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Introduction

Electrical well logging was introduced to the oil industry over half a century ago. Since that time, many additional and improved logging devices have been developed and put into general use.

As the science of well logging advanced, the art of interpreting the data also advanced. Today, the detailed analysis of a carefully chosen suite of wireline services provides a method of deriving or inferring accurate values for the hydrocarbon and water saturations, the porosity, the permeability index, and the lithology of the reservoir rock.

Hundreds of technical papers have been written describing the various logging methods, their application, and their interpretation. This abundance of literature is overwhelming in content and frequently unavailable to the average well log user.

This document therefore presents a review of these well logging methods and interpretation techniques. The various openhole services offered by Schlumberger are discussed in some detail, together with essential methods of interpretation and basic applications. The discussion is kept as brief and clear as possible, with a minimum of derivational mathematics.

It is hoped that the document will serve as a useful handbook for anyone interested in well logging. For those who may be interested in more detailed material, the references at the end of each chapter and the other well logging literature can be consulted.

HISTORY

The first electrical log was recorded in 1927 in a well in the small oil field of Pechelbronn, in Alsace, a province of northeastern France. This log, a single graph of the electrical resistivity of the rock formations cut by the borehole, was recorded by the "station" method. The downhole measurement instrument (called sonde) was stopped at periodic intervals in the borehole, measurements were made, and the calculated resistivity was hand-plotted on a graph. This procedure was carried on from station to station until the entire log was recorded. A portion of this first log is shown in Fig. 1-1.

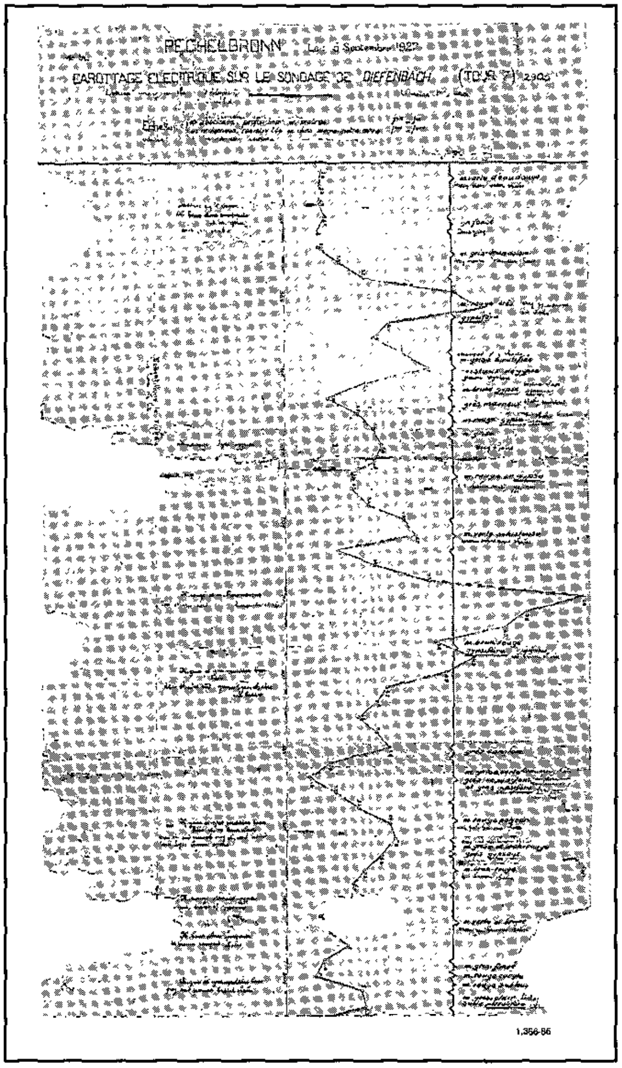

Fig. 1-1—The first log: points plotted on graph paper by Henri Doll.

In 1929, electrical resistivity logging was introduced on a commercial basis in Venezuela, the United States, and Russia, and soon afterwards in the Dutch East Indies. The usefulness of the resistivity measurement for correlation purposes and for identification of potential hydrocarbon-bearing strata was quickly recognized by the oil industry.

In 1931 the spontaneous potential (SP) measurement was included with the resistivity curve on the electrical log. In the same year, the Schlumberger brothers, Marcel and Conrad, perfected a method of continuous recording and the first pen recorder was developed.

The photographic-film recorder was introduced in 1936. By then, the electrical log consisted of the SP curve and short normal, long normal, and long lateral resistivity curves. This combination was predominant in logging activity from 1936 to the late 1950's. After about 1946, these curves were recorded simultaneously.

The development of a dipmeter log began in the early 1930's with the anisotropy dipmeter tool. The three-arm dipmeter device, with an associated photoclinometer, was introduced in 1943; it permitted both the direction and angle of the formation dip to be determined. Each arm contained an SP sensor. In 1946, the SP sensors were replaced by short resistivity devices; this made dip measurements possible in wells where the SP had little correlatable detail.

The first continuously recording electrical dipmeter sonde, which used three microresistivity arrays and contained a fluxgate compass, followed in the mid-1950's. Since then, numerous developments have further refined the measurement of formation dip. Today, a four-arm dipmeter tool records 10 microresistivity curves simultaneously, and a triaxial accelerometer and magnetometers provide highly accurate information on tool deviation and azimuth. The processing of these data into formation dip information is now done exclusively with electronic computers.

The gamma ray (GR) and neutron tools represented the first use of radioactive properties in well logging and the first use of downhole electronics. Unlike SP and resistivity tools, they are able to log formations through steel casing, as well as in air- or gas-filled holes or in oil-based muds. The neutron log was described by Pontecorvo in 1941.

In combination with the GR log, a neutron log enhances lithological interpretations and well-to-well stratigraphic correlations. After about 1949, attention was given to the neutron log as a porosity indicator. However, the early neutron logs were greatly influenced by the borehole environment. It was not until the introduction of the SNP sidewall neutron porosity tool in 1962 and the CNL* compensated neutron tool in 1970 that the neutron gained acceptance as a porosity measurement. The Dual Porosity neutron tool combines those two neutron measurements into a single tool.

Early attempts at porosity determination employed microresistivity measurements. The Microlog tool, introduced in the early 1950's, uses a miniature linear array of three electrodes imbedded in the face of an insulating pad, which is applied to the borehole wall. A borehole caliper is provided by the arm carrying the electrode pad and an opposite backup arm.

The Microlog recording is also useful to delineate permeable beds, and other microresistivity devices help establish the resistivity profile from the invaded zone near the borehole to the noninvaded virgin formation. The Microlaterolog tool was developed for salt muds in 1953. The MicroProximity log and MicroSFL* log have followed.

In 1951, the laterolog tool, the first focused deep-investigating resistivity device, was introduced. It uses a focusing system to constrain the surveying current (emitted from a central electrode) to substantially a horizontal disc for some distance from the sonde. Focused resistivity logs are well adapted for investigation of thin beds drilled with low-resistivity muds. The laterolog device quickly supplanted conventional resistivity logs in salt muds and highly resistive formations.

Over the years, several laterolog tools were developed and used commercially. Today, the DLL* dual laterolog tool, which consists of deep laterolog and shallow laterolog measurements, is the standard. It is usually run with a MicroSFL device as well.

In freshwater muds, the original electrical log has been replaced by the induction log. The induction log was developed in 1949, as an outgrowth of wartime work with mine detectors, for use in oil-base mud. However, its superiority over the electrical log in freshwater muds was soon recognized.

By 1956, a five-coil induction device was combined with the SP curve and a 16-in. normal to make the induction-electrical tool. In 1959, the five-coil device was replaced by one with a six-coil array with deeper investigation.

The DIL* dual induction log, introduced in 1963, is now the standard. It consists of deep induction, medium induction, and shallow resistivity measurements. The shallow resistivity-measuring device is now a focused resistivity device — a Laterolog 8 on the 1963 tool and an SFL device on current tools. A new dual induction log, the Phasor* induction, provides improved thin-bed response, deeper depth of investigation, and greater dynamic resistivity range.

Since the 1930's, logging cables have been used to lower geophones into wells to measure long-interval acoustic travel times from sound sources at the surface.

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*Mark of Schlumberger

In the late 1950's, the sonic log gained acceptance as a reliable porosity log; its measurement responds primarily to porosity and is essentially independent of saturation.

The sonic log, coupled with the focused resistivity logs — laterolog and induction — made possible modern formation evaluation from well logs. The sonic log provided a measurement of porosity; the focused resistivity logs, a measurement of true resistivity of the noninvaded virgin formation.

Subsequent improvements in sonic logging included the BHC borehole compensated sonic, the LSS* long-spaced sonic, and the Array-Sonic* tools. The latter tools permit the recording of the entire sonic wavetrain. From an analysis of the wavetrain, the shear and Stoneley transit times can be extracted as well as the compressional transit time.

The logging of formation bulk density, another measurement primarily dependent on formation porosity, was commercially introduced in the early 1960's. An FDC* compensated formation density log, which compensated for the mudcake, quickly followed in 1964. In 1981, the Litho-Density* log provided an improved bulk density measurement and a lithology-sensitive photoelectric absorption cross section measurement.

The recovery of physical rock samples and formation fluid samples with wireline tools also has a rich history. Sidewall coring, using a hollow, cylindrical "bullet" shot into the formation and retrieved by pulling it out, has existed since 1937. Obviously, this technique has undergone continuous improvement over the one-half century since its introduction. For very hard rocks, downhole mechanical coring tools exist that actually drill out the rock samples.

In 1957, a formation tester was introduced. It recovered a sample of the formation fluids and the pore pressure was measured during the sampling process. The FIT formation interval tester and the RFT* repeat formation tester have followed. The older tools could make only one pressure measurement and recover only one fluid sample per trip into the well; the RFT tool can make an unlimited number of pressure measurements and recover two fluid samples per trip.

To handle those formations in which the formation water is fresh, or varies in salinity, or in which the salinity is unknown, dielectric measurements have been developed. The EPT* electromagnetic propagation log was introduced in 1978; the DPT* deep propagation log, in 1985.

The preceding historical sketch has not, by any means, covered all the measurements now made with wireline well logging devices. Other logging measurements include nuclear magnetic resonance, nuclear spectrometry (both natural and induced), and numerous cased hole parameters.

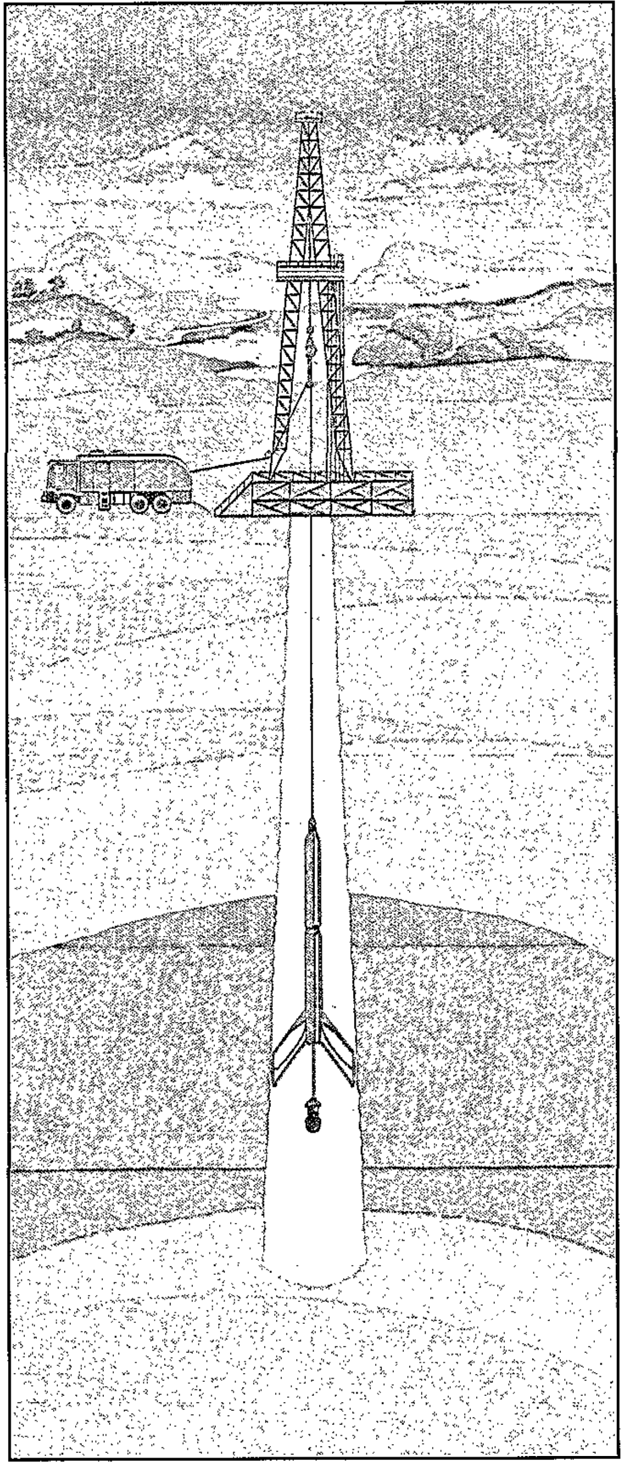

Fig. 1-2—Wireline logging operation.

THE FIELD OPERATION

Wireline electrical logging is done from a logging truck, sometimes referred to as a "mobile laboratory" (Fig. 1-3). The truck carries the downhole measurement instruments, the electrical cable and winch needed to lower the instruments into the borehole, the surface instrumentation needed to power the downhole instruments and to receive and process their signals, and the equipment needed to make a permanent recording of the "log."

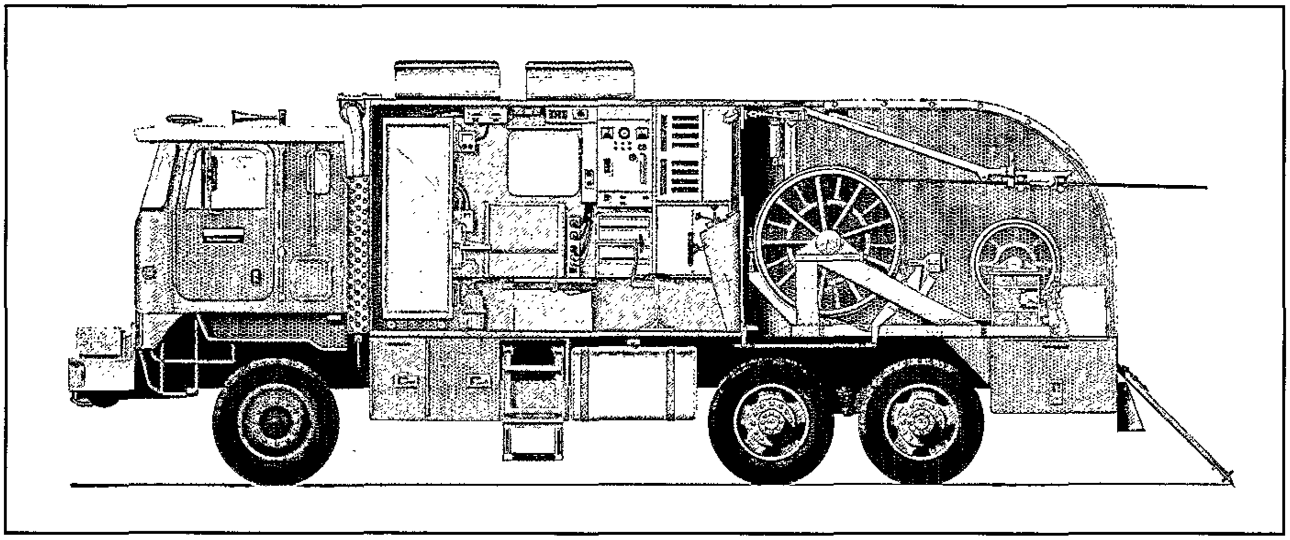

Fig. 1-3—A typical CSU wellsite mobile laboratory. The main winch contains up to 30,000 ft of seven-conductor logging cable; the optional small winch at the rear contains 24,000 ft of slim monoconductor cable for servicing producing wells under pressure. Data acquisition and computer equipment are inside the logging cab. For offshore-remote locations, the cab and winch assemblies are mounted on a skid.

The downhole measurement instruments are usually composed of two components. One component contains the sensors used in making the measurement, called the sonde. The type of sensor depends, of course, upon the nature of the measurement. Resistivity sensors use electrodes or coils; acoustic sensors use transducers; radioactivity sensors use detectors sensitive to radioactivity; etc. The sonde housing may be constructed of steel and/or fiberglass.

The other component of the downhole tool is the cartridge. The cartridge contains the electronics that power the sensors, process the resulting measurement signals, and transmit the signals up the cable to the truck. The cartridge may be a separate component screwed to the sonde to form the total tool, or it may be combined with the sensors into a single tool. That depends, of course, upon how much space the sensors and electronics require and the sensor requirements. The cartridge housing is usually made of steel.

Today, most logging tools are readily combinable. In other words, the sondes and cartridges of several tools can be connected to form one tool and thereby make many measurements and logs on a single descent into and ascent from the borehole.

The downhole tool (or tools) is attached to an electrical cable that is used to lower the tool into and remove from the well. Most cable used in openhole logging today contains seven insulated copper conductors. New cable developments include a fiber optics conductor in the center of six copper conductors. The cable is wrapped with a steel armor to give it the strength to support the tool weight and provide some strength to pull on the tool in case it becomes stuck in the borehole. The cable and tools are run in and out of the borehole by means of a unit-mounted winch.

Well depths are measured with a calibrated measuring wheel system. Logs are normally recorded during the ascent from the well to assure a taunt cable and better depth control.

Signal transmission over the cable may be in analog or digital form; modern trends favor digital. The cable is also used, of course, to transmit the electrical power from the surface to the downhole tools.

The surface instrumentation (Fig. 1-4) provides the electrical power to the downhole tools. More importantly, the surface instrumentation receives the signals from the downhole tools, processes and/or analyzes those signals, and responds accordingly. The desired signals are output to magnetic tape in digital form and to a cathode-ray tube and photographic film in analytical form.

The photographic film is processed on the unit, and paper prints are made from the film. This continuous recording of the downhole measurement signals is referred to as the log.

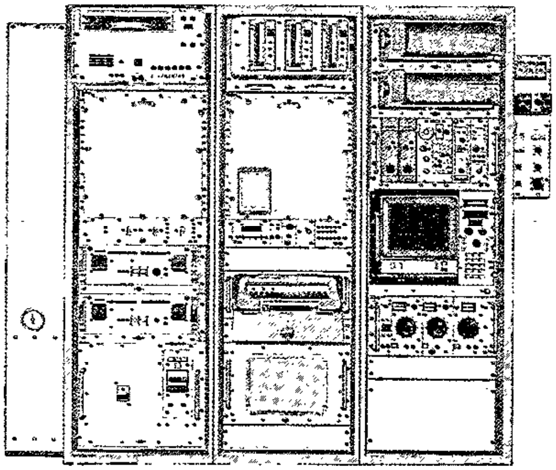

Fig. 1-4—The CSU is a computer-based integrated data acquisition and processing system. The main elements are—Right: a video data display and optical film units to record data. Center: the keyboard/printer unit below three cartridge tape drives. Left: twin DEC 1134 computers each having 256K memory; at the top, a dual hard-disk drive with 42-megabyte capacity and a backup 48-megabyte cartridge tape unit.

LOG DATA ACQUISITION

Wireline-logging technology is being changed by the rapid advancements in digital electronics and data-handling methods. These new concepts have changed our thinking about existing logging techniques and remolded our ideas about the direction of future developments.

Affected are the sensors, the downhole electronics, the cable, the cable telemetry, and the signal processing at the surface.

Basic logging measurements may contain large amounts of information. In the past, some of this data was not recorded because of the lack of high data-rate sensors and electronics downhole, the inability to transmit the data up the cable, and inability to record it in the logging unit. Similarly, those limitations have prevented or delayed the introduction of some new logging measurements and tools. With digital telemetry, there has been a tremendous increase in the data rate that can be handled by the logging cable. Digital recording techniques within the logging unit provide a substantial increase in recording capability. The use of digitized signals also facilitates the transmission of log signals by radio, satellite, or telephone line to computing centers or base offices.

In Table 1-1 the data rate for one of the older tool systems, the induction-sonic combination, is contrasted with the data-rate transmission requirements for some of the newer tools. It illustrates the tremendous increase in the data rate that can now be handled by the newer downhole sensors, by the logging cable, and by the surface instrumentation as a result of digital techniques.

Table 1

Data rate transmission requirements of some well logging tools.

ISF Induction-Sonic		200 Bits/Borehole Ft
High-Resolution Dipmeter	10 Dip Channels	25,000 Bits/Borehole Ft
Array Sonic	Full Waveform	60,000 Bits/Borehole Ft
Inelastic Spectroscopy	Energy Spectrum	20,000 Bits/Second
Well Seismic Tool	5-Second Wavetrain	80,000 Bits/Second

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DATA PROCESSING

Signal processing can be performed at at least three levels: downhole in the tool, uphole in the truck, and at a central computing center. Where the processing is done depends on where the desired results can most efficiently be produced, where the extracted information is first needed, where the background expertise exists, or where technological considerations dictate.

Where it seems desirable, the logging tool is designed so that the data are processed downhole and the processed signal is transmitted to the surface. This is the case when little future use is envisioned for the raw data or when the amount of raw data precludes its transmission. In most cases, however, it is desirable to bring measured raw data to the surface for recording and processing. The original data are thus available for any further processing or display purposes and are permanently preserved for future use.

A wellsite digital computer system, called the CSU* unit, is now standard on all Schlumberger units throughout the world (Fig. 1-4). The system provides the capability to handle large amounts of data. It overcomes many of the past limitations of combination logging systems (the stacking or combination of many measurement sensors into a single logging tool string). It also expedites field operations. Tool calibration is performed much more quickly and accurately, and tool operation is more efficiently and effectively controlled.

The CSU system provides the obvious potential for wellsite processing of data. Processing of sonic waveforms for compressional and shear velocities is already being done, as is the processing of nuclear energy spectra for elemental composition and, then, chemical composition. More sophisticated deconvolution and signal filtering schemes are practical with the CSU system.

Nearly all the common log interpretation models and equations are executable on the CSU unit. Although not quite as sophisticated as the log interpretation programs available in computing centers, the wellsite interpretation programs significantly exceed what can be done manually. Wellsite programs exist to determine porosity and saturations in simple and complex lithology, to identify lithology, to calculate formation dip, to calculate permeablity, and to determine many more petrophysical parameters. In addition, data (whether recorded, processed, or computed) can be reformatted in the form most appropriate for the user.

The demand for wellsite formation evaluation processing will undoubtedly increase and programs will become more sophisticated.

The computing center offers a more powerful computer, expert log analysts, more time, and the integration of more data. Schlumberger computing centers are located in major oil centers throughout the world. They provide more sophisticated signal processing and formation analysis than the wellsite CSU system. Evaluation programs range in scope from single-well evaluation programs to a series of special application products to reservoir description services that evaluate entire fields. Statistical techniques can be employed more extensively, both in the selection of parameters and in the actual computations.

Log processing seems to be moving more and more toward integrated treatment of all log measurements simultaneously. Programs are being designed to recognize that the log parameters of a given volume of rock are interrelated in predictable ways, and these relationships are given attention during processing. New programs can now use data from more sources, such as cores, pressure and production testing, and reservoir modeling.

DATA TRANSMISSION

The CSU system is able to transmit logs with a suitable communication link. The receiving station can be another CSU system, a transmission terminal, or a central computing center. Data can be edited or reformatted before transmission to reduce the transmission time or to tailor the data to the recipient. Built-in checks on the transmission quality ensure the reliability of the transmitted information.

With the LOGNET* communications network, graphic data or log tapes can be transmitted via satellite from the wellsite to multiple locations (Fig. 1-5). This service is available in the continental U.S. and Canada, onshore and offshore. Virtually any telephone is a possible receiving station.

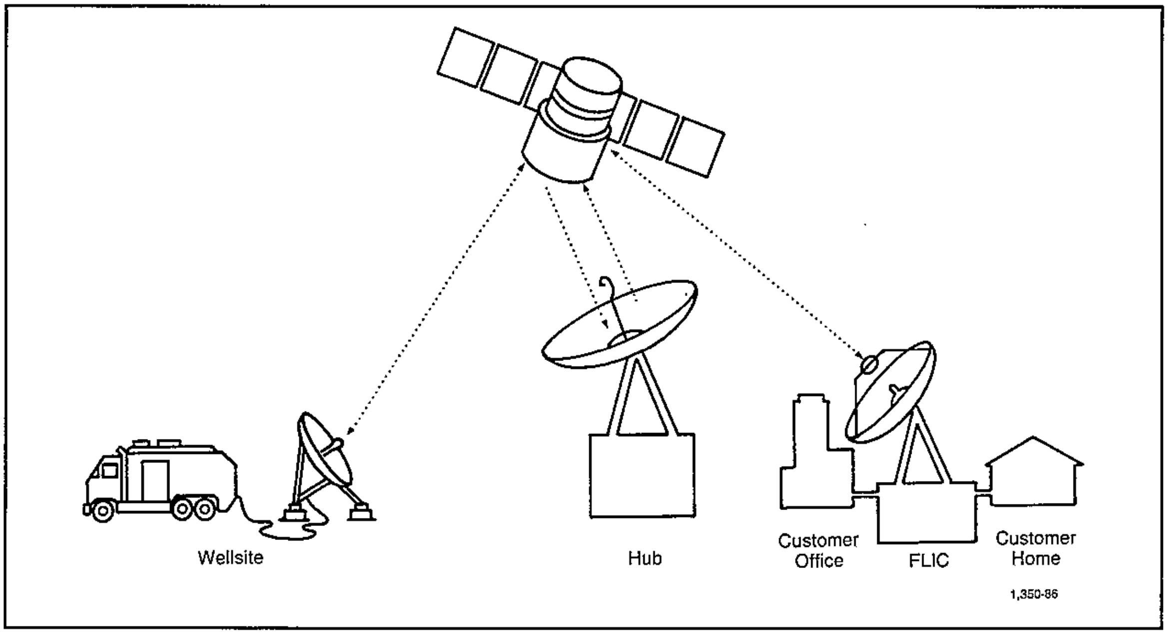

Fig. 1-5—Schematic of LOGNET communications system.

A small transportable communications antenna at the wellsite permits transmission of the well log data via satellite to a Schlumberger computing center and then by telephone to the client's office or home. Since the system is two way, offset logs or computed logs can be transmitted back to the wellsite. The system also provides normal two-way voice communication. There are several receiving station options:

- A standard digital FAX machine will receive log graphic data directly at the office.
- A Pilot 50* portable telecopier plugged into a standard telephone outlet at the office or at home allows clients to take advantage of the 24-hour service.
- A Pilot 100* log station can be installed in the client's office to receive tape and log graphics and to make multiple copies of the log graphics. Since this station is automatic, it can receive data unattended.
- An ELITE 1000* workstation can be installed in the client's office to receive data from the LOGNET communications network. A complete library of environmental corrections as well as the entire range of Schlumberger advanced answer products are available with this new workstation.

All data are encrypted to provide security while transmitting over the airways.

Other local transmission systems exist elsewhere in the world using telephone, radio, and/or satellite communications. In some instances, transmission from the wellsite is possible. In others, transmission must originate from a more permanent communication station. With some preplanning, it is possible to transmit log data from nearly any point in the world to another.

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