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Results of ADS Communications Testing

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Abstract—Automated Dependent Surveillance or ADS is an improvement to current Vessel Traffic Service (VTS) operations and a step towards a "voiceless VTS." The two main requirements for an ADS system are an accurate position sensor on the vessel and a communications link between the vessel and the Vessel Traffic Center (VTC). The first is satisfied by the operational United States Coast Guard Differential GPS (DGPS) service. The second has been the subject of recent research. Three existing communications technologies were evaluated and tested: Advanced Mobile Phone Service (AMPS) cellular, VHF-FM Digital Selective Calling (DSC), and Newcomb L-Band Satellite. These communications methods were tested in the Narragansett Bay Rhode Island area and evaluated according to the following criteria: coverage area, reliability, integrity, reporting interval, latency, and cost. Of the three communications methods, the DSC and Newcomb Satellite technologies were found to be well-suited for ADS implementation.

I. INTRODUCTION

Automated Dependent Surveillance (ADS) is a concept that holds the potential to improve current Vessel Traffic Service (VTS) operations. ADS is a technology capable of transferring information in a digital format from vessels of interest to the Vessel Traffic Center (VTC). The United States Coast Guard (USCG) Research and Development Center (R&D Center) has been studying the technologies available to enable this digital information flow. Three communications methods were selected for test and evaluation: Advanced Mobile Phone Service (AMPS) cellular, VHF-FM Digital Selective Calling (DSC), and Newcomb L-band satellite. Information concerning each of the three communication systems tested, their advantages and disadvantages, and a system diagram for each system can be found in [1]. This report focuses on the evaluation of the data collected during the test period.

A VTS Gateway was developed to integrate these disparate communications links into a single common format for use by a geographic display system. Separating the communications systems from the display system enables the end-user to select a display designed around operational requirements using a single information format. This concept is illustrated in Fig. 1. In the Narragansett Bay testing, three different communications links were tested. Each link was controlled by a computer (the Link Control Computer) which provided the data to the display and recording system through a serial data multiplexer.

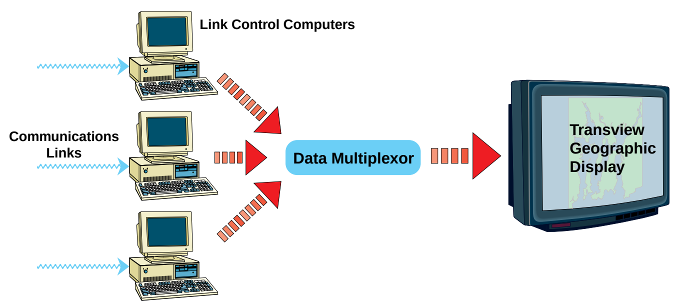

Fig. 1. VTS Gateway

II. AMPS CELLULAR

AMPS or Advanced Mobile Phone Service, is the standard analog cellular system in use throughout the United States. Coverage in the Narragansett Bay, RI area (at the time of testing) was provided by Bell Atlantic Mobile (A-side) and NYNEX Mobile Communications (B-side)[1]. Both systems claimed coverage throughout the Bay area [2]. A DGPS receiver aboard the vessel *Vista Jubilee* was configured to output the NMEA 0183 [4] sentences ($GGA, $VTG, $ZDA) at a one second interval to a MNP-10 [5] modem and standard cellular telephone.

A. Evaluation

Once a cellular connection was made by the Link Control Computer (LCC), in essence, a virtual circuit existed between the DGPS receiver and the LCC at the VTS Gateway. Although NMEA 0183 reports arrived every second, only every fifth report was recorded for analysis (resulting in a five second reporting interval). During the course of the months of testing, over ninety-three hours of data (over 53,000 reports) were logged for the vessel *Vista Jubilee*. The data collected is summarized in Table 1.

[1] Coverage is now provided by Cellular One of RI/SNET (A-side) and Bell Atlantic Nynex Mobile (B-side) [3].

TABLE 1
Cellular Data Summary

Date	Hours of Data	# of Raw Reports	# of Good Reports	% Data Error	# of Missed Reports	Percent Success	Missed Report Intervals (in seconds) Max	Mean	Std Dev.
25-Aug	4.91		2,933		592	83.21%	551	66.06	115.04
26-Aug	6.01		3,028		1282	70.26%	491	42.60	89.22
29-Aug	4.23	2,836	2,835	0.04%	192	93.66%	332	32.58	60.27
30-Aug	4.10	2436	2,435	0.04%	270	90.02%	748	47.00	129.33
31-Aug	3.86	2,423	2,422	0.04%	342	87.63%	547	63.33	121.52
1-Sep	5.47	3458	3,456	0.06%	466	88.12%	619	52.72	111.36
2-Sep	3.77	2,583	2,583	0.00%	109	95.95%	146	24.23	24.23
7-Sep	3.87	2,371	2,362	0.38%	407	85.30%	427	57.48	99.05
11-Sep	2.54	1,468	1,323	9.88%	400	76.78%	334	16.39	34.66
14-Sep	0.80	564	490	13.12%	91	84.34%	21	10.79	2.02
15-Sep	8.80	4,887	4,419	9.58%	1884	70.11%	768	21.03	53.15
16-Sep	7.60	4,057	3,645	10.16%	1072	77.27%	420	16.55	35.77
20-Sep	6.52	3,727	3,282	11.94%	1384	70.34%	427	16.64	30.57
28-Sep	3.77	2,251	2,028	9.91%	668	75.22%	377	16.50	30.23
29-Sep	7.56	4,267	3,809	10.73%	1613	70.25%	344	16.97	27.59
7-Oct	3.52	2,193	1,965	10.40%	556	77.95%	240	14.86	22.10
8-Oct	3.51	2,268	2,053	9.48%	453	81.92%	280	14.15	23.79
12-Oct	4.04	2,473	2,219	10.27%	680	76.54%	227	16.14	23.62
14-Oct	5.33	6,457	3,071	52.44%	748	80.41%	370	16.06	31.74
22-Oct	3.61	2,290	2,034	11.18%	541	78.99%	435	14.58	29.79
Overall	93.82	53,009	52,392	1.16%	13,750	79.21%			

1) Coverage Area: All of the received reports were plotted on a chart of the area using MAPINFO™ software (Fig. 2). As can be seen, there is no geographic area in which reports were not received; coverage did exist as advertised. Further analysis of the areas where some reports were missed did not show any correlation between geographic area or vessel course/speed and poor coverage performance.

2) Reliability / Integrity: A review of Table 1 suggests that the cellular link was very unreliable. However, some additional explanation is in order. Starting with the 11 September test, there was approximately a 10% error rate in the received reports. This was the result of either duplicate, incomplete, or garbled reports. During the data analysis, reports of this type were deleted. These errors were most likely introduced through a combination of cellular channel induced errors and problems in the Link Control computer code. The missed report count for each test date is determined using the set of good reports by calculating the time interval between reports. Analyzing the data set, it was noticed that most of the missed reports were single misses. That is, the reports were received ten seconds apart versus five seconds. This explains why the mean missed report interval is usually close to ten seconds. However, most of the missed reports in the count are due to a small number of longer data "drop-outs" or periods with no reports. The large number of reports missed during a prolonged drop-out tends to dominate the total number of missed reports.

Another item of interest that is not immediately clear from Table 1, is that the cellular link was maintained continuously during the testing period. The MNP-10 cellular protocol of the modems worked as advertised to maintain the link through most of the periods of poor channel conditions. It was very rare that the modems would not be able to recover from a fade. However there were times when it was impossible to re-establish a dropped connection for a few minutes. This was probably due to cellular system loading in the vessel's area.

3) Reporting Interval / Latency: Due to the nature of the communications channel (circuit switched), a continuous telephone service connection had to be maintained. There was a certain amount of time overhead required to establish the connection. Typically it would take from thirty to forty-five seconds from the start of dialing to when the mobile phone would answer (about half of this delay was due to the phones being used outside their Home area; i.e. Roaming). Then it was typically an additional fifteen seconds before the modems negotiated speed and protocol settings prior to data being sent through the connection. However, once the circuit was established, there was virtually no delay in the information being provided by the DGPS receiver and being received by the Link Control Computer (LCC). A small amount of processing delay was introduced by the LCC in assembling the ADS report before passing it to the display system. Also, as mentioned earlier, the LCC only passed every fifth report to the display system.

Fig. 2. All Vista Jubilee cellular reports plotted on a cart of Narragansett Bay using MAPINFO™

4) Cost: It was known prior to the tests that cost was a severe disadvantage of the cellular system. Due to having to maintain the link continuously, we were paying for more bandwidth than was needed to transmit the ADS information. At the time of testing, cellular service was 38¢/min. peak, 26¢/min. off-peak and about 75¢/min. roaming. An average four hour test would cost around $180.

B. Conclusions

The cellular system was never considered an economic ADS communications method due to the cost and complexity of maintaining the connection continuously. It was expected that the cellular connection would be the most reliable, and that it would act as a reference for the performance of the other systems. Unfortunately, we experienced a lot of difficulty with the system; fading channels caused data dropouts for extended periods (1-2 minutes). At times, the dropouts lead to the loss of the connection. High cellular system loading also caused problems with call hand-offs as the vessel traversed the Bay. At times it was difficult to re-establish connections.

On the positive side, cellular did function reliably if you consider that most of the missed reports (by count) were due to a few long dropouts (at a five second reporting interval a two minute dropout would equal twenty-four missed reports). A five second reporting interval was definitely more frequent than was needed for a vessel with marine dynamics. For the speed and course changes the test vessel typically made, a 30 second reporting interval was sufficient.

III. VHF-FM DSC

Digital Selective Calling or DSC is an international standard defined by the ITU-R (formerly the CCIR) for various frequency bands. There are various standards describing the use (Rec. 541) and composition (Rec. 493) of a DSC call. In addition there are several expansion calls (Rec. 821) and VTS extensions (Rec. 825) that were used. These are all defined in [6]. For the ADS testing the VHF-FM DSC frequency of 156.525 MHz (channel 70) was used.

VHF-FM DSC is an element of the Global Maritime Distress and Safety System (GMDSS) and will slowly become an integral part of every large ship’s electronic capability over the next five years. The goal of GMDSS is to provide every ship around the world with the essential communications tools needed to provide for the safety of the crew, passengers, and cargo. The GMDSS equipment, such as the VHF DSC radio, will be connected to a navigation receiver and will be capable of initiating an automated distress alert. The DSC standards also provide for the transponder capabilities that were evaluated during the R&D Center tests presented here.

A. Evaluation

In order to conduct tests of VHF-FM DSC, shore facilities were developed, constructed, and installed. This paper describes the results obtained with the shore facility installed in Newport, Rhode Island. During the research program, similar shore facilities were also installed in Groton, Connecticut and on Governors Island, New York. The findings of this section are based on more than ninety-three hours of tests performed with the vessel *Vista Jubilee* out of Warren, Rhode Island and the *USCG Cutter Towline* out of Bristol, Rhode Island. The tests were scheduled around the standard operations of the *Vista Jubilee.* Additional experimentation using the *CGC Towline* was done when

TABLE 2
Vista Jubilee DSC Data

Date	Hours of Data	Total # of Reports	Reports rcvd w/no Cse/Spd	Percent Incomplete Reports	# of Reports Missed	Percent Success	RSS	
							MIN	MAX
25-Aug	4.09	351	0	0.00%	116	75.16%	8	46
26-Aug	4.49	510	3	0.58%	56	90.11%	18	47
29-Aug	4.09	429	0	0.00%	55	88.64%	21	47
30-Aug	5.87	641	1	0.16%	66	90.66%	20	47
31-Aug	3.85	429	2	0.46%	35	92.46%	22	47
1-Sep	10.84	1203	0	0.00%	55	95.63%	20	47
2-Sep	3.70	404	0	0.00%	40	90.99%	23	47
7-Sep	4.05	429	3	0.69%	58	88.09%	16	47
11-Sep	2.04	241	37	13.31%	4	98.37%	20	46
15-Sep	3.01	333	35	9.51%	29	91.99%	19	32
16-Sep	8.71	845	102	10.77%	78	91.55%	15	47
20-Sep	6.38	661	80	10.80%	91	87.90%	21	47
27-Sep	5.68	649	63	8.85%	32	95.30%	19	23
28-Sep	3.58	413	43	9.43%	17	96.05%	18	47
29-Sep	5.66	741	132	15.12%	65	91.94%	17	47
7-Oct	4.01	452	81	15.20%	31	93.58%	15	47
8-Oct	3.95	450	63	12.28%	25	94.74%	15	47
12-Oct	4.28	469	52	9.98%	44	91.42%	15	47
13-Oct	5.28	619	97	13.55%	12	98.10%	17	47
13-Dec	5.52	565	76	11.86%	65	89.68%	13	25
Overall	99.06	10,834	870	7.43%	974	91.75%	8	47

TABLE 3
CGC Towline DSC Data

Date	Hours of Data	Total # of Reports	Reports rcvd w/no Cse/Spd	Percent Incomplete Reports	# of Reports Missed	Percent Success	RSS	
							MIN	MAX
25-Aug	1.96	117	4	3.31%	4	96.69%	22	27
26-Aug	3.11	524	0	0.00%	15	97.22%	19	27
30-Aug	0.07	8	0	0.00%	0	100.00%	23	24
31-Aug	0.42	38	0	0.00%	13	74.51%	8	19
1-Sep	3.55	373	0	0.00%	55	87.15%	8	29
27-Sep	5.64	628	0	0.00%	49	92.76%	10	32
13-Oct	4.75	552	2	0.36%	17	97.01%	20	26
13-Dec	0.42	39	2	4.88%	12	76.47%	11	20
Overall	19.92	2,279	8	0.35%	165	93.25%	8	32

operations of that vessel coincided with the *Vista Jubilee* schedule. All of the DSC data collected is summarized in Tables 2 and 3.

1) Coverage Area: A DSC coast station was established at the Castle Hill Coast Guard Station (near the mouth of Narragansett Bay). A Yagi antenna was mounted on an existing tower about 110 feet above sea level, and it was used to both transmit and receive. The Yagi had a 60° horizontal beamwidth and 9 dB of gain. It was aimed due North. This provided good coverage of the area traversed by the *Vista Jubilee*. The DSC receiver at the coast station provided relative signal strength (RSS) measurements which were included in the ADS report passed to the VTS Gateway. All the DSC ADS reports received from the *Vista Jubilee* and the *CGC Towline* were plotted on a chart of Narragansett Bay and have been shaded according to RSS value using MAPINFO™ (Fig. 3). Due to differences in the shipboard installations, the RSS values from the *CGC Towline* were different from those from the *Vista Jubilee* for a given location. This constant offset was calculated and used to adjust the *CGC Towline* values to match those of the *Vista Jubilee*. Reviewing Fig. 3, as expected, the RSS decreased as the vessels moved away from the Castle Hill station or as they moved outside the primary beamwidth of the antenna. The actual coverage was adequate throughout the Bay using the single coast station and antenna at Castle Hill. The only place where the vessels could not be reliably tracked was in Providence harbor.

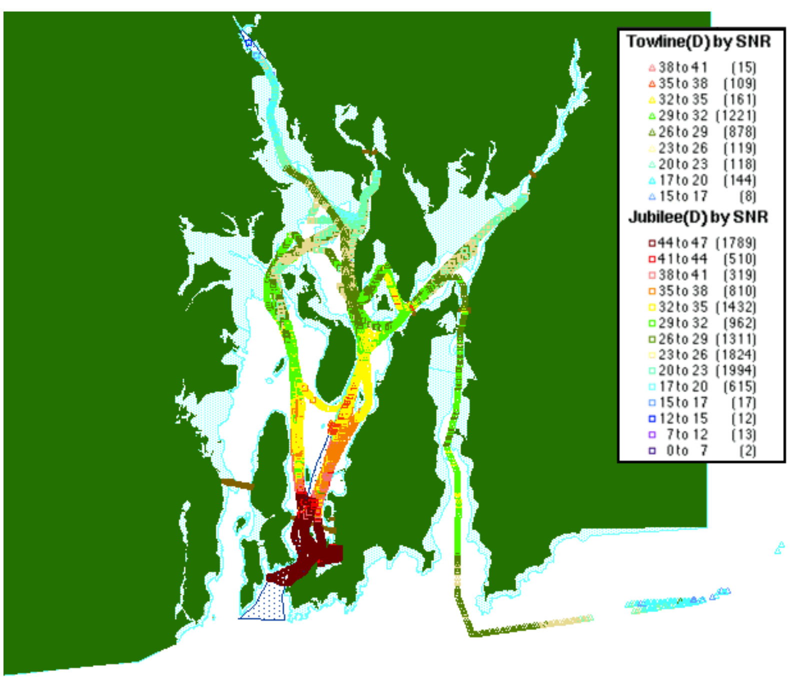

Fig. 3. *Vista Jubilee* and *CGC Towline* DSC reports shaded by RSS

2) Reliability / Integrity: The DSC system as a whole was very reliable. The results in Tables 2 and 3 show that almost 92% of the reports were received from the *Vista Jubilee* and 93% were received from the *CGC Towline*. During most of the test periods, the vessels operated in areas with adequate coverage. Missed reports were primarily due to a problem with the coast station transmitter. We found that occasionally the coast station DSC board would "lock up." Unfortunately, the only way to determine that this "lock up" had occurred was by not receiving reports from a local DSC transceiver. A process to monitor and correct this problem was automated; however, a complete polling cycle was lost each time a "lock up" occurred. The poor performance on 25 August was due to a faulty antenna installation at Castle Hill. When the antenna was replaced on the twenty-sixth, signals from the same geographic locations improved by 16 dB over their 25 August signals. The poor performance of the *Vista Jubilee* on 13 December and *CGC Towline* on 31 August was due to the vessels operating for part of the time in fringe coverage areas (low RSS).

A more troubling problem is the lack of complete data reports. This was more evident in reports from the *Vista Jubilee* than from the *CGC Towline.* We believe this problem was with the specific DSC radio or installation onboard the *Vista Jubilee*. In fact, no correlation of incomplete reports to RSS or geographic position can be found in the data. Additional testing conducted in the area around the R&D Center concurs with this. Why certain DSC radios sometimes fail to report complete data is still under investigation.

3) Reporting Interval / Latency: The coast station software used for the Narragansett Bay testing polled all vessels under test at identical intervals. A thirty second reporting interval was chosen to limit radio activity on GMDSS channel 70. The thirty second interval was judged to be long enough so as not to tie up the channel and short enough to allow adequate vessel tracking. In fact, a thirty second report interval, when combined with dead reckoning (DR) positions generated by the display system, was more than adequate to keep an accurate track of the vessels. In fact, it was found that, due to the slowly changing position dynamics of the vessels under test and the very accurate course and speed over ground provided by the DGPS, the DR positions were highly accurate.

The latency of a DSC report was found to be about four seconds. This was due in large part to operating the DSC equipment in a poll-response mode. This was done in order to maintain tight control on channel usage. The times required for the coast station to transmit a poll and for the shipboard radio to transmit a response are shown in Table 4. These values were also measured experimentally using an oscilloscope (last row of Table 4) and found to be quite close to those calculated. In addition to these times, there is some processing overhead on both ends. However, the biggest single factor contributing to the time required for a complete poll-response cycle is a provision of the DSC protocol that requires a random 0–2 second delay[2] prior to a poll response. This delay time was measured experimentally, and an average of 1.55 seconds was observed. Thus, on average, it requires 3.36 seconds plus processing overhead for a complete poll-response cycle. This limits a DSC coast station to about fifteen poll-response cycles per minute when using the channel 70 GMDSS frequency (realistically this would not be achievable because sometimes retransmissions are required).

4) Cost: It is difficult to fully assess the cost of a DSC ADS system. On the surface, it appears to be free. There is no cost for each transmission. However, the entire cost of installing and maintaining the system equipment must be recognized. Also, there are the incremental costs of operating the system. For example, the cost of items such as power, facilities, and spare equipment must be considered. Many of these costs would be dependent upon the geographic area being serviced; for example, the number of antenna sites required for coverage, availability of existing facilities, and local infrastructure costs. If there was an existing VHF-FM network, then DSC capability could be added for minimal additional cost. However, it needs to be recognized that ADS operational objectives could conflict with the existing VHF-FM needs.

TABLE 4
DSC Timing Calculations

	Individual Poll	Poll Response	Notes
Data Count to/from DSCPC Board	16 bytes	34 bytes	
Actual Data Bytes	15 bytes	33 bytes	
Header Info	14 bytes	14 bytes	Add in Format (2), Orig. Add (5), Freq info (6)
Total Msg Length	29 bytes	47 bytes	
10 bits per symbol	290 bits	470 bits	
Each Info symbol is xmted twice	580 bits	940 bits	
Phasing Sequence (6 DX, 8 RX)	140 bits	140 bits	
EOS (3 DX, 1 RX) plus cksum (2)	120 bits	120 bits	Using expansion data so double
Dot Pattern	20 bits	20 bits	
Total bits to transmit	860 bits	1220 bits	
Transmit at	1200 bps	1200 bps	
Transmit Time	**0.72 sec**	**1.02 sec**	**Calculated**
Avg. Transmit Time	**0.77 sec**	**1.04 sec**	**Measured**

[2] This is one manufacturers implementation to minimize call collisions and ensure that the provisions of Rec. 493 are met .

B. NY DSC Testing

During the Fall of 1995, additional DSC ADS testing was conducted in New York City. Two high-speed water taxis were outfitted with DSC ADS equipment. They made regular trips between Sandy Hook, New Jersey and lower Manhattan as well as occasional sight-seeing excursions around Manhattan. A DSC coast station was established at the USCG VTS located on Governor's Island using an existing omni-directional antenna about 100 feet above sea level. Coverage from this antenna was adequate for the New York harbor area, but it did not reach Sandy Hook, New Jersey.

Although the New York effort emphasized incorporation of the ADS reports into the existing radar-based VTS system, some interesting communications testing was also done. One way to increase DSC capacity is to use additional VHF-FM channels. During the New York tests, a working channel of 157.175 MHz (channel 83A) was used. Initial DSC contact was made on channel 70 and then the vessel's VHF radio was directed (automatically) to shift to the working channel, 83A. Periodically, an "all-ships" DSC call would be made on channel 70 in order to pick up any new vessels.

One major advantage to using the working channel was a faster "poll-response cycle." Because a working channel is not used for distress calls, there is no requirement for a delay prior to a polled response being transmitted. The radios used in these tests, the Ross DSC-500, had the feature of no delay when transmitting on a working channel. The delay between a poll being received and a response transmitted was measured experimentally using an oscilloscope. The average delay was approximately 0.2 seconds. Thus a poll-response cycle would take, on average, approximately 2 seconds versus the approximate 4 seconds discussed earlier for channel 70 polling. This represents a two hundred percent increase in channel capacity.

C. Conclusions

DSC is a viable choice for ADS in certain areas. The system's reliability and integrity are very good, and the latency on a working channel is also good. Coverage can be achieved using omni or directional antennas. Actual geography is an important factor in achieving adequate coverage and controlling the coverage area of a coast station. Depending upon the geographic area, several DSC sites might be needed. This increases the complexity of the system. In fact, one of the design challenges in the USCG Prince William Sound ADS system was the remote VHF-FM sites that needed to be installed and linked back to the VTC. The other calculation that needs to be made, is the cost of the system. Depending upon the area and vessel traffic density, it could be either inexpensive or quite costly.

For use in a VTS area of responsibility, the “poll-response” method of DSC has the information capacity to monitor the movement of all the large ships. The use of working channels can increase the system capacity. Also, installing multiple coast stations using VHF cellular siting strategies can significantly increase the data capacity of the overall system. Increasing VTS requirements to monitor the movements of smaller vessels could cause the reporting interval for larger vessels to increase. However, DSC can be operated in modes that can pass information more quickly than the “poll-response” method that was used during these tests. Use of any or all of these implementation alternatives can significantly increase the ADS capacity of DSC.

TABLE 5
Newcomb Satellite Data for Vista Jubilee

Date	Hours of Data	# of Reports Rcvd	# of Reports Missed	Percent Success	# Reports Missed per Interval			# of Intervals per dataset	# Intervals >1 report missed	% Single Miss Intervals
					Max	Mean	Std Dev.			
25-Aug	5.24	1,715	73	95.92%	8	1.35	1.20	55	7	87.27%
26-Aug	4.36	1,357	44	96.86%	4	1.42	0.83	31	8	74.19%
29-Aug	4.23	1,331	79	94.40%	17	1.80	2.94	44	8	81.82%
30-Aug	5.69	1,867	32	98.31%	2	1.14	0.35	28	4	85.71%
31-Aug	3.86	1,260	26	97.98%	4	1.30	0.71	20	4	80.00%
1-Sep	5.51	1,759	80	95.65%	4	1.27	0.65	63	12	80.95%
2-Sep	3.84	1,214	66	94.84%	9	1.83	1.82	36	11	69.44%
7-Sep	4.01	1,268	71	94.70%	16	2.03	2.72	35	13	62.86%
11-Sep	2.33	751	23	97.03%	3	1.15	0.48	20	2	90.00%
14-Sep	0.79	266	2	99.25%	1	1.00	0.00	1	0	100.00%
15-Sep	8.38	2,658	123	95.58%	6	1.41	0.87	87	22	74.71%
16-Sep	6.32	2,023	36	98.25%	3	1.13	0.42	32	3	90.63%
20-Sep	6.87	2,076	71	96.69%	9	1.54	1.44	46	11	76.09%
27-Sep	5.69	1,852	40	97.89%	12	2.22	2.78	18	4	77.78%
28-Sep	2.59	826	34	96.05%	3	1.21	0.49	28	5	82.14%
29-Sep	6.65	2,120	106	95.24%	13	1.71	2.19	62	14	77.42%
7-Oct	3.98	1,279	45	96.60%	5	1.32	0.87	34	6	82.35%
8-Oct	3.89	1,204	88	93.19%	24	2.38	3.95	37	12	67.57%
12-Oct	1.50	467	30	93.96%	4	1.30	0.69	23	5	78.26%
14-Oct	5.33	1,704	32	98.16%	3	1.28	0.53	25	6	76.00%
22-Oct	0.30	93	8	92.08%	3	1.33	0.75	6	1	83.33%
13-Dec	3.85	1,236	41	96.79%	9	1.37	1.45	30	4	86.67%
Overall	95.21	30,326	1150	96.35%	24	1.51	1.73	761	162	78.71%

IV. NEWCOMB SATELLITE

The Newcomb Satellite system was developed, in part, under a Small Business Innovative Research (SBIR) contract with the Coast Guard R&D Center and is described in detail in [7]. Newcomb Communications designed and built small satellite terminals to use the RDSS band (1610-1626.5 MHz). The Earth Station used was operated by Mobile Datacom (MDC) in Clarksburg, MD.

A. Evaluation

One Newcomb CP-1 (transmit only) ADS unit was used during the Narragansett Bay testing. It was installed on the Vista Jubilee. An additional unit was installed on a research vessel local to the R&D Center (the *Envirolab II*). It was used to check the system operation. Both units were on continuously and they transmitted reports every 10–12 seconds, twenty-four hours a day. However, all of the transmitted information was not recorded as much of the time the vessels were at the pier. Data recording was scheduled during the underway trips of the *Vista Jubilee* and over ninety-five hours of data was recorded (Table 5).

1) Coverage Area: The Newcomb CP-1 utilizes a geostationary satellite and therefore has broad geographic coverage. At L-band frequencies the satellite footprint is quite large. Coverage is good throughout CONUS and out to more than two hundred miles off-shore. In fact the satellite has been successfully used as far North as the North Slope of Alaska [8]. The coverage in the Narragansett Bay area was thus quite good. Fig. 4 shows all of the Newcomb ADS reports received in the Narragansett Bay area.

2) Reliability / Integrity: The Newcomb system proved to be the most reliable of the three systems tested. Overall, greater than 96% of the reports transmitted from the *Vista Jubilee* and greater than 97% from the *Envirolab II* (not shown) were received. When a report was not received, in most cases (~79%) it was a single missed report. There were some long periods when as many as twenty-four consecutive reports were missed. An estimated position, course, and speed was calculated for each missed report. Plotting these estimated positions did not show any geographic correlation. However, analysis of the data and additional experimentation did reveal that the success of the transmission was sensitive to the heading of the *Vista Jubilee*. The antenna, although nominally omnidirectional, exhibited definite pattern nulls when installed aboard the *Vista Jubilee*. Fig. 5 shows a bar graph of the percentage of missed reports as a function of ship’s course. A percentage of all reports for a particular heading plus or minus two degrees is used since the ship did not travel all headings equally. In this figure, one large and two smaller nulls can clearly be seen. When the vessel operated in a direction outside of the nulls, the performance was close to 99% successful.

A similar analysis was not done on the *Envirolab II* data to determine if installation induced nulls existed. Due to a peculiarity in the GPS board used in the Newcomb CP-1, all speeds less then 0.5 knot result in the course and speed both being filtered to zero. Since the *Envirolab II* spent most of her time sitting in different locations taking water and

Fig. 4. Newcomb ADS Reports Plotted on the Chart of the Narragansett Bay in MAPINFO™

sediment samples, and at slow speeds trawling, most of the reports from her have zero course and zero speed indicated. There was not enough data (with valid courses and speeds) to evaluate.

Due to the nature of the CP-1 transmission (digital, Direct Sequence Spread Spectrum, with Forward Error Correction), if a report was received, it was received correctly. The integrity of the reports was very good.

3) Reporting Interval / Latency: The reporting interval for the CP-1's was controlled by a value that was loaded into the EPROM by the manufacturer and could not be easily changed. We requested and used for all of our testing, the minimum interval possible for the CP-1 transmitters—around 10–12 seconds. The units, would transmit on their own clock as long as they were powered up and the GPS receiver was locked onto three or more satellites. No polling was required.

The latency of received reports at the VTS Gateway was variable. All of the transmitted reports would be received at the MDC Earth Station very quickly (propagation delay of about 0.25 seconds). The Earth Station imposed some processing delay in despreading and decoding the signal and providing the data to our electronic mailbox on their system. The variability came in the connection method between the VTS Gateway and the Earth Station. If a direct modem connection was made and maintained, the overall end-to-end latency was about two seconds. However, if a TELNET connection was made across the Internet, the latency ranged from two seconds to two minutes depending upon traffic loading. Although, the latency with the Internet connection was generally comparable to the direct modem connection, it was unpredictable. When we wanted guaranteed minimum delay, we would use the direct modem connection.

As a matter of interest, the latency seen at the display system was closer to six seconds. The display system used, was designed to calculate the age of the ADS report based upon the time tag of the GPS position and the current GPS time. In another design quirk, the CP-1 did not transmit the most recent position. It was usually about four seconds old. Thus, even though the ADS reports would be received in one to two seconds after transmission, the GPS position was actually five to six seconds old.

4) Cost: This satellite system was being developed under an SBIR contract for the Coast Guard R&D Center and the system was still under development at the time of our ADS testing. As a result, the service was free. As a commercial system, there would be a charge to use it, either a flat monthly fee and/or a charge per packet. Although the actual cost is unknown, we estimate that it would probably cost about $400 per month for four hours of use each day.

B. Conclusions

The Newcomb system performed well as an ADS communications method. The coverage, reliability, integrity, and latency were all very good. Because of the space infrastructure available for this satellite-based system and the compact size of the Newcomb ADS transponders, it was very easy to install this ADS capability on vessels in the field on

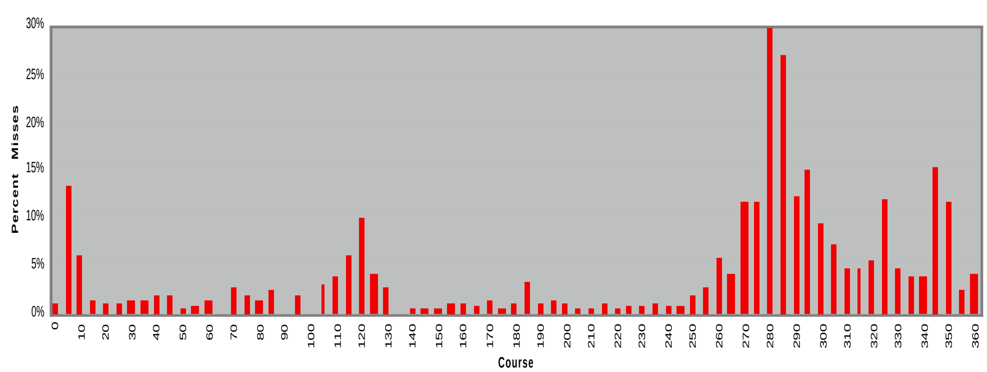

Fig. 5. Vista Jubilee Newcomb Performance as a Function of Course

short notice. This was done several times: a Pilot vessel in the Narragansett Bay, a riverboat and a Coast Guard buoy tender on the Mississippi River in New Orleans, a water shuttle and a tugboat in New York harbor, and even a Coast Guard helicopter. ADS reports from all of these platforms were easily brought into the VTS display system due to the use of a single Earth Station connection. A system such as this is a very good technology for ADS use. Although there could be problems with using the Newcomb system in the future (the FCC has given the Big LEO systems priority in the RDSS frequency band), the system is representative of other packet data satellite systems.

V. VOICELESS VTS

A. ADS, the transponder element of Voiceless VTS

The USCG research program is developing and evaluating technologies that will support a concept described as “voiceless VTS.” This automated dependent surveillance research was conducted to assess typical transponder capabilities within the context of the voiceless VTS design concept. Automation of the vessel reporting process reduces the operator workload at the vessel traffic center and increases the accuracy, frequency, and timeliness of vessel reports. The combination of automation and timeliness opens the opportunity for the VTS to provide navigation grade information.

B. Voiceless VTS— Concept Overview

The concept of voiceless VTS is based on the idea that VTS information should be automatically transferred between the VTS computers and computer systems aboard each ship. Such a facility would significantly reduce the need for voice communications between the VTS and each ship’s pilot. The voiceless VTS concept is developed by considering a series of four simple models. Each model centers on the ship piloting process and the need for good decision making information. Each model represents alternative methods of acquiring and presenting navigation information to the ship’s piloting process. In the four models, the piloting process is assumed to be performed by a human. The first model depicts traditional piloting in the absence of a VTS. The second model represents the marine piloting process where VTS information is available. The third model represents the change being made to traditional piloting using electronic navigation technology that is now becoming commercially available. And the fourth model is a general concept of how piloting processes can gain better access to VTS information in the future. The commercial components for the fourth model, voiceless VTS, need to be developed and integrated.

1) Model 1: Normal marine piloting is accomplished with the assistance of navigation information. It is the responsibility of the navigator to gather information relevant to the safe piloting of the vessel and present the information to the pilot. When piloting in coastal areas, a nautical chart provides a good backdrop upon which to present information. It contains the geographic information needed by the pilot. The gathering of navigation information and the piloting process has traditionally been the responsibility of one or more persons. The interaction is represented in a simple diagram, Fig. 6.

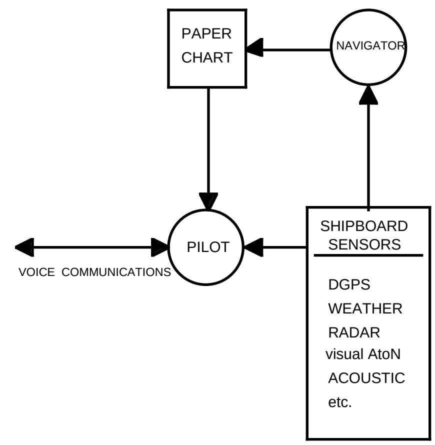

Fig. 6. Simple model of normal marine piloting process

The circles in Fig. 6 represent the human processes. The boxes represent the tools that the human processes depend upon for their decision making. The lines with arrow heads represent the general flow of navigation information supporting the pilot’s decision making process. Voice communications is the only real time information link used by the pilot to exchange information with other vessels. This model serves the marine world very well. Notice that improving sensor technology simultaneously improves both the navigation and piloting processes.

2) Model 2: There are geographic areas where conditions cause problems that diminish the performance of the first model. One method, that has been found to be successful in recovering or improving performance, is a vessel traffic service. The vessel traffic service (VTS) is a shore facility staffed with operators familiar with the problems facing a pilot navigating a specific geographic area. Using shore facilities, such as radar, video, hydrographic instruments, weather sensors, etc., the VTS operator is able to create, update, and maintain a current waterways management overview for a particular section of the waterway known as an AOR (area of responsibility). In modern VTS systems, this information is maintained in a database located in a single computer. Larger VTS areas are subdivided into AORs based on the amount of information one VTS operator can reasonably manage. In a modern VTS AOR, this information is exchanged with the vessel pilots using voice

communications. A diagram of this augmentation is shown in Fig. 7.

Like the pilot, the VTS operator performance can be improved by improving the sensors that acquire information for the VTS database. The research work presented in this paper supports the view that shipboard transponders are sensors that improve the quality of the database and improve VTS operator performance. As new technologies, such as transponders, are added to the VTS operation, the voice communications link becomes the limiting factor in moving information from the VTS to the ship. Future USCG research will investigate digital technologies that could be used to move VTS database information to each ship.

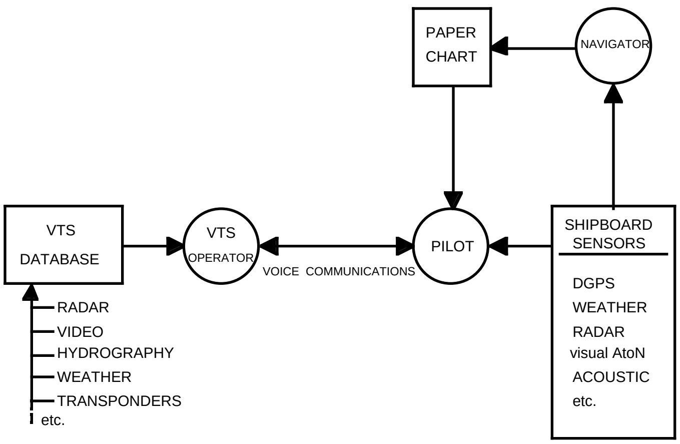

Fig. 7. Normal marine piloting model augmented with VTS information

3) Model 3: The improvement of shipboard sensors, in particular, the introduction of Differential Global Positioning System (DGPS) technology and the creation of electronic chart replacements for the paper chart, is making it possible to automate the bulk of the navigator's responsibilities. Fig. 8 shows the impact that electronic chart systems (ECS) are already having and will continue to have on traditional piloting. Many of the human navigator responsibilities are being automated, and the word "*navigator*" will become a term for a machine rather than a person. The automated presentation of information has also allowed the industry to improve the efficiency and effectiveness of the interface with the ship's pilot. Many features, such as grounding warnings, are now a routine feature of an ECS where they previously were too computationally prohibitive for a human navigator using paper charts.

4) Model 4: It is reasonable to expect that the ECS will also be the system that processes navigation information provided by the VTS. The creation of an automated data path from the VTS database to the ECS can be approached two ways; wireless digital communications technology can be used to access the database using TCP/IP Internet-like solutions, or the navigation related contents of the database can be distributed in a wide area digital broadcast. Future USCG research will investigate the digital broadcast option (Fig. 9). By automating the exchange of VTS navigation information, the need for voice communications between the VTS operator and pilots can be reduced. This should allow more time for the operator to acquire and validate information. It may also be possible to increase the size of a VTS operators AOR, and reduce the total number of operators needed for a given waterway.

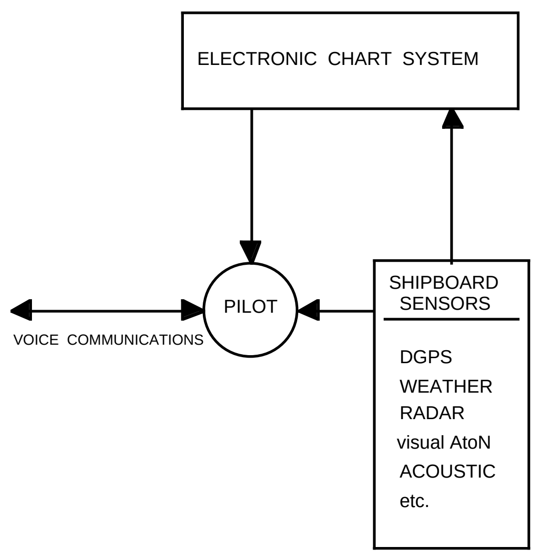

Fig. 8. Marine piloting with electronic charts

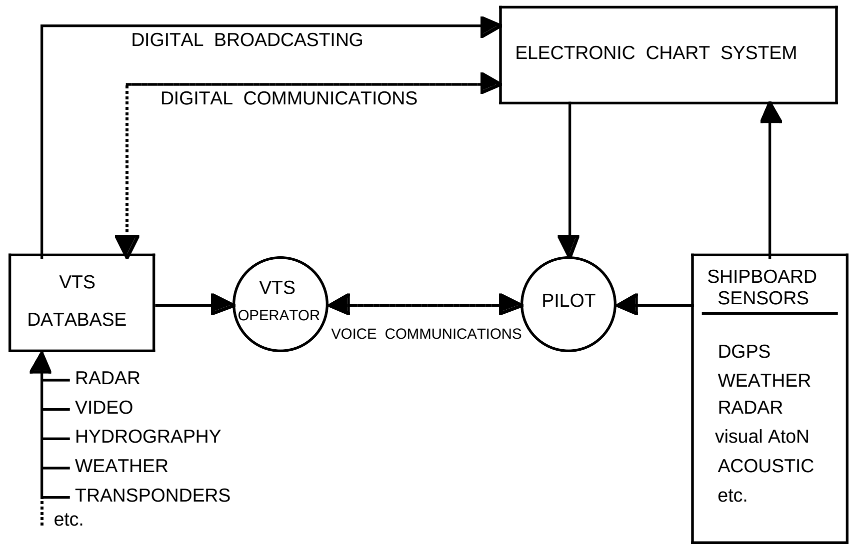

Fig. 9. Marine piloting with electronic charts and augmented with voiceless VTS information.

C. Conclusions

A number of benefits would be realized with the deployment of voiceless VTS. First, the digital broadcasts would gradually become the primary source of VTS information. This would significantly reduce the amount of voice communications between pilots and the VTS operator. Second, the workload of the VTS operator would be reduced. Third, the quality of the VTS information would improve and the increased handling capacity would allow more types of information to be provided. Fourth, the VTS information would go automatically to the ship's computer systems, systems such as an ECS, and be immediately available for custom shipboard processing. Fifth, the ships pilot would have immediate access to timely VTS information without the burden of requesting and handling the same information using voice communications. Finally, automated VTS technology may be viewed as an enhanced port facility.

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