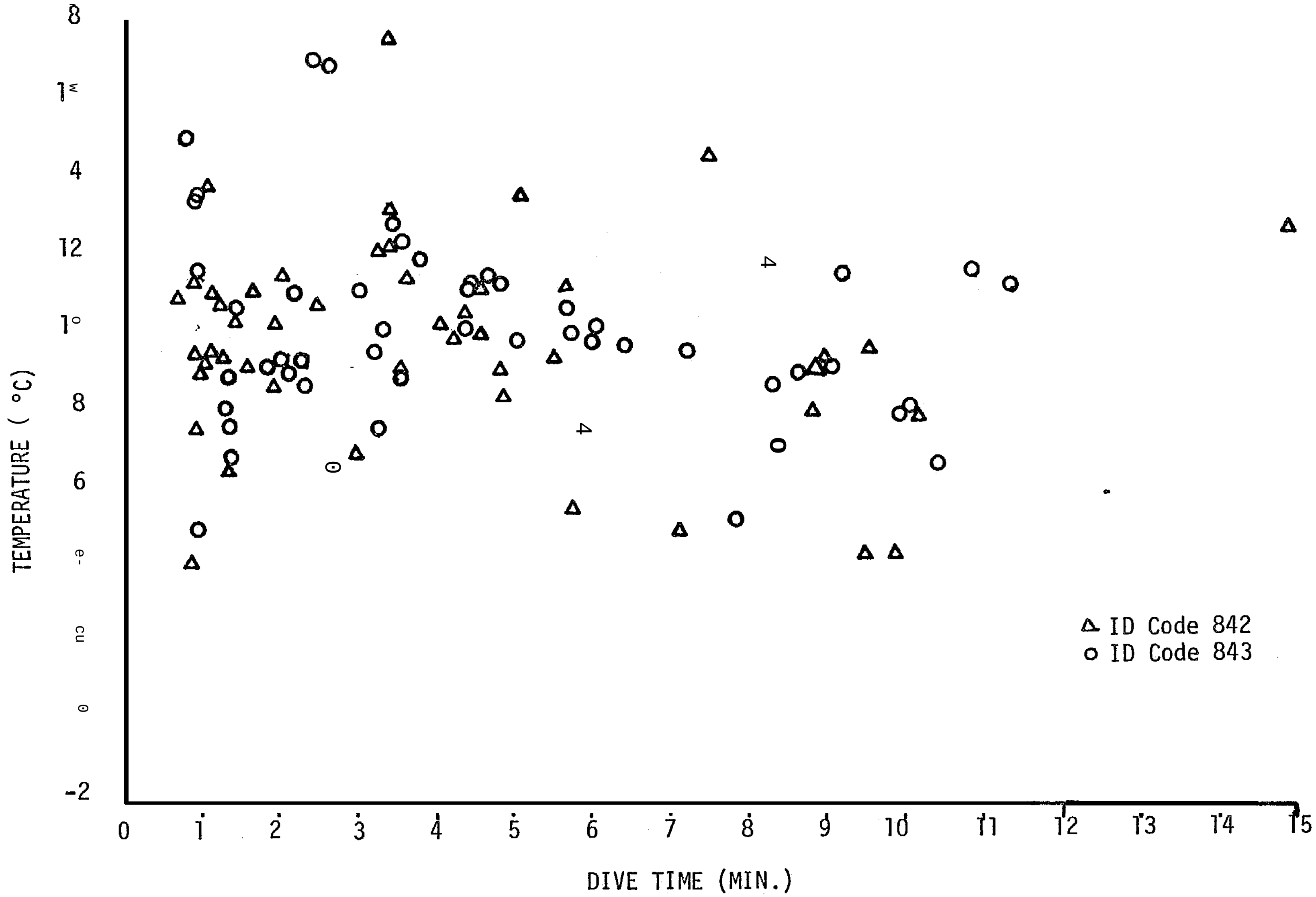


FIGURE 8. Temperatures and related dive times from an SWT tagged humpback whale off the Newfound and Atlantic coast (15-21 July. 1983).

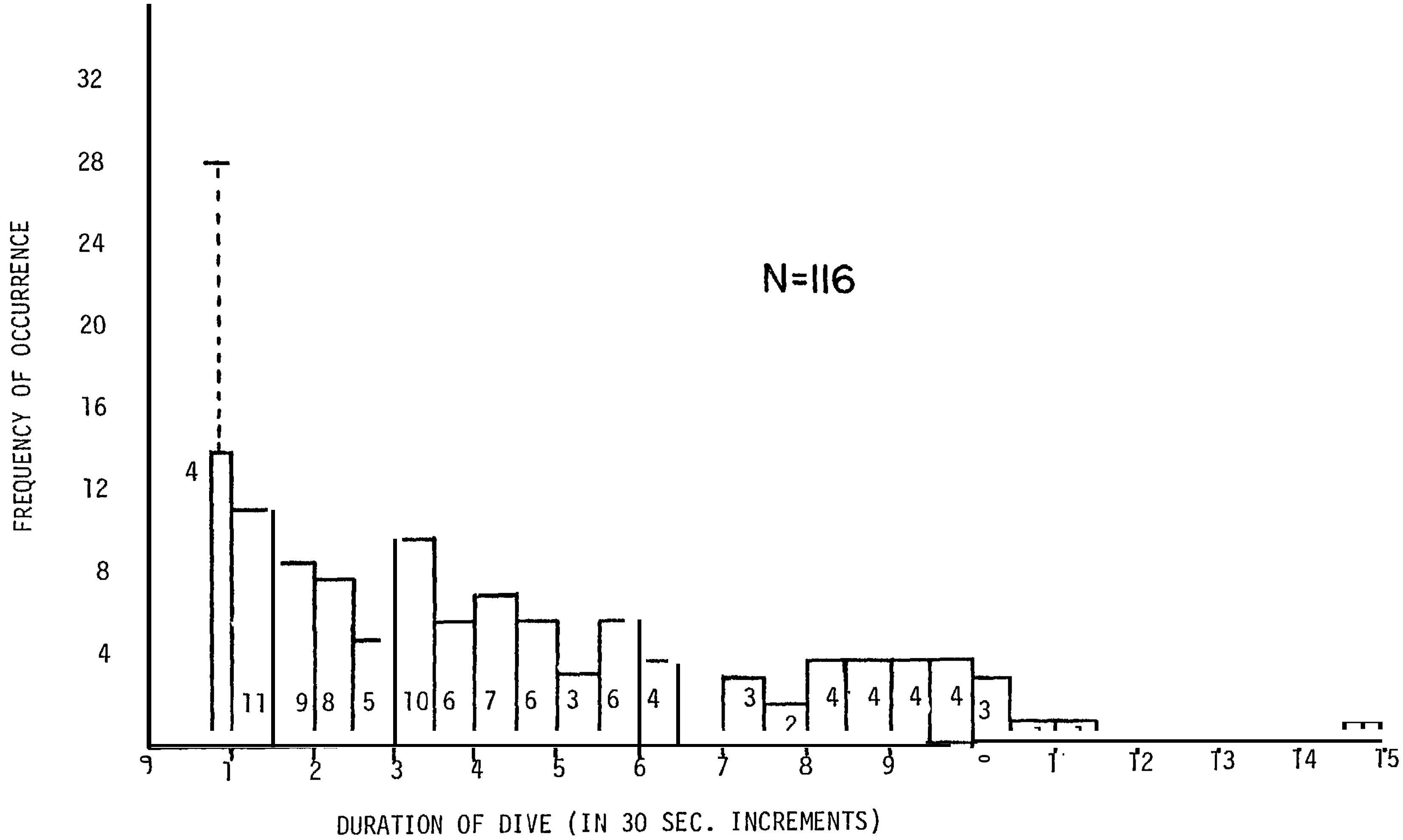


FIGURE 9 . The frequency of 116 dives of varying duration in 30 second increments from an SWT tagged humpback whale.

increments. Because the SWT could transmit no more than once every 45 seconds, there are no O to 30 second dives and the 30 to 60 second category only reflects dives between 45 and 60 seconds. Therefore, a reasonable estimate of twice the latter value has been indicated by a dotted line. Short dives (<1 minute) are likely to be more frequent than any other category. The number of surfacings resulting in a transmission during a single orbit is of course partly a reflection of the amount of time the satellite spends passing over the area for that time of day and also the duration of the dives themselves (i.e., more short dives are possible than long dives in a given amount of time). The dive distribution data for the SWT-tagged humpback whale (Figure 9) is less exponential than the data obtained by radio tags for gray whales (Figure 10), substantiating that there is not one “generic” dive pattern for all whales. Dives over 20 minutes would be considered rare for humpback whales. Two very long dives (53.68 and 74.49 minutes) were recorded and by cross-checking between the ID codes and satellite recorded reception times, both were confirmed errors.

Figure 11 summarizes the duration of whale dives for the six day monitoring period by time of day. The lack of data between 1130 and 1230 and between 2230 and 0230 reflects the lack of suitable satellite passes during these times (Figure 4).

Although the information is scant, there appeared to be times of the day when longer and shorter dives were more prevalent. Short dives occurred just before and at first light (0600), followed by longer dives midday and short dives again in the late afternoon (1700). The shortest documented dives occured around 2200. These changes throughout the day may represent a feeding cycle or changes in feeding strategy related to prey

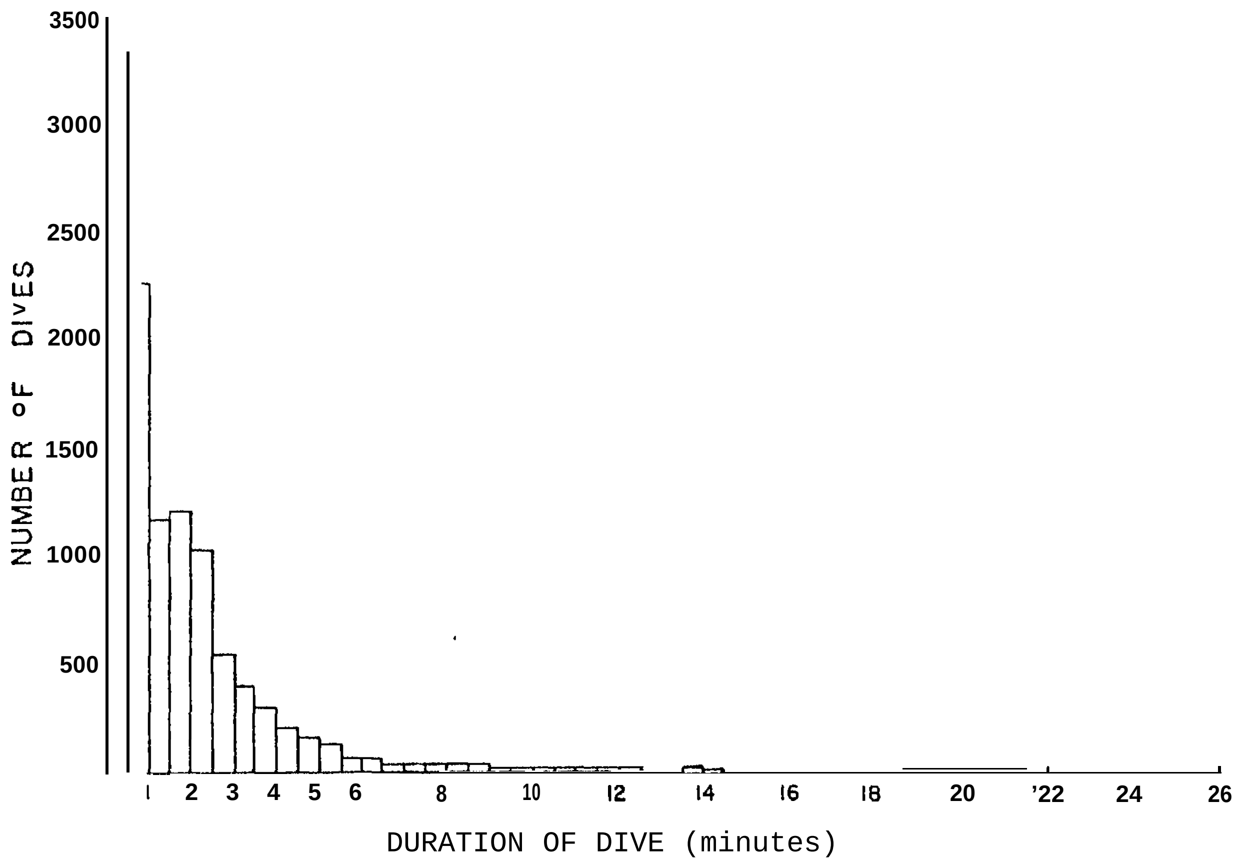


Figure 10. The frequency distribution of 11,080 dive durations from 10 different radio-tagged whales in San Ignacio Lagoon monitored for 303.7 hours. The mean is 1.57 + 0.02 (SE) minutes (Harvey and Mate, in press).

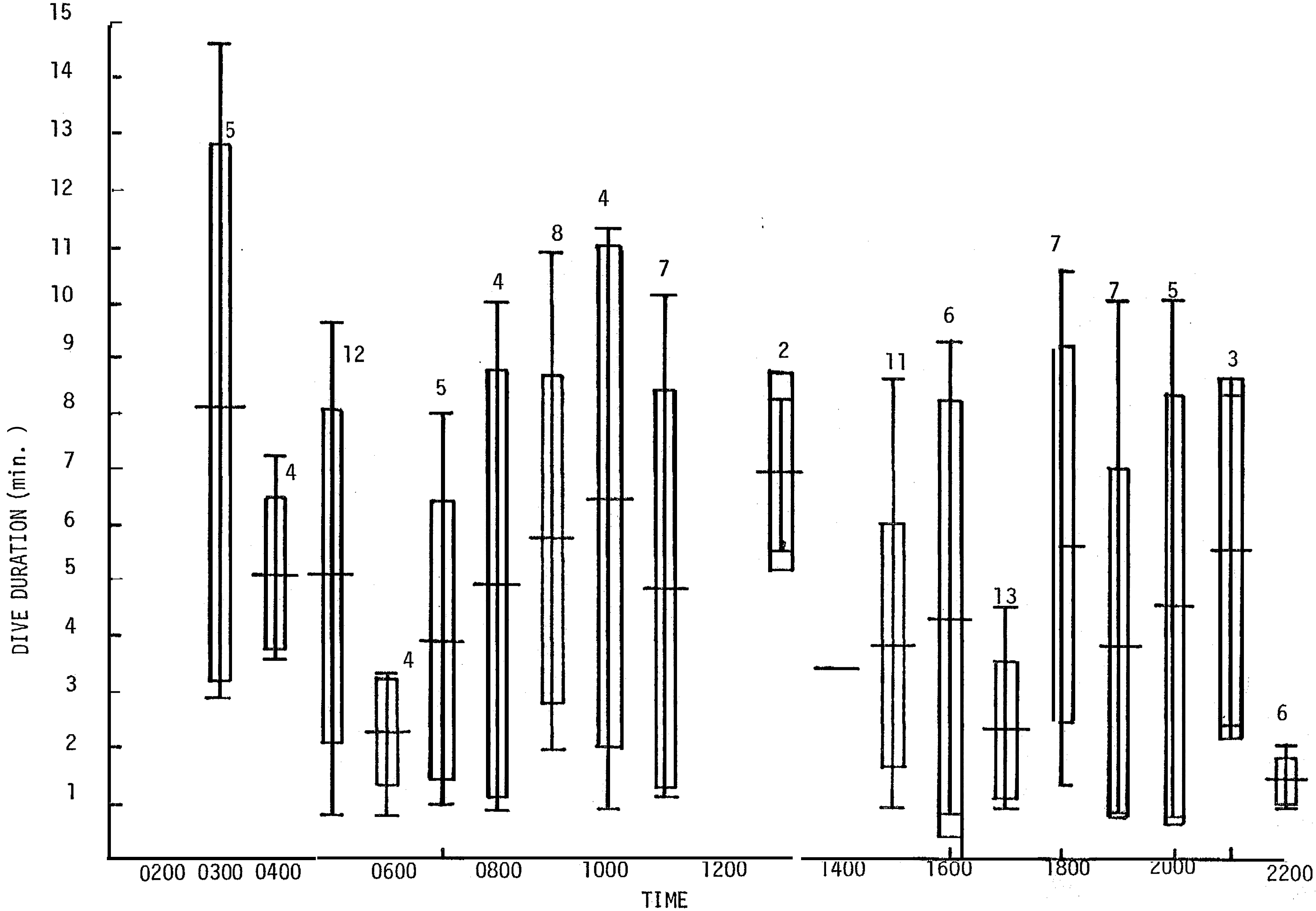


FIGURE 11. The mean, standard deviation and range of d ve durations by t me of day for an ARGOS-monitored humpback whale.

behavior (and hence availability). Douglas and Green (1980) observed the inshore activity of humpback whales in St. Vincent's, Holyrood Bay. They noticed a decrease in whale activity midday. Capelin rise to the surface and scatter during the dark, perhaps in association with their vertically migrating prey species. In the morning schools of capelin are found in shallower water so shallow dives are sufficient for whales to feed, while later in the day deeper dives (cooler temperatures) are needed as capelin migrate to deeper waters. This is born out by looking at the temperature. For example, on day 201 the 10 morning dives (0533 to 0913) are all 11.83° C or more (avg. = 13.55), while the 13 dives from 1048 to 2030 averaged only 9.51°C. This may also represent animals foraging along the rip where there is a steep temperature gradient between the Labrador and Gulf Currents. Bredin (1983) has seen foraging by individual whales throughout the day.

DISCUSSION AND CONCLUSIONS

The use of umbrella anchors to attach radio transmitters to gray whales has shown the potential for long term attachment. Quality control in the production of the attachments has been resolved. The problem pressure cartridges during this experiment were at least 3 years old and, more importantly, had been totally submerged in sea water many times in March of 1983 during attempts to tag gray whales. Although the cartridges are hermetically sealed with a metal foil welded over the powder charge as a moisture barrier and glass electrical feed-throughs for the ignition primers, we surmise moisture was the problem. We are certain that these cartridges are adequate from our previous tests on fresh humpback carcasses, a successful attachment of a 148.6 MHz radio tag in 1982 and the successful attachment of the 148.6 MHz radio tag during this humpback whale experiment. We do not know how long a properly attached SWT will stay attached to a whale.

The electronics have worked well. The terrestrial trials and the dive simulations have shown excellent location capability. However, without re-sighting the SWT-tagged humpback whale, we were unable to confirm the location accuracy of the SWT at sea on a live whale. The first location from ARGOS data was quite reasonable. Five hours after release the animal was 8.25 km from the tagging site, requiring a mere 1.52 km/hr. The whale had last been observed moving slowly and was within 20 km of the tagging site during the locating orbit as judged by VHF signals.

Data from the SWT appear to be generally reliable. Only 7 questionable dive times and 2 questionable temperatures were reported in 121 occurrences of each. The reasons for all these aberrations are presently unknown, although we are analyzing available information to determine how much can be attributed to bit-synchrony error. Other sources of error may be encoding, transmission or translation errors. Several errors occurred at low elevation angles (range 4°to 85°, average of 16.80].

The specialized antenna design appears to be quit adequate. Signal strength at the satellite was good to excellent during terrestrial trials and fair to good while the SWT was on the whale. The position of the antenna perpendicular to the major axis of the whale and adjacent to the shorter salt water switch on the top of the SWT assures that the antenna will clear the water before the salt water switch activates the transmitter.

The salt water switch functioned well in laboratory experiments and appeared to work well on the whale. We are exploring a method of determining salinity from conductivity measurements (corrected for temperature and pressure) as a future capability in a SWT designed to profile pressure, temperature, and salinity throughout a whale's dive. This will necessitate an external temperature probe and will allow good surface temperature comparisons for locations. Acquiring this valuable oceanographic information will increase our knowledge of water masses in general and potentially tell us a great deal about how whales find their prey and navigate. The principal problem at the present time with acquiring so much information is the limitation of only 32 eight-bit words allowed during each transmission. We are seeking the most efficient means of encoding information within this limited number of bits and welcome suggestions.

The two ID codes used by the SWT acted essentially like two separate transmitters. Each ID code (842) accounted for 50% of the total data (121 telemetered dives). Only 18 surfacings (15%) resulted in data from both ID codes. Thus, we believe it was an important design strategy to have two ID codes, as having only one may have resulted in much less data. The strategy of having two ID codes should be maintained. In this preliminary experiment we decided to have the transmitter transmit as frequently as Service ARGOS would allow with 5 seconds added error margin (i.e., every surfacing at least 45 seconds separated from a previous transmission). By combining the data from both ID codes, 13 orbits produced 3 or more messages. We used these data to calculate SWT locations (see Appendix). Now that we are assured that this strategy is adequate for data gathering and location determination, we are considering a sampling strategy to increase the functional life of the present SWT or use a smaller unit which would last for the same period of time. Although it would reduce the life of the SWT by half, if a waiver of the ARGOS criteria were possible for experiments like ours to allow transmission at each surfacing, the number of signals for locations might double, while the overall transmission rate would remain very low (average <l/rein). These additional signals would contribute significantly to the determination of additional locations, but still not ‘threaten to saturate the system.

The functional life of the SWT is governed by the battery capacity and energy demands. Transmissions account for most of the power use, while maintenance functions (microprocessor, continuous oscillator, interrogation of sensors, quartz clocks , etc.) draw substantially less current. As shown in Figure 4, certain portions of the day have more satellite coverage than others. In all locations, as in Newfoundland, there is very little satellite activity from 2230 hours to 0230 hours. The present unit is estimated to last 3 months. Adoption of a 25% duty cycle would extend the SWT's life to 12 months, or perhaps more conservatively, to 9 months. A 25% duty cycle might only allow transmission upon surfacing during just 6 hours of each day.

It appears unlikely that we will be able to get locations determined from Service ARGOS software with the present system. Changes in the rate of transmission policy and/or processing software would be quite helpful, but are unlikely. However, a new Service ARGOS program to give users access to the complete data files in nearly real time may solve this dilemma as we are now capable of determining locations with our own algorithm from a complete data base. The appreciation of whale movements in nearly real time is desirable not only to check system accuracy by observation of the tagged whale, but possibly for future experiments involving interception of “known” individual whales to study their response to noise. The development of industrial activities such as petroleum seismic surveys may pose a threat to whales and is a critical conservation and management issue in some areas where endangered species migrate, feed, and give birth.

Investigators conducting studies of humpback whales on their breeding grounds this winter have been alerted to watch for the 148.6 MHz radio and its white streamer attached to a humpback whale. Well-attached umbrella tags have remained on gray whales for up to 27 months. We are hopeful that this whale will be sighted along its migration route or in the breeding area. A few humpback whales cataloged by natural marks off Newfoundland have been observed off Silver and Navidad Banks (20.5″ N) where the bulk of winter breeding season research is carried out (Whitehead et al, 1982; Katona et al, 1980).

Our next experiment will be to apply two SWT's to gray whales during the mid-January through February (1984) field season in Baja, Mexico. This will be an important test of SWT endurance. One SWT will incorporate new dive profiling features. This experiment will be the first satellite-monitored instrumentation to give a three dimensional analysis of whale movements and behavior.

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APPENDIX

The procedure for computing whale positions entirely from the ARGOS Probationary File is now outlined. While the ARGOS position reductions are more accurate, this scheme has merit where the data do not meet the more stringent ARGOS requirements. This algorithm has been included as an enhancement to a FORTRAN DCS Station Location Program currently installed on a Data General Nova 3 Computer in the User Terminal Systems Branch of the Goddard Space Flight Center.

The algorithm determines the classical keplarian elements from the ARGOS spacecraft position vectors included with the Probationary File messages. A minimum of three distinct messages are required. Once the spacecraft orbit is determined, the whale is located using standard least squares regression techniques.

The derived keplarian elements are globally poor but are adequate locally in the region of message acquisition when a J2 gravity model is used. More favorable circumstances would favor the inclusion of a known reference station in each pass. When present, reference station messages may be used to improve the orbital element accuracy using well known differential correction methods. Also, a minimally determined system (3 messages) lacks certain desirable statistical measures of accuracy. Therefore, the following technique is presented from the position that apriori orbital elements are not available, a reference station is not included, and the risks inherent in a minimal solution are acceptable.

The procedure is described in ref. 1,2 and is not difficult; three non-colinear spacecraft position vectors are selected from a pass and rotated to an inertial coordinate system. The cross product of two position vectors establishes a vector normal to the orbital plane. This vector defines the orbital plane orientation in inertial space; that is, the inclination angle and the ascending node angle. further, the position vector dot and cross products may be used to compute the sines and cosines of the angles between the true anomalies. From an equation of the ellipse, the true anomalies, orbital eccentricity, and semi-major axis, are expressed as functions of these sine and cosine terms.

Let R_i i=1,2,3 be three distinct time-ordered spacecraft position vectors in earth fixed geocentric coordinates each with components r_x, r_y, r_z. The Z-axis points northward and the X-axis is in the direction of the Prime Meridian with the X and Y axes in the equatorial plane. Each position vector may be rotated to an inertial reference frame by

$$R'_i = R_x\cos(Q) - R_y\sin(Q)$$
$$R'_j = R_x\sin(Q) + R_y\sin(Q)$$
$$R'_k = R_z$$

where Q is the instantaneous Greenwich Hour Angle and R′ is a position vector in the inertial coordinate system and i is in the direction of the Vernal Equinox (Aries).

The choice of the Greenwich hour angle is arbitrary; a simpler method would be to rotate two position vectors into a frame defined by the third using an angle computed from the earth's rotation. Further, since the position vectors and their corresponding times are internally consistent, a clock correction using the DCS datation register is not necessary.

The sines and cosines of the differences in true anomalies f_1, f_2, f_3 corresponding to each position vector are

$$\sin(f_3 - f_i) = |R'_i \times R'_3| \;/\; |R'_i|\,|R'_3|$$

$$\cos(f_3 - f_i) = |R'_i \circ R'_3| \;/\; |R'_i|\,|R'_3| \qquad i=1,2$$

For brevity let $S_{3j} = \sin(f_3 - f_j)$

$C_{3j} = \cos(f_3 - f_j) \qquad j=1,2$

From an equation of the ellipse $R'_i = \dfrac{a(1-e^2)}{1+e\cos(f_i)} \qquad i=1,2,3$

where a is the orbital semi-major axis and e is the eccentricity it may be shown that

$$f_3 = \tan^{-1}\left[\frac{r_1(r_2-r_3)C_{31} + r_2(r_3-r_1)C_{32} + r_3(r_1-r_2)}{r_1(r_2-r_3)S_{31} + r_2(r_3-r_1)S_{32}}\right]$$

with r_i i=1,2,3 the scaler values of R'_i. Note that f_3 may assume two values. The correct value gives a positive eccentricity in the equation below. Computing the remaining anomalies from the correct f_3:

$$f_1 = f_3 - \cos^{-1}(C_{31})$$
$$f_2 = f_3 - \cos^{-1}(C_{32})$$

and $e = \dfrac{r_i - r_j}{r_j\cos(f_j) - r_i\cos(f_i)}$ the orbital eccentricity

$a = r_i\left[\dfrac{1+e\cos(f_i)}{1-e^2}\right]$ $\quad i,j = 1,2,3 \quad i \neq j$ the orbital semi-major axis

$E = 2\arctan\left[\sqrt{\dfrac{1-e}{1+e}}\,\tan\left(\dfrac{f_2}{2}\right)\right]$ the eccentric anomaly for R'_2

$M = E - e\sin E$ the mean anomaly for R'_2

The remaining elements are obtained from the cross product of two position vectors. Let VI, V_2, V_3, be the vector components of $R_1 \times R_3$. then from geometric considerations the angle of inclination is

$i = \pi/2 \pm \sin^{-1}\left[\dfrac{V_3}{(V_1^2 + V_2^2 + V_3^2)^{1/2}}\right]$ where the algebraic sign is that of $-V_3$.

Also, the ascending node angle is

$$\Omega = \tan^{-1}\left[V_2/V_1\right] \pm \pi/2$$ where the algebraic sign is that of $V_1 V_3$.

and from spherical trigonometry the argument of perigee is

$$w = \mp\cos^{-1}\left[\frac{r_x \cos\Omega + r_y \sin\Omega}{r_z}\right] - f_2$$ where the sign is that of r_z

and r_x, r_y, r_z, are the components of R'_2.

The method was verified using Probationary file data from a well-surveyed DCS station (0026) located at the Goddard Space Flight Center in Greenbelt, Md. Messages from several NOAA-7 passes were parsed in groups of three to simulate a minimal number of whale transmissions. Some whale positions were recovered from passes containing messages separated by one second intervals. This could not be emulated in the validation tests because the reference station transmits at 39 second intervals.

Assuming a spherical earth, the great circle displacement errors may be taken to be

$$d_\phi = R_e(\phi_e - \phi_s)$$

$$d_\lambda = R_e \cos\phi_s (\lambda_e - \lambda_s)$$

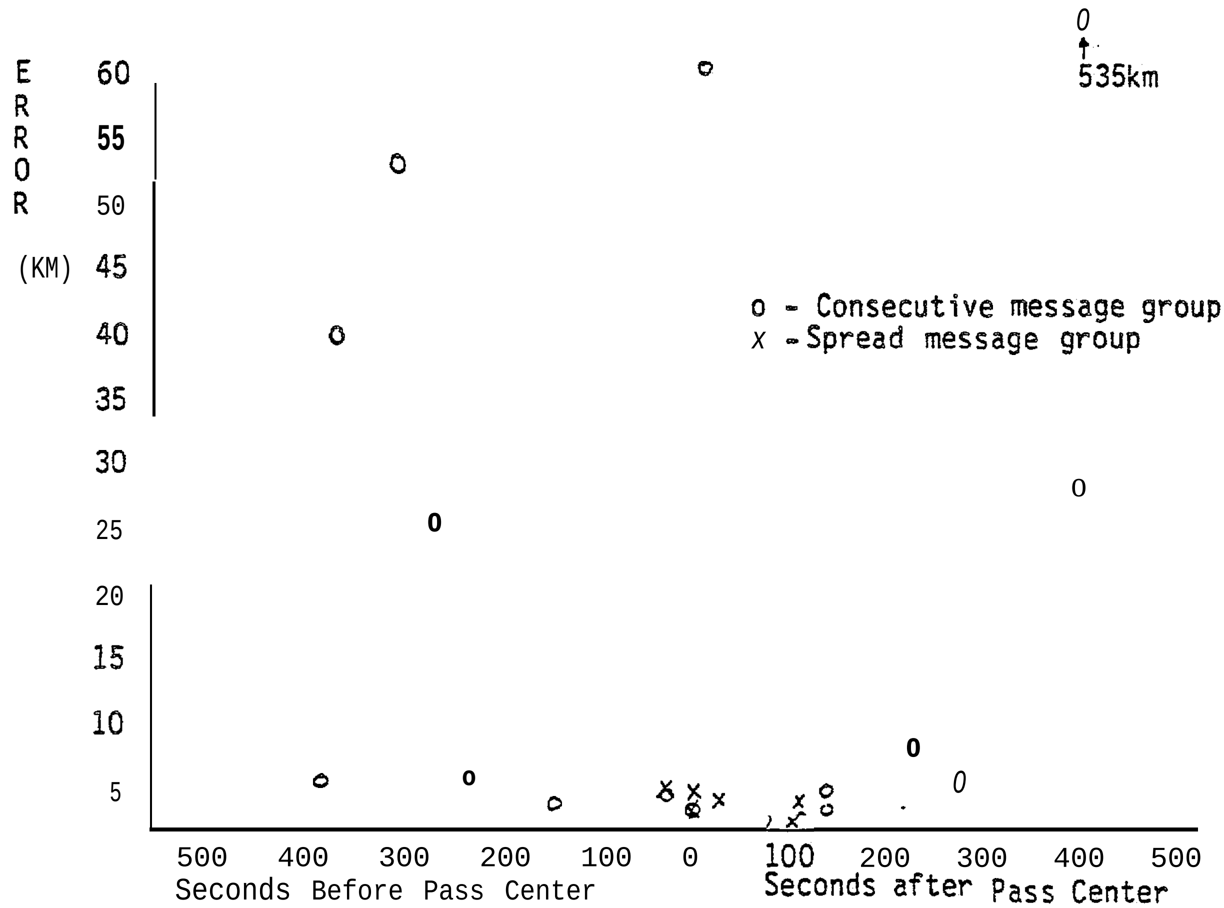
Where ϕ_s and ϕ_e are the surveyed and estimated geodetic latitudes and λ_s and λ_e are the surveyed and estimated geodetic longitudes, and R_e = earth radius.

and the linear displacement error is then approximately $d_e = \sqrt{d_\phi^2 + d_\lambda^2}$

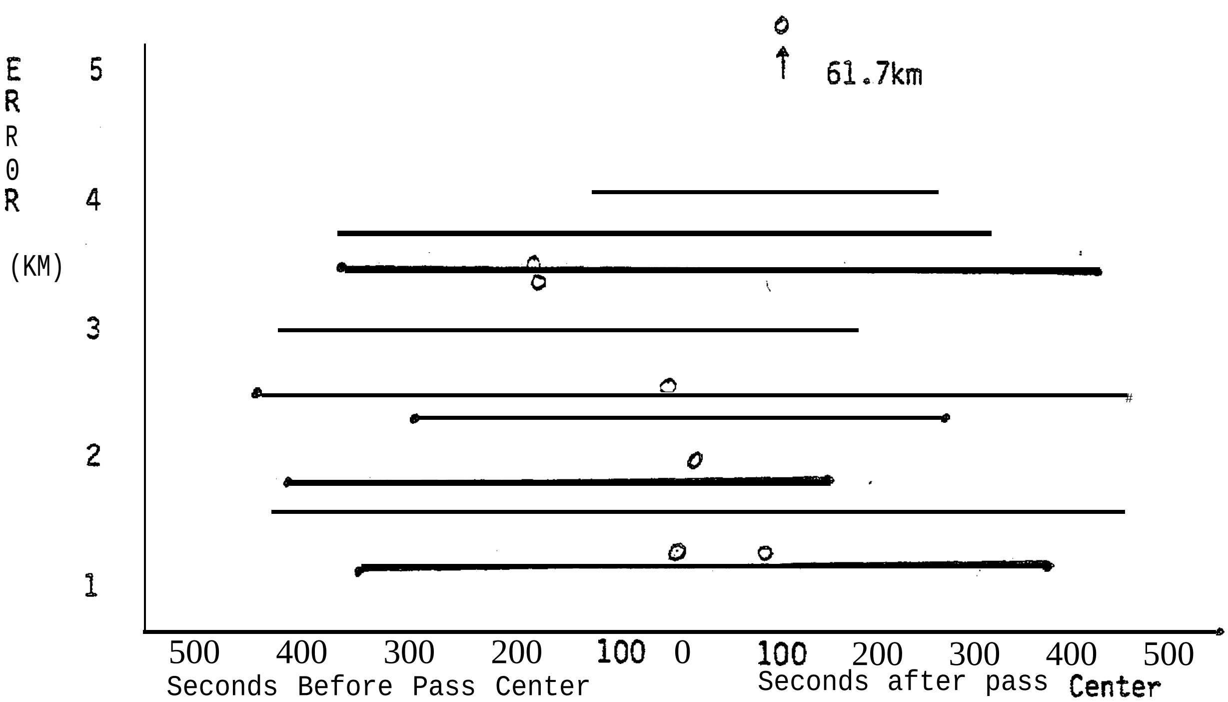
The displacement errors are presented in figure 11 as a function of time from the center of the pass. The pass center is the time when the spacecraft is closest to the transmitter and is taken here to be equivalent to the inflection point on the doppler curve. The center is estimated by a linear interpolation between the doppler frequencies in the messages bracketing the inflection point. Two message group types have been included; consecutive message groups containing 3 consecutive messages spanning a 78 second interval and spread groups containing 3 messages dispersed in an interval of approximately 800 seconds. By comparison, the shortest whale data collection interval is 168 seconds and the longest is 625 seconds (table 6).

The error distribution of figure 11 is a consequence of the poor global quality of the orbital elements. While even a short extrapolation outside the span of the position vectors yields large errors, the displacement errors in the region of interest corresponding to the whale data collection intervals are generally less than 5 kilometers.

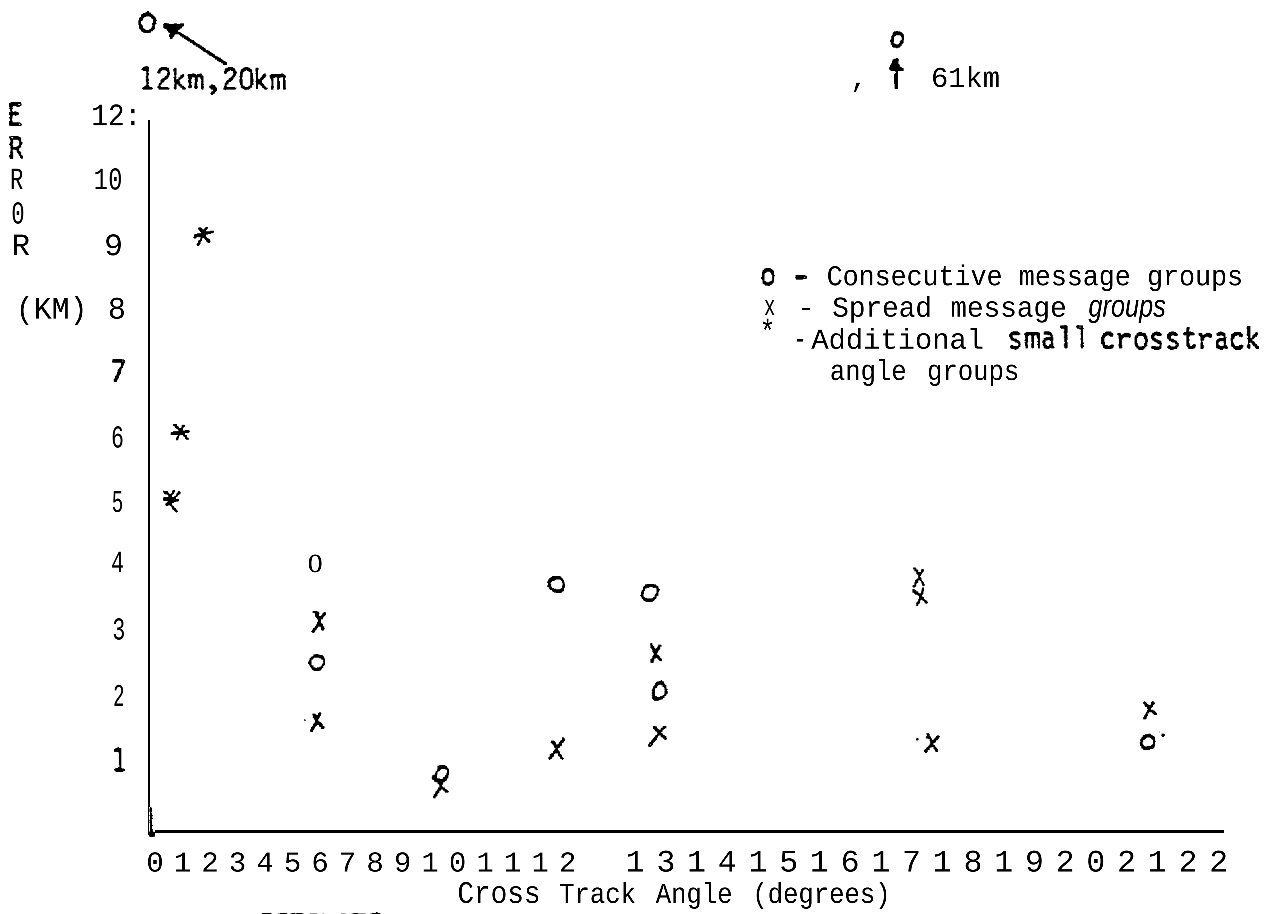
Figure 12 presents the displacement errors as a function of the data collection interval and the interval offset from the pass center. The consecutive groups in figure 11 near the pass center are included with several additional groups.



REFERENCE STATION LOCATION ERRORS AS A FUNCTION OF TIME IN SATELLITE PASS
FIGURE 11



REFERENCE STATION LOCATION ERRORS AS FUNCTION OF DATA SPAN
FIGURE 12



LOCATION ESTIMATE DISPLACEMENT ERROR AS A FUNCTION OF CROSS TRACK ANGLE
FIGURE 13

The location estimates are especially sensitive to spacecraft position errors when the cross track angles are small. This is a consequence of geometric considerations inherent in the location method. The cross track angle here is the geocentric angle between the transmitter and the orbital plane. Figure 13 shows displacement errors as a function of cross track angles. To characterize the program performance at small angles, additiona" passes not part of the original set are also plotted.

An optimistic interpretation of these preliminary validation results should be tempered with the cautionary reminder that three of the whale position estimates are based on spacecraft position vectors only 1 second apart and this could not be considered in this evaluation. Also, 3 positions were computed where the cross track angles were less than 1 degree (Table 6).

PASS START Day sec	no. of messages	Data Interval (see)	1 sec Epoch	message interval location	small xtrack
196 64540	4.	625			X
196 70770	8	488			
197 40727	3	382	X	X	
197 47176	3	314			
198 74904	4	168	X	X	
199 62334	4	668		X	
201 25635	4	614		X	X
201 41949	3	220	X	X	X

TABLE 6 CRITICAL PARAMETERS EFFECTING WHALE LOCATION ACCURACY
(Small cross track angles less than 1 deg. are flagged)

To minimize the estimate errors, the position vector angular deviations from the orbital plane were measured and the orbital elements were checked for reasonable values but these tests are not conclusive. Where more than three whale messages were available, the differences between the observed and expected doppler shifts were examined. Some messages were rejected by other editing and statistical checks.

Four of the 14 ARGOS Probationary files containing more than three whale messages were without position vectors and were discarded. The remaining passes were processed by the location program. Two passes were rejected by the editing procedures.

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