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A large, suspended ocean measurement structure was developed and operated. The structure was a tripod configuration 5100 m high with a base footprint of 6190 m, all of which is suspended by a single 6150-lb buoyant float. The three 6200-m-long legs contained environmental measurement instrumentation and engineering sensors located in the top 2150 m of the legs. Communications with the system was via a single steel coaxial cable, which also moored the tending vessel during operation. This paper focuses on the ocean engineering for developing, testing, and operating the system. A new, lightweight cable design facilitated storage, deployment, and retrieval of more than 18,600 m (10 nmi) of cable from a relatively small, 210-foot-long tending vessel. The deployment scenario was optimized to allow this single vessel to transport and deploy over 67 tons of system equipment. An acoustic positioning system was employed to "fly" the 7000-lb anchors to precise bottom locations. The system was the largest ocean measurement structure to be successfully deployed in the deep ocean (5200 M).

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Development, Testing, and Operation of a Large Suspended Ocean Measurement Structure for Deep-Ocean Use

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ABSTRACT

A large, suspended ocean measurement structure was developed and operated. The structure was a tripod configuration 5100 m high with a base footprint of 6190 m, all of which is suspended by a single 6150-lb buoyant float. The three 6200-m-long legs contained environmental measurement instrumentation and engineering sensors located in the top 2150 m of the legs. Communications with the system was via a single steel coaxial cable, which also moored the tending vessel during operation. This paper focuses on the ocean engineering for developing, testing, and operating the system. A new, lightweight cable design facilitated storage, deployment, and retrieval of more than 18,600 m (10 nmi) of cable from a relatively small, 210-foot-long tending vessel. The deployment scenario was optimized to allow this single vessel to transport and deploy over 67 tons of system equipment. An acoustic positioning system was employed to "fly" the 7000-lb anchors to precise bottom locations. The system was the largest ocean measurement structure to be successfully deployed in the deep ocean (5200 m).

INTRODUCTION

The Navy has the need to deploy large measurement systems in deep water for monitoring environmental parameters. Some of these systems must span the complete water column and provide a stable structure for performing the measurements. The measurements need to be monitored in real time to provide the scientist with the ability to alter other experiment assets with changes in the environment. Such a requirement existed for a system to be used in a summer 1991 experiment. This led to the development, testing, and operation of a buoyed, suspended, three-legged tripod cable structure 5100 m high and a base footprint of 6190 m.

Background

In 1969, a large, three-legged structure was deployed in 3 miles of water. The structure consisted of three each 4-mile-long cable legs, three 23,000-lb anchors, a 26,000-lb buoyant apex buoy, and approximately 4000 glass floats attached to the legs to render them neutrally buoyant. The total equipment load on the deployment vessel was 425 tons. A second simpler structure, but of the same magnitude, was deployed in 1970. Both structures failed to produce data due to steel armor cable kinking, conductor insulation lack of integrity and the general difficulties in deployment. The conventional technology base of steel double-armored well-logging cable simply did not meet the requirements of long, suspended, neutrally buoyant cables populated with a multiplicity of sensors.

Thus, in 1971, the Navy initiated a program to develop the components and techniques to meet this explicit requirement. This program ultimately produced the Kevlar instrumented cables and the torque-free, lightweight steel cables now commonly used today. Although many instrumented structures and systems used this evolving technology base in the ensuing years, the Navy's vertical instrumented cable system deployed in 1988-1989 clearly demonstrated the feasibility of future volumetric structures at modest cost and deployment scenarios.

This structure consisted of a single moored vertical instrumented cable, which spanned the water column in 3 miles of water; a mass weight anchor and 5 miles of spaced armor; 0.69-inch coax cable, which served the multiple functions of lowering the anchor to the seafloor, mooring the structure-tending ship, and communicating with the multiplexed instrumented cable system. This single example clearly showed that a multiplicity of legs could be deployed, utilizing the same components and procedures.

Technology

The Kevlar instrumentation cable was the fundamental component that made the instrumented structure feasible within many interlocking constraints, such as cost, time, deployment vessel and machinery, contracting, staffing, etc. This free-flooding, 0.95-inch diameter cable had a breaking strength in excess of 20,000 lb, an in-water weight of 0.33 pound/meter, and a maximum stretch of only 0.6 of 1% at its deployed tension. In addition, it was equipped with a filament fairing to suppress strumming. Conductors were easily accessed anywhere along its length for sensor placement, was terminated with a simple Kevlar grip, which would allow the jacketed cable to pass through the terminations. The resulting structure cable could be easily coiled in coiling tanks with a minimum 3-foot diameter, which in turn provided for water bath testing and storage without concern for corrosion.

A similar transmission cable utilizing a single 0. 56-inch coax, but with a Kevlar 49 strength member, had the phenomenally low elastic stretch of only 0.2 of 1% at a working load of 3000 lb.

References and illustrations at end of paper.

Given these lightweight cables, the entire structure legs were rendered slightly positively buoyant by using approximately 110 clamp-on syntactic foam cable floats. Advances in this material provided cost-effective floats that would provide 50 to 70 pounds of buoyancy, could withstand pressure up to 6000 m deep, and be applied to and removed from the cable in approximately 30 seconds.

The third essential component for the system was 9100 m length of spaced armor steel coaxial umbilical cable. This cable was used to lower the 7000-lb anchors to the seafloor in 5200 m of water. The ship was then moored for several days; the potential of kinking the cable at the seafloor touch-down location was ever-present. The cable's length was predicated by the depth of water and mooring scope to hold the ship. Given the length, the diameter was constrained to 0.69 inches, which was based on a previous design and the traction winch capacity of the deployment ship.

The resulting spaced armor cable had a modest in-water weight of 1.0 pound/meter, a measured breaking strength in excess of 21,000 lb and a near-linear torque of only 21 inch-pounds at 10,000 lb tension, a nonrecoverable stretch to 10,000 lb of 0.2 of 1% and an elastic stretch of 0.5% at 3000 lb and approximately 1% at 10,000 lb. (These numbers are given for comparison with its Kevlar counterpart.) This amazing cable was used repeatedly to lower anchors to the seafloor, to go slack, to release the anchor, and to be recovered. In one occasion, the anchor was pulled out of the mud and raised to the surface, which produced tension with approximately 75% of yield.

The structure employing these components, depicted in Fig. 1, is configured with three legs of equal length. All three legs are instrumented with environmental measurement sensors distributed over the top one-third section of each leg. These sections also contain engineering sensors (shape and tension) to measure parameters for assessing structure shape. Two of the legs (Leg 1 and 2) are secured from the instrumented sections to the anchors with mooring line. The third leg (Leg 3) employs a synthetic fiber strength member coaxial transmission lead-in cable from the instrumented section to its anchor. The lengths of these legs combined with the structure height result in a leg tilt angle of approximately 35 degrees referenced to vertical.

The total structure is suspended with a syntactic foam (caged multiple blocks) buoy at the apex. The telemetry data from all the sensors is communicated via a steel coaxial umbilical cable attached from the leg 3 anchor to the tending vessel. This cable also moors the tending vessel throughout the experiment measurement period. The anchors are placed at precise locations with a transponder-based navigation system operated from the deployment/tending vessel. A 210-foot-long oceanographic research vessel deploys, tends, and transports all structure components - all of which weigh about 67 tons.

HARDWARE CHARACTERISTICS

Structure and Deployment Hardware Description

Cables

The major system components are also identified in Fig. 1. The top 2150 m of each leg consist of six identical electromechanical cable sections. These sections contain 15 twisted-pair electrical leads and a Kevlar overjacket strength member. The mechanical breaking strength of all cables/components is at least 20,000 lb. The Kevlar is then overbraided with a nylon jacket containing a filament fairing to reduce strum. The termination points between each section contain either a telemetry multiplexer (three/leg) canister or a mechanical dummy termination. The engineering sensors are attached at these termination points. Legs 1 and 2 employ 4050 m of a Kevlar lead-in (mooring line) between the cable sections and the anchors. These lines also have the filament fairing. Leg 3 has 4050 m of a coaxial lead-in tranmission cable overjacketed with a Kevlar strength member and the filament fairing. The coaxial umbilical cable running from anchor 3 to the tending vessel is a spaced armor, low-torque, steel cable that is 9100 m long and has a 21,000-lb break strength. This cable is the communication link to the system and is also used to moor the tending vessel during the operation.

Buoyancy

The legs are rendered slightly positive buoyant when block syntactic foam flotation is attached along the total length of the legs. A low-density (37 pounds/cubic foot buoyancy) foam is used down to a depth of 2000 m and a higher density (29 pounds/cubic foot buoyancy) foam is used at greater depths. A total of 110 floats, each 2 ft^3 in size were used. The result of this flotation was to render each leg about 850 lb positively buoyant. These floats were designed to clamp on the cable, which made attaching/removing the floats quick and easy. The apex buoy employed 95 low-density floats of the same design as that used on the legs. The apex floats were contained in an aluminum cage that measured 7 ft x 7 ft x 4 ft and resulted in 6150 lb of buoyancy. A radio beacon and a light flasher, each of which would activate when the buoy was on the surface, and a radar reflector were attached to the buoy.

Anchor Assemblies

The anchors were a basic clump design with 18-inch flukes on one end to help prevent dragging, and each weighed 7000 lb in water. The lowering point was positioned so that the anchors would not rotate during deployment. The structure's mooring lines and coaxial cables were attached at the anchors through a pair of acoustic releases/transponders. Dual-release packages were employed to improve reliability in the event of a single release failure. The communication cable for leg,3 was faired through the anchor for protection and terminated at the anchor with an electrical quick-disconnect connector. This connector kept the cables from flooding during the recovery operation.

Deployment Handling Equipment

Only a minimum of special handling equipment was required beyond that provided by the vessel. A "V" puller sheave was designed that clamped on the deck capstan and was the primary device used in recovering of the neutrally buoyant structure cables. The structure cables were fairleaded to the "V" puller through a special 4-ft-diameter snatch block sheave. The structure legs were coiled in three individual tanks, 8 ft diameter x 4 ft high, for storage and transportation. The legs were hand-deployed from these tanks. A fourth tank, 6 ft diameter x 2 ft high, was used to store spare leg sections. The remaining handling equipment is discussed below.

Tending Vessel

The USNS LYNCH was used during the development and testing phase and on the experiment. This vessel was built in 1965 to support Navy oceanographic and geophysical experiments.. (Note: Subsequent to the summer 1991 operation schedule this vessel has been laid-up.) The handling equipment was designed for deep-water use. The vessel was 210 ft long with a 39 ft beam. It had a single screw and a bow thruster. The operation employed two winches, which were part of the vessel's support equipment. The first was a direct drive drum winch, termed the intermediate winch, containing 7000 m of 3 x 19 one-half-inch crown wire rope. This winch was to be used for the lowering legs 1 and 2 anchors. The second winch was a traction winch used for lowering the leg 3 anchor. This unit had two supply drums available, and each contained 9100 m of the coaxial umbilical cable. One cable was a spare. In addition, instrumentation was provided for measuring cable-out and tension for each winch system. A stern U-frame was employed for overboarding large loads, the apex buoy, and the anchors. The structure's leg flotation blocks were stored in the hold below the main deck fantail area.

Anchor Navigation System

The anchor navigation system places each anchor at a specific location during the deployment operation. The placement of the anchors controls the structure's leg tilt angles and orientation; therefore, precise knowledge of anchor location is required. The navigation system provides the Deployment Director with critical information required to position the vessel during the deployment.

The following equipment was used for anchor navigation: navigation transponders; position processor; acoustic transceiver; and acoustic releases/transponders.

The navigation transponders are common interrogate, at 11 kHz, and unique reply. These transponders provide the navigation data base necessary to navigate the anchors to their locations and to position the ship within the net. They are bottom-mounted and suspended 100 m above the bottom in the immediate site area. The acoustic releases/transponders located on the structure legs at the anchors have two receive/transmit channels. The channel used for anchor navigation receives at 9 kHz and transmits at 11 kHz.

The position processor contains a control computer, a data processor, a 4 Mbyte RAM and an 85 Mbyte Winchester drive for storing data and programs. The processor uses UNIX as its multiuser, multitasking operating system. It has nine RS-232 ports to run a display console, a printer, an acoustic transceiver, a GPS receiver, and a remote monitor. The processor also drives a nine-track magnetic tape unit for permanent data storage.

The acoustic transceiver is a modular microprocessor-controlled navigation and command unit. It can transmit and receive at multiple frequencies through the shipboard interrogate transducer. The transmit-interrogate frequencies are between 7 kHz and 17 kHz with a 191-dB//µPa @ 1-m source level.

To navigate the location of the bottom-mounted transponders, a sound speed profile must be taken and entered into the computer. The desired location and its estimated depth are entered for each transponder. The transponders are then dropped as close as possible to their desired location. The ship then travels back and forth over the transponders' locations at various ranges to collect sets of travel time measurements. Better results will be obtained with more range sets. All data are collected while the processor is operating in a navigation mode, which allows comparing the location of the transponders to the GPS. This routine results in determining the precise location and depth of each transponder.

The acoustic release/transponders are set to listen at 9 kHz and to reply at 11 kHz. Therefore, the acoustic transceiver is set to transmit at 9 kHz. This frequency interrogates the releases and causes them to reply at 11 kHz, which in turn interrogates the navigation transponders, and they reply at their unique frequencies. This data set allows the navigation system to calculate the location of the anchor. The ship's location is tracked at the same time, thus allowing positioning of each reference to the transponder net.

Communications System

The increasing sophistication of numerical models of oceanographic measurement has placed stringent requirements on the design of engineering systems to acquire and process oceanographic data. The communications system is a multichannel oceanographic data acquisition system designed to acquire calibrated oceanographic data at full ocean depth and to telemeter these data to a surface platform.

The system consists of two groups of electronic equipment, the subsurface equipment suite and the shipboard equipment suite (see Fig. 2).

Subsurface Equipment

The subsurface equipment consists of one steel electromechanical coaxial umbilical cable 9100 m long, a telemetry repeater, a Kevlar electromechanical coaxial lead-in cable 4050 m long, a power splitter/repeater, 18 (6 per leg) Kevlar electromechanical data cables 345 m long, 9 (3 per leg) telemetry/control canisters and 198 (66 per leg) oceanographic/engineering sensors. Each of the 9 telemetry/control canisters control 22 data channels. These canisters also transmit the 22 data channels to the shipboard equipment using frequency-division multiplexed amplitude modulation (AM). The analog AM system was chosen because of the long lengths of cable (during the system development period, fiber optic cables were not available). The bandwidth of the cables used were simply not great enough for digital data transmission. The total frequency spectrum used for the data transmission was from approximately 200 kHz to 500 kHz. The cable attenuations of these frequencies required that two repeaters (amplifiers), identified on the figures as the power splitter and repeater, be inserted to maintain that each data channel's dynamic range was greater than 60 dB. All control/telemetry power was supplied from the surface ship. The power splitter, located on leg 3, incorporated the provision for independent power/signal paths for each leg, thus reducing the risk of losing the complete system in case of a seawater leak in any one leg.

Shipboard Equipment

The shipboard equipment consisted of a cable interface box, a system control computer, a high-voltage direct current power supply, AM frequency band equalizers, 198 AM demodulators, 180 channel sample and hold circuitry, a 12-bit analog-to-digital converter, a pulse-code modulation (NRZ-L) formatter, an engineering sensor period counter and display computer, a time code generator, and an 8-mm digital cassette recorder. The AM telemetry signals are stripped off the coaxial umbilical cable and brought to the AM frequency band equalizers. The equalizers amplify each control/telemetry canister's packet of 22 data channels to the appropriate levels for the demodulators. The demodulator outputs are then either sent to the sample and hold circuitry or to the engineering sensor period counters. The signal is then digitized and formatted to be recorded on the 8-mm recorder. The time code information is also embedded in the digital data stream, allowing an accurate time stamp for the recorded data. The control computer allows the shipboard personnel to control various functions of the subsurface control/telemetry canisters, as well as to monitor certain parameters of the subsurface system.

Engineering Sensor Suite

Sensor Type

Two types of sensors were used for determining the physical orientation and configuration of the structure: shape and tension. The shape sensor measures tilt in two dimensions, heading (with respect to the sensor case), pressure, temperature and conductivity of seawater. The tension sensors measure the leg tension via in-line load cells at the top and bottom of each leg.

Shape Sensor Description

The primary function of the shape sensor is to measure the legs' degree of tilt (from vertical) and the direction of that tilt. The secondary function provides measurements of temperature, pressure and conductivity of seawater.

Tilt magnitude is measured by two vertical sensing electrolytic potentiometers mounted in a precision holder to provide the two horizontal axes. The tilt transducer holder is mounted on the top plate of the heading transducer with one axis (the y-axis) aligned with the north reference. Tilt direction is calculated from the heading transducer output and the tilt magnitudes of the two tilt transducers. Because the heading transducers report the orientation of the tilt transducers, the engineering sensor housing can be attached to the leg without regard to physical orientation, except that it must be parallel to the long axis of the structure leg. Temperature, pressure, and conductivity are sensed by transducers that protrude from one endcap of the pressure housing.

A cylindrical, nonmagnetic pressure housing of 4-inch diameter and 19-inch length encloses the interface electronics and transducers of the sensor. The shape sensor has approximately 3 lb of negative buoyancy.

Tension Sensor Description

The tension sensor measures the tension of the structure legs caused by the combined excess buoyancy of the distributed floats and the apex buoy working against the weight of the structure cable and drag caused by ocean currents. The tension sensor has a separately mounted pressure-compensated load cell that is mechanically attached to the structure leg cable and is electrically attached to the sensor housing that contains the interface and telemetry electronics. The sensor housing is 3.87 inches in diameter and is 16 inches long. The tension sensor with load cell has approximately 17 lb negative buoyancy.

Sensor Attachment Description

The sensors are enclosed in a schedule-40 polyvinylchloride (PVC) housing for protection against handling and deployment mishaps. The PVC housing is bolted at the section's termination points to an aluminum strength member that serves as the load-bearing member for the structure cable tension. The sensor is attached to the PVC housing by stainless steel straps. Cable pigtails are secured with plastic tie-wraps and taped to prevent loose sections and to streamline the installation to the maximum.

Sensor Data Telemetry

Data are transmitted by the engineering sensor to the multiplexer canister on the same two wires that provide power to the sensor. The multiplexer transmits the sensor signal to the surface as a specific carrier frequency. The transmitted signal is demodulated and is sent to custom-designed period counters. The period counters determine the frequency of the signal to a resolution of better than 0.1 percent and convert the signal to a digital representation that is recorded and converted to engineering units by a custom-designed software program. When the raw data are converted to engineering units, the sensors' parameters are identifiable as real-world data, i.e., temperature, depth, tilt, etc.

DEPLOYMENT SCENARIO REVIEW

The major constraint on the deployment plan was the requirement to deploy the entire system from only the 26-year-old LYNCH, employing only existing deck and winching equipment. This problem was further aggravated by an ever-changing crew, who in most cases, were not familiar with its operations, the deployment procedures, or the technology involved. Principal constraints were a small deck space of only about 28 ft x 40 ft, a maximum payload-carrying capacity of about 70 tons, no at-sea deck-service crane, and as it turned out, a single traction winch for anchor deployment.

The solution was a very simple deployment plan made possible by the friendly components previously described. Central to the plan was coiling each leg completely made up and tested, in a coiling tank 8 ft in diameter and 4 ft high. Thus, to deploy a leg, the instrumented cable was payed out from the tank by hand and on demand as the ship proceeded down the track at approximately 1 kt. Syntactic foam cable floats were clamped on along the way, which in turn floated the cables and in the process avoided the need for holding back machinery. Instruments thus attached to the cable did not have to negotiate winches, capstans, or other conventional cable-handling equipment.

Recovery was basically the same process in reverse, except inhaul was assisted by a "V" puller clamped to an existing deck capstan. All lifting was done with the stern "U" frame. Anchors were snaked in place via the deck capstan, "U" frame, and associated winch.

Fig. 3 illustrates the deck layout and shows the necessity of deploying one leg from a tank placed on the second deck. The deployment steps were as follows:

- Initiate leg one 7 miles down-track by placing the apex buoy in the water, paying out the leg on demand as the ship proceeds at approximately one knot up track. Once the leg is deployed and floating on the surface, the anchor is hoisted into the water via the "U" frame and lowered away at approximately 1 kt. As the anchor nears the bottom, the ship maneuvers it in place with the aid of information from the anchor navigation system. Once on bottom, the lowering cable is released via an acoustic release and recovered while the deck is being prepared for the next leg deployment.

- The second leg is deployed in the same manner. The second leg is attached to the apex buoy, which is now moored via the first leg in a single point mooring and tending down-current. The ship then proceeds in the mandatory direction, paying out cable and then lowering the second anchor in place. In the process, approximately 11 miles of cable is swept through the 3-mile-deep water column. Because of the high drag, relatively low breaking strength, and lack of gravitational catenary on the cables, this, has to be done in a very gingerly fashion.

- Finally, the last leg is deployed, but in the process of setting the anchor, the apex buoy is hauled down to its desired depth. An additional 2 miles of cable is laid on the bottom for mooring scope. At the end, the ship slows, secures cable payout, and proceeds into a stern moor for the duration of the exercise.

- If the ship tends back into the moor or if the weather increases to the extent that the mooring load becomes excessive, the engine is utilized to alleviate the condition. If a storm or other events require, the ship can release itself from the third anchor via an acoustic release and recover the umbilical cable leaving the moor intact.

Recovery is initiated by hauling in the umbilical cable; rolling the third anchor out of the mud; and recovering the umbilical cable, anchor, and structure cable until the apex buoy is reached and detached. The next leg is recovered by activating its anchor release and retrieving its lower end for structure cable recovery once it has reached the surface. The last leg is done in the same manner. However, when the apex buoy is reached, it is hoisted aboard via the "U" frame and deck capstan.

ENGINEERING TESTS

1/3 Scale Test

The evolution in the deployment of the full operational tripod system was initiated with a 1/3-scale system deployment. The objective of this test was to develop the deployment/retrieval procedures, to evaluate the deployment vessel and machinery, to familiarize personnel with their functions, to evaluate the weather dependence of the operation, and to test structure components.

The LYNCH operated off the U. S. east coast and was available for future tests and the actual experiment operation. The maneuverability and load-carrying capacity of this ship for deployment of the large full-scale structure was a prime concern. This 1/3-scale test would establish the feasibility for the full-scale system. The test was performed during Nov/Dec 1990 in the Gulf of Mexico approximately 200 nmi south of Lake Charles, LA. A site assessment study[1] was performed to predict the anticipated environmental conditions.

The structure test configuration is presented in Fig. 4. The dimensions of the structure and the water depth were scaled to approximately one-third the full-scale system. The one exception was the anchors. The full size and weight anchors were used to evaluate the ship's handling and the deck maneuvering hardware. The transit took 1.5 days and another 0.5 day was used to perform a bathymetry survey of the site. The deployment was performed during the next two daylight periods in sea state 2-3. The deployment went well, confirming the maneuverability of the ship, the adequacy of the handling equipment, the deployment scenario approach, and the ability of personnel to deploy this new and unique set of hardware.

The ship was in the moor for approximately 12 hours when the weather was predicted to increase to seas of 15-20 ft and winds up to 35 kt. This condition would not allow maintaining the ship's moor. A contingency was implemented by releasing the coaxial umbilical cable from anchor 3, leaving the tripod structure moored to the bottom. The ship proceeded north to shoal waters to ride out the weather. After the front passed 12 hours later, the ship returned to the site. The weather had subsided enough to allow implementing a reattachment procedure. Leg 3 was released from anchor 3.

During the initial operating period an electrical problem was noted in the leg; therefore, the total leg 3 was recovered and disconnected at the apex buoy to assess this problem. The remaining two legs were left in the moored configuration. After repair, the leg was reattached to the buoy and the redeployment was executed using a spare anchor and the previously used procedure.

The system was deployed approximately 12 hours when the engineering sensors on leg 3 indicated a large change in leg depth. The apex buoy also surfaced at about the same time. The indication was that leg 3 had parted. This leg and the anchor were recovered to assess the problem. The leg had been severed at a depth of 217 m. Postanalysis[2] indicated a fish bite. The specific fish could not be determined, but the damaged ends were similar to damage caused by White Tip Oceanic Shark teeth. The distance between two major cuts was 6 inches, which may indicate the jaw width. A repair could have been implemented at that time, but due to the short sea time remaining the decision was made to recover the remaining two legs. These recoveries went as planned. The suspected fish bite resulted in fabrication of additional spare structure sections to facilitate rapid field repair should this occur in the future.

This test confirmed the basic deployment and retrieval scenario and the adequacy of the hardware (structure and ship), and provided training for the personnel. The problems encountered were satisfactorily covered by contingency options. It was also determined the ship did have the deck space and load-carrying capacity to handle the full system.

chor Navigation Test

An anchor navigation test was performed in 5400 m of water, again using LYNCH, to determine the accuracy and ability of the navigation system to lo- c and track the anchor while being deployed. The test also provided training refine the procedures in the use of the system.

The navigation transponders were deployed, and all were within 100 yards their desired locations. The transponders were then navigated to determine ir precise location. The ship was tracked with both the navigation system d the GPS during the test. The difference between the two navigation ap- oaches was a consistent 0.08 nmi. The GPS was predominantly used to posi- n the ship but the anchor navigation system was used when reception was poor.

Strumming of the anchor deployment cable caused false triggering of the oustic releases/transponder during the lowering. When the ship's speed was duced, the cable strumming stopped, which allowed the navigation system to ck correctly. Because the anchor lowering cable was not faired, future plans w include the use of the acoustic releases/transponders located on the structure ble, which was faired and should not strum. It was thought that this proce- re should eliminate the false triggering problem, which proved to be the case later tests.

ull-Scale Test

The final system test prior to the operational experiment was the deploy- ent of a full-scale system using the structure components to be deployed for the periment. The test was conducted in Mar/Apr 1991 at the same Atlantic loca- on planned for upcoming experiment. Environmental assessments[3,4,5] of the e were performed to provide an insight to the expected conditions. The objec- ve of this final test was a full-system dress rehearsal to refine the deployment/re- ieval procedures and to test all system components.

The structure's test configuration is presented in Fig. 5. Leg 1 consisted f mooring line only due to instrumentation fabrication delays, but the other two gs were instrumented in the final configuration. The mooring line for leg 1 onsisted of two sections. The first (4050 m long) was the section planned for e leg, and second section (2150 m long) was from available and previously sed stock. This used second section had a breaking strength of only 12,000 . The total hardware suite with five anchors (two spares) was loaded on the YNCH; space and load-carrying capacity were adequate.

The initial site effort was the deployment and navigation of the anchor navi- ation transponders. These transponders were left at the site for use during the ummer operation. Leg 1 was deployed as planned, but during the deployment f leg 2 the second section of this leg 1 parted. This was the result of lowering nchor 2 at a speed of 2 kt versus the planned 1 kt. The higher lowering speed as required in order to place the anchor at the desired location. Leg 2 was left eployed; leg 1 was recovered and the break repaired. Legs 1 and 3 were then eployed without further problems by lowering the anchors at a slower rate. he anchor navigation system successfully operated; the anchors were placed ithin 50 m of the desired locations.

The system was deployed with the ship attached for 2.5 days when a main ngine generator problem required releasing the coaxial umbilical cable from the tructure. Repair of the generator required returning to port, so the tripod struc- re was left moored at the site. The repair and transit took 10 days. When we turned to the site for recovery, the system was found intact and recovery was ompleted without problem in 2 days.

The test validated the deployment and retrieval approach for the full-scale onfiguration. The ship, other than the generator problem, performed well. he test results confirmed the feasibility and allowed us to finalize the approach nd hardware for the full-up experiment.

YSTEM EXPERIMENT OPERATION

The experiment was conducted during Jun/Jul 1991 in the Sargasso Sea. he final configuration was as previously depicted in Fig. 1. The environmental ssessment[3] for the area identified the potential for an oceanographic front, Sub- opical Front, to meander through the area during the experiment period. This ront would manifest itself with currents in a different direction than the historical prevailing currents and with near surface magnitudes up to 1.2 kt. This front was found in the area and required rotation of the moor 120 degrees to put leg 3 near downcurrent. This relative high current persisted for most of the period but did not cause any unsurmounted problems.

The initial deployment of leg 1 encountered problems with the steel crown wire on the intermediate winch. The wire parted at the winch but remained buried on the drum. This required release of the anchor from the crown wire and free falling the leg 2400 m to the bottom. The crown wire was then recovered. The leg was checked and found to have an electrical problem not associated with the free fall. The leg was recovered and a repair implemented. All subsequent deployments utilized the coaxial umbilical cable for anchor deployment with no difficulty. All legs were then deployed as planned. The anchors were placed very near their desired locations with the apex buoy at a final depth of 65 m. The ship remained tethered to the structure for 11 days whereupon the structure was recovered as planned in 2 days.

Numerous contingencies were incorporated into a comprehensive deployment plan as a result of the testing program. These plans included such obvious things as actions to be taken due to adverse weather, ship equipment failure, structure component failure, instrumentation failure, navigation failure, high sea current, delays, etc. These actions precipitated a suite of back-up equipment and spares. During the course of this effort, some of the contingencies were exercised as reviewed. The final result was the successful deployment of this large tripod structure.

CONCLUSION

The largest suspended ocean cable structure to acquire environmental measurements in the deep ocean was successfully deployed, operated, and retrieved during the summer of 1991. This success was the result of extensive field testing to develop the deployment techniques and hardware for the tripod structure. The hardware and deployment scenario was optimized for operation from a relatively small oceanographic research vessel. These techniques and hardware will provide the Navy with a valuable asset for future measurements.

ACKNOWLEDGMENT

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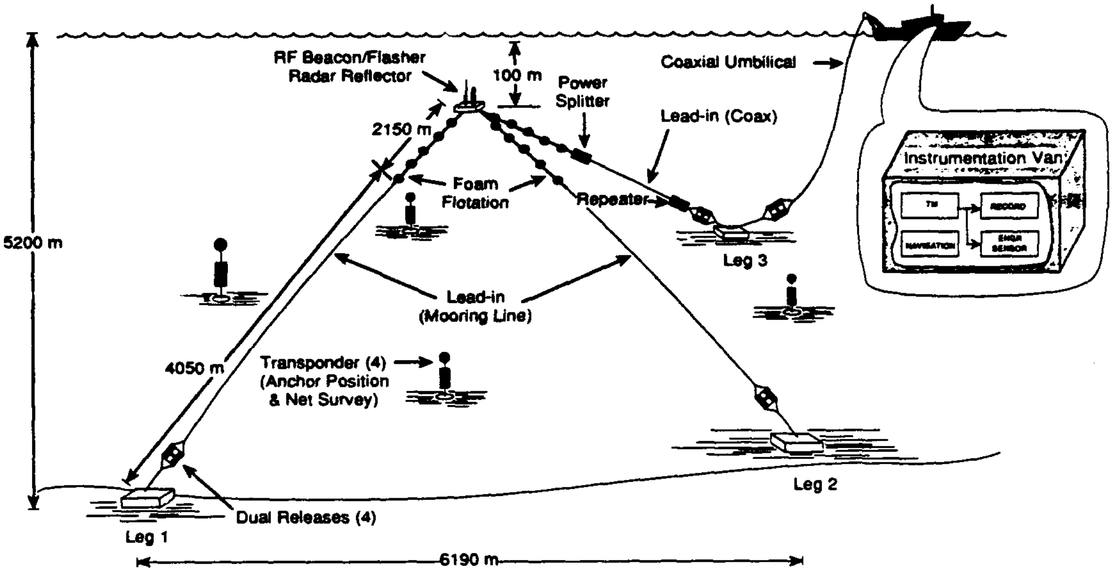

Fig.1 Tripod Structure Configuration

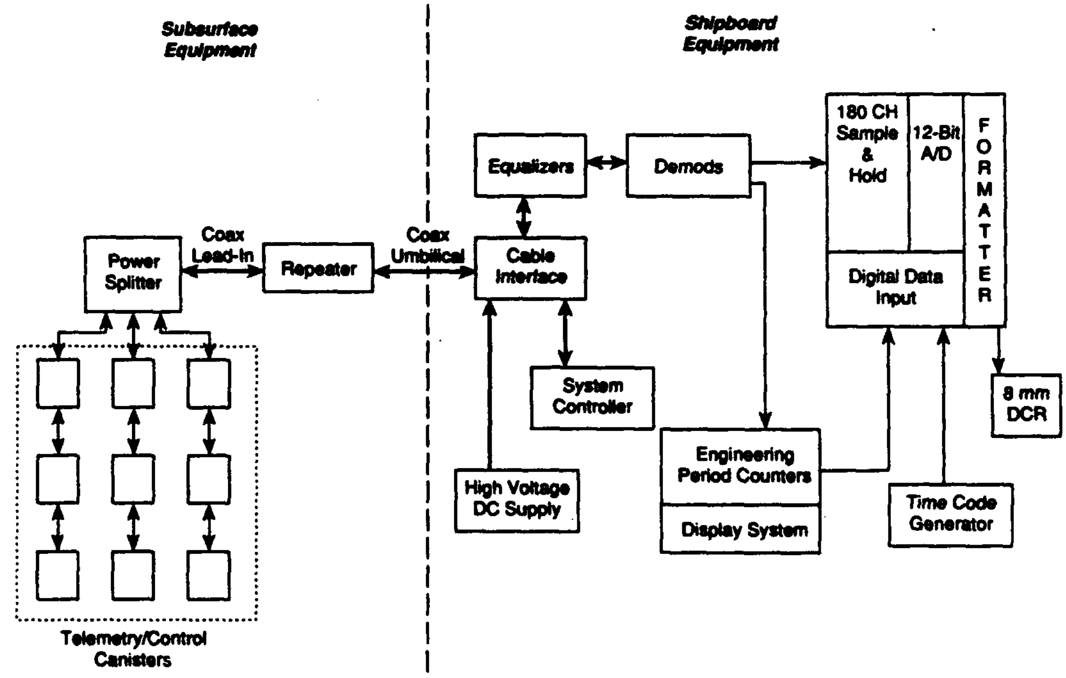

Fig. 2 Block Diagram of Communications System

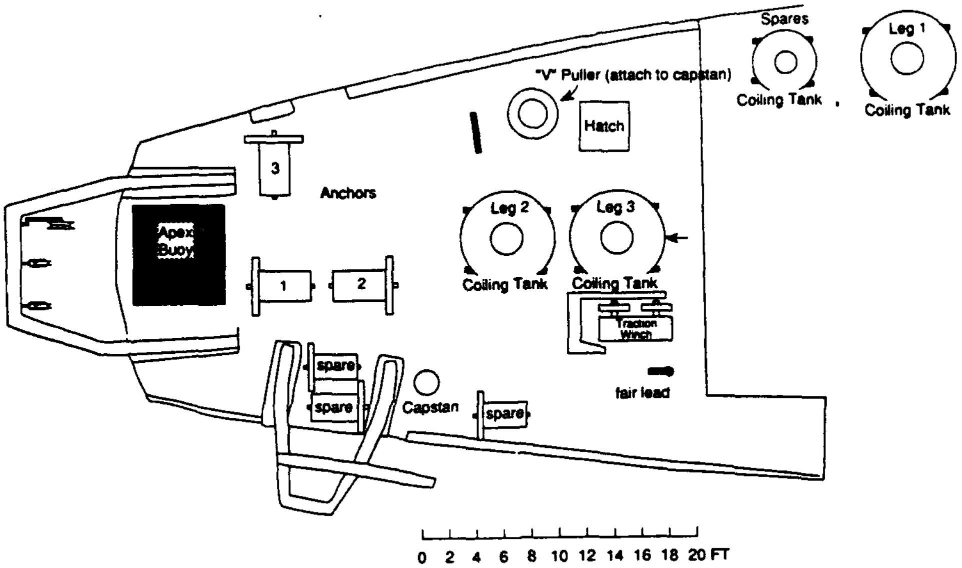

Fig. 3 Deck Layout

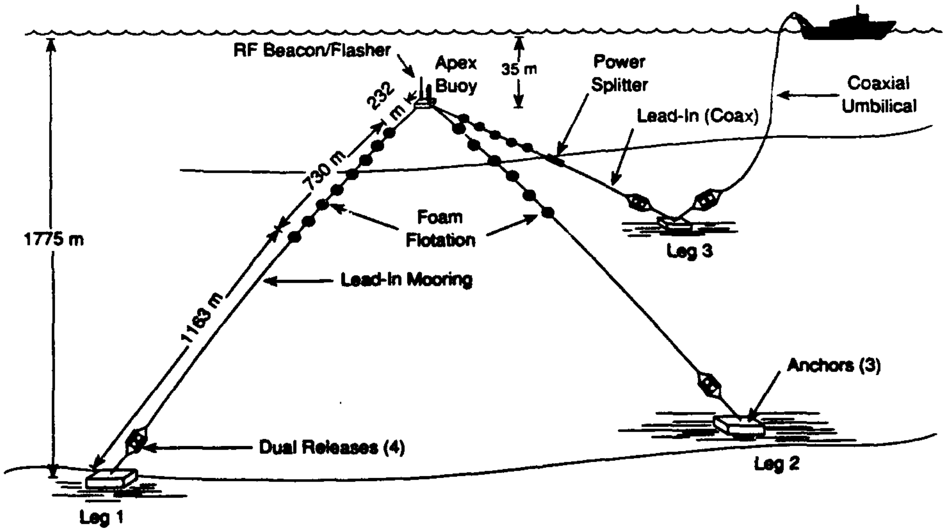

Fig. 4 1/3-Scale Structure Test Configuration

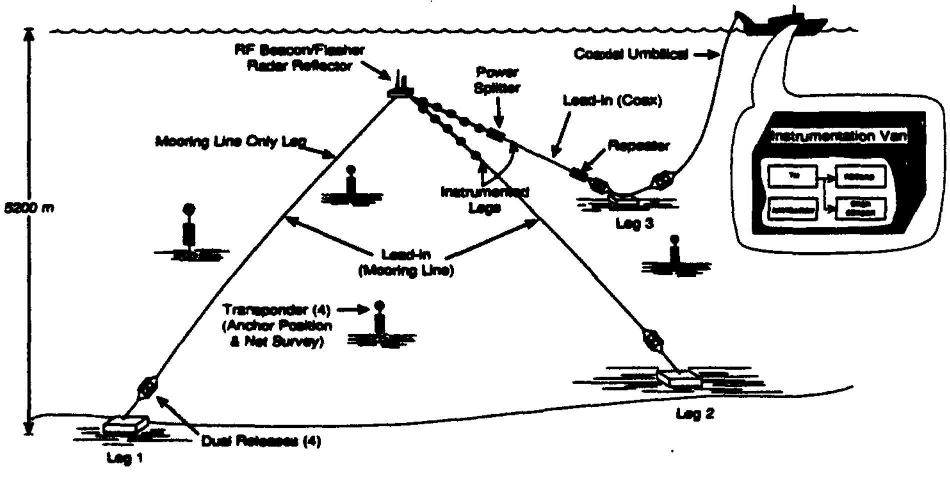

Fig. 5 Full-Scale Structure Test Configuration