America In Space | The First Decade

LINKING MAN AND SPACECRAFT

National Aeronautics and Space Administration

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Introduction

For a decade, NASA has probed the cosmos with numerous manned and unmanned spacecraft, each having a specific purpose and each, most often, having its own unique characteristics. Yet, common to every undertaking, whether simple sounding rocket or complex manned Apollo, is the need to communicate between the ground and the spacecraft.

"Linking Man and Spacecraft" deals with the transfer of vital information between spacecraft and the Earth. Spacecraft communication is difficult to separate from spacecraft tracking in the sense that NASA's three worldwide ground-based networks perform both functions. Most NASA network stations possess systems that can simultaneously track and acquire spacecraft data. Despite this dual capability of NASA hardware, spacecraft tracking—a subject dealing with the precision location of spacecraft—has a different theoretical background. Because of this distinction, "Spacecraft Tracking" is the title of another booklet in this series.

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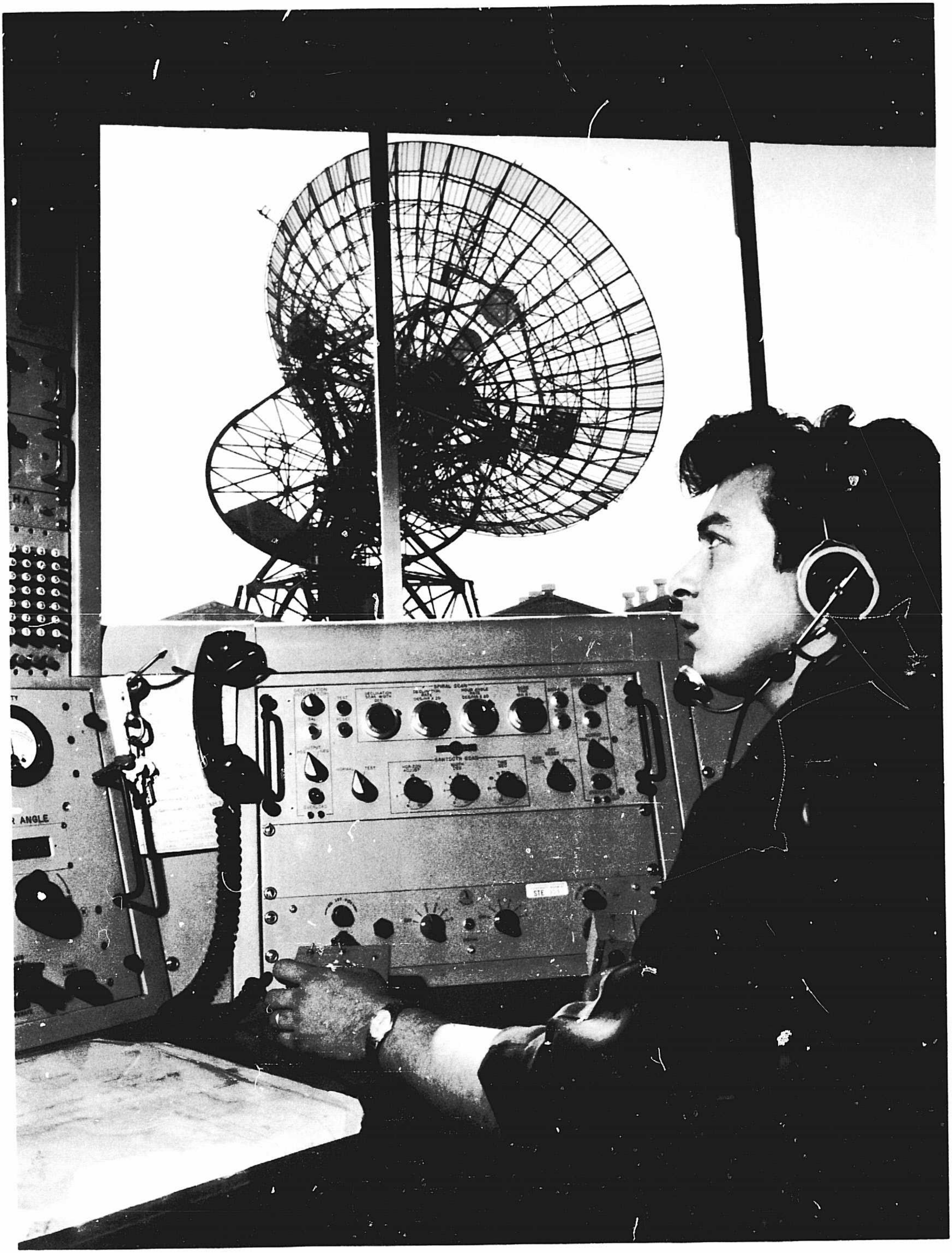

R ANGLE

Linking Man and Spacecraft

Conversations With a Machine

A man who lifts his telephone receiver and dials a number commands a vast, electrically connected machine with hundreds of millions of input-output stations all over the world. NASA has constructed a similar man-machine system to control and converse with its spacecraft. NASA's machine is connected by hundreds of thousands of miles of submarine cables, microwave relays, and radio links. In the case of the planetary probe, Mariner IV, the man-machine system stretched some 200 million miles out into space.

The basic commodity of both the telephone system and the spacecraft communication system is information. On the downlink from the spacecraft come (1) scientific data from spacecraft instruments; (2) housekeeping data from thermometers and other instruments that gauge the health of the spacecraft; (3) tracking signals that help ground stations pinpoint the location of the spacecraft; and (4) the voices of the astronauts if the spacecraft happens to be manned. On the uplink travel commands to spacecraft equipment and the other half of the astronaut-ground controller conversation.

The complete space data system consists of much more than the radio link connecting Earth and spacecraft. Let us define the complete system by beginning with the data sources on the spacecraft and following the data through spacecraft circuits, to the Earth, through terrestrial data handling equipment, and finally to the ultimate user of the data.

The most prolific spacecraft data generators are the scientific instruments, such as Geiger counters and magnetometers. Television cameras on weather satellites are also prodigious gatherers of information. Collectively, satellite instruments gather over 200 million data points each day. These data converge on the spacecraft radio transmitters. Before they are dispatched to Earth, however, they are processed; that is, modified so that all are expressed in the same language or perhaps condensed through the removal of unimportant information. After processing, they move on to the transmitter, to the antenna, and to Earth. Radio antennas at terrestrial data acquisition stations follow the spacecraft, pick up radio signals, and convey them to receivers where they are amplified. If everything has functioned properly, the signals emerging at the receiver output terminals will be identical with those emanating from the spacecraft transmitter.

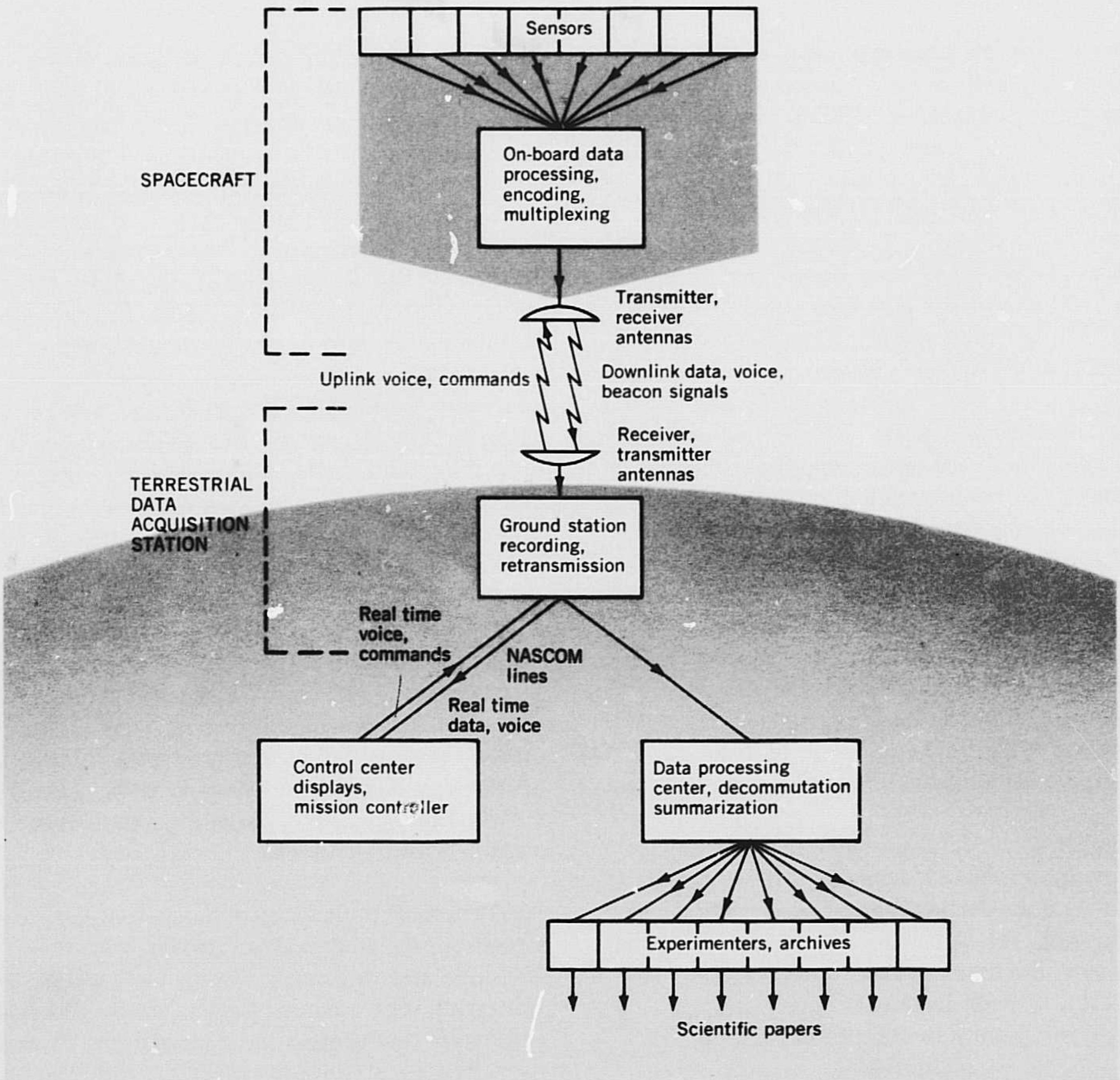
The trip is not over for the data. Important information is sent directly to the control center managing the spacecraft via NASA's worldwide terrestrial communication system NASCOM. Critical data are transmitted in real time, with total delays of less than one second. Most scientific data are recorded on magnetic tapes and shipped back to the control center by airmail.

At the control center, urgent data are usually displayed visually to the spacecraft controller, who then makes decisions and dispatches commands back to the spacecraft. The scientific data tapes are fed into computers that process the data and put them in the form most useful to the scientists. The computer may even draw graphs or summarize the data in other ways. This critical line of demarcation between man and machine is called the man-machine interface; it is here that machine is matched to man.

Once a scientist has digested the spacecraft data, he draws his conclusions, writes his reports, and publishes them for the world of science. The link between spacecraft sensor and the human data user is now complete.

1 *Diagram showing how information flows between the spacecraft sensors and data users in a space data system.*

2 *Trend of data quantities produced by Earth satellites. The number inside each spacecraft indicates the number of launchings.*



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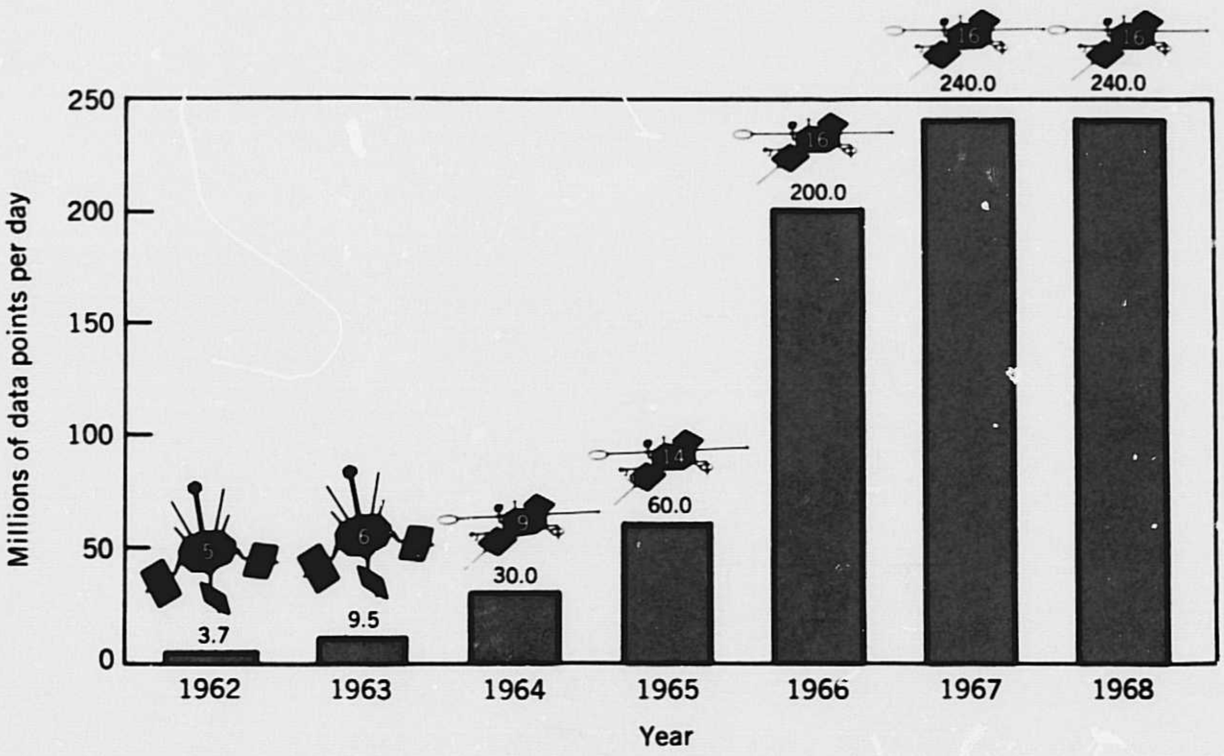

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Some Space Communication Problems

The Question of Power

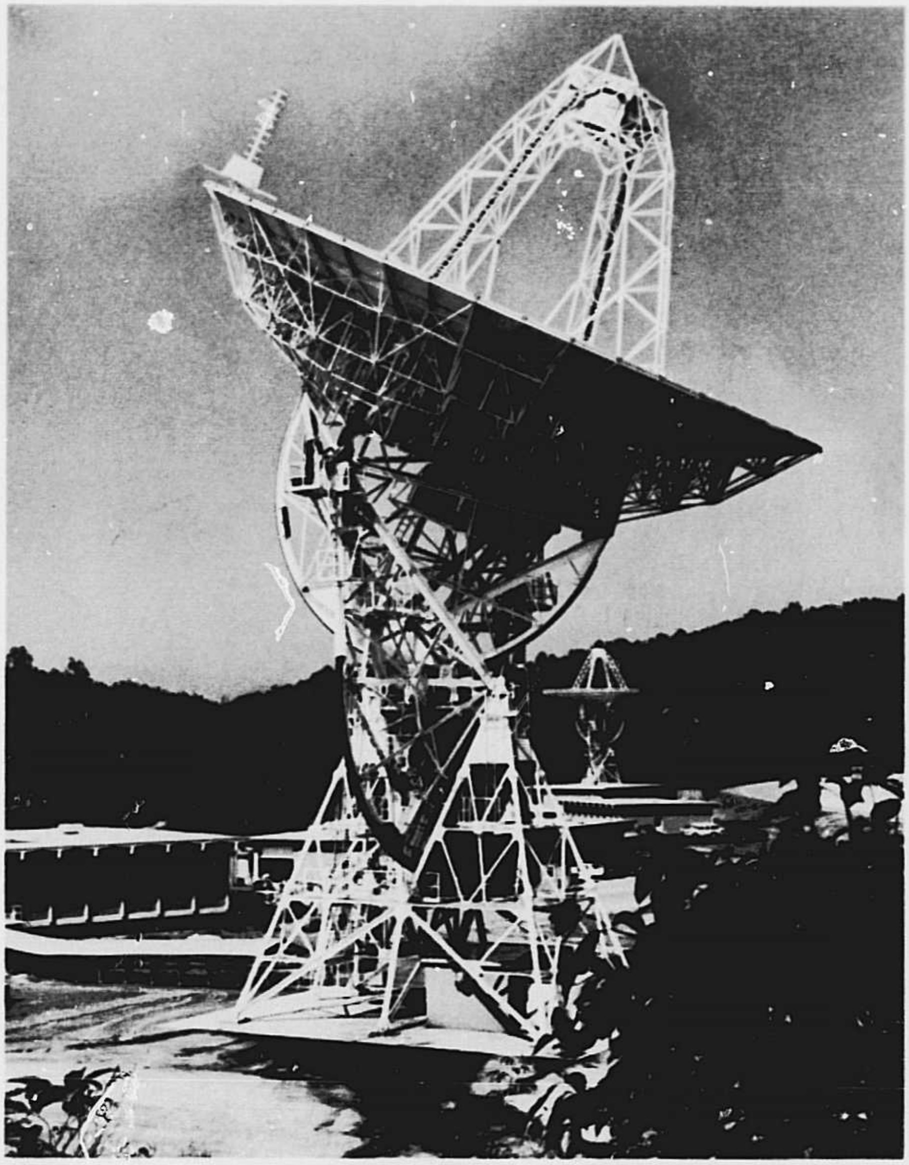
Conversing with satellites and space probes by radio is radically different from building a radio in the attic and talking to another amateur in Japan. The problem is sheer distance when communicating with a space probe at lunar or planetary distances. Earth satellites, however, are usually only a few hundred miles away when they pass over terrestrial data acquisition stations. In the case of satellites, the problem is transmitting the flood of data collected by the craft's instruments. Within limits, the problems of distance and data quantity can be solved by increasing the power level of the spacecraft transmitter. But power is not the only factor involved. To understand space communication, some technical terms must be defined:

Bandwidth: The faster one wishes to send information, the bigger the bandwidth has to be; that is, the larger the piece of the electromagnetic spectrum occupied by the radio signal. A radio channel bandwidth may be compared to a water pipe; if the pipe area is doubled, twice as much water (information) can be pumped. Unfortunately, doubling the bandwidth also doubles the power required.

Antenna Gain: The more sensitive the antennas on the spacecraft and at the data acquisition station, the easier it is to transmit information back and forth. Good antennas, at both locations, reduce the requirement for power aboard the spacecraft. Sensitive antennas are large and highly directional; they have to be pointed accurately. Antenna pointing imposes a burden on the spacecraft.

Noise: Radio noisemakers are everywhere: the Sun, the Milky Way, the Earth's atmosphere and warm surface, and man's multitude of machines. High transmitter power can drown out noise; a wise choice of transmitter frequency simplifies the problem.

Atmospheric Attenuation: Radio waves travel practically unhindered through outer space, but the Earth's atmosphere absorbs radio waves



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uplink and downlink. Again, more transmitter power is a potential solution, though absorption is reduced greatly by selecting the proper frequency.

The radio engineer aims to insure that the signal power delivered to the radio receiver by the receiving antenna is greater than the noise power by a factor of ten or more. The receiver power is directly proportional to the transmitter power, the gain (amplification) of the transmitter antenna, and the gain of the receiving antenna. It is inversely proportional to the atmospheric attenuation and the square of the distance between the transmitter and receiver.

To illustrate the interplay between these factors, consider first a satellite transmitting three watts of signal power toward a data acquisition station on the Earth. The three watts is no more than the power consumed by a flashlight bulb, but it is sufficient for loud, clear satellite signals. Satellites are so close to the Earth that transmitter power can be used to increase bandwidth rather than overcome distance. In contrast to planetary probes, satellites transmit large quantities of data per unit time over relatively short distances.

NASA's Venus probe, Mariner II, also transmitted three watts of signal power in the direction of the Earth. But Mariner II's signal power was employed to conquer distance rather than increase bandwidth. Just after its encounter with Venus in 1962, Mariner II transmitted data across 36 million miles to Earth—a distance 100,000 times that of most Earth satellites. However, the data flow rate from Mariner II was many thousands of times less than it is for most satellites.

Power also overcomes noise. The Mariner II probe was so far away from Earth that one wonders how

3 *The Rosman, N.C. STADAN station. The two 85-foot dishes are used for acquiring data from the larger satellites.*

4 *For interplanetary communication, the paraboloid antenna on Mariner II had to be kept pointed at the Earth.*

its weak transmissions were ever heard above all the noise generated in space and on the Earth.

Space probes like Mariner II cannot spare the power necessary to blast through noise; noise reduction is the better solution. Therefore NASA has placed its data acquisition stations in areas where man-made noise is weak. The Goldstone station in NASA's Deep Space Net, for example, is far out on the California desert, ringed by hills that cut off noise emanating from cities on the Pacific coast.

Noise created within the receiving equipment itself is reduced by cooling the most sensitive portions of the receiver to near absolute zero with liquid helium. The intense cold slows the motion of the noise-making electrons in the circuitry.

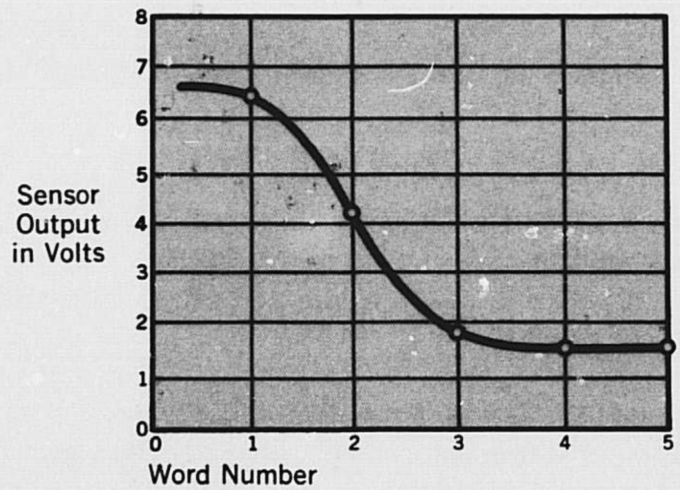
Since the signal power at the receiver terminals depends directly upon the gains of the transmitting and receiving antennas, NASA has emphasized the design and installation of large, sensitive antennas at its Earth-based data acquisition facilities and on the spacecraft proper. In particular, the Deep Space Net, which must maintain contact with probes across the solar system, searches the sky with paraboloidal dishes 85 and 210 feet in diameter. The gain of such an antenna is very high in the direction it points. If the probe is slightly off the antenna axis, however, its signals will go unnoticed. The probe itself obviously cannot carry an 85-foot paraboloid into space, but dishes several feet in diameter are common on probes. When spacecraft and terrestrial antennas are pointed right at each other, the product of their respective gains will be maximum and so will the signal power at the receiver. The terrestrial antenna can be pointed by man, but that of the probe must be pointed toward the Earth by the spacecraft which is free to turn in all directions.

The effectiveness of the space data system thus depends to some degree upon the ability of the spacecraft to locate Earth, lock onto it, and turn its antenna in the right direction. The space data system cannot be designed independently of the spacecraft and its capabilities. The astronautical engineers call this an *interface* between the space data system and the spacecraft attitude control subsystem.

Of Bits, Codes, and Languages

Information is the basic commodity of communication. A bit is the smallest amount of meaningful information that can be exchanged: that amount of information inherent in a yes or no; a 1 or a 0; an electrical pulse or its absence; or any other two-valued phenomenon. A bit is a digit in the binary system of numbers; the binary system is based on powers of two.* Any number may be represented by an equivalent binary number; decimal 11 for example is 1011, a four-bit binary word. If a satellite Geiger counter counts 11 Van Allen region electrons per second, it can so inform the experimenter on Earth by sending a train of pulses so: pulse—no pulse—pulse—pulse, to represent 1011. Continuously varying (analog) data can be approximated by a series of binary numbers as shown in the illustration. The spacecraft

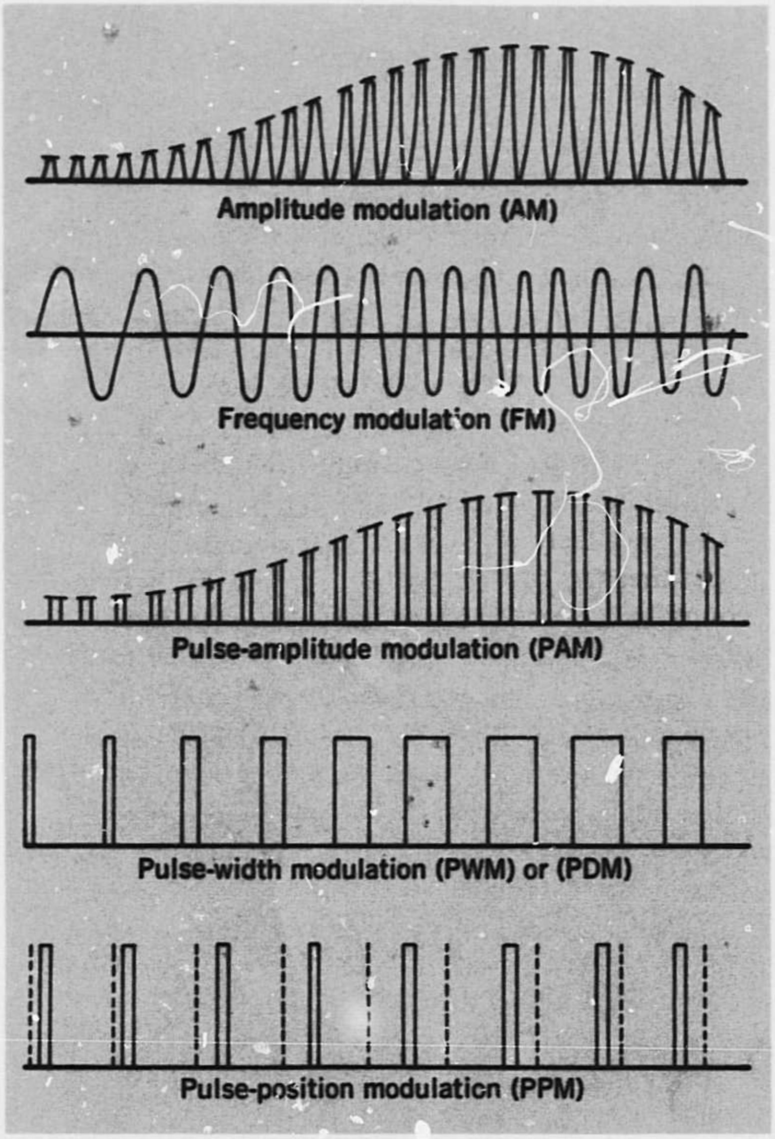
5 *An analog signal represented by 3-bit and 4-bit words. A 3-bit word permits a resolution of 1 volt; a 4-bit word allows a resolution of 0.5 volt.*



Data word number	Decimal sensor reading	3-bit words	4-bit words	4-bit pulse train
1	6.3	110	1101	
2	4.1	100	1000	
3	1.8	010	0100	
4	1.6	010	0011	
5	1.7	010	0011	

**Using three-bit "words," the binary-decimal equivalents are:*

000 = 0	011 = 3	110 = 6
001 = 1	100 = 4	111 = 7
010 = 2	101 = 5	



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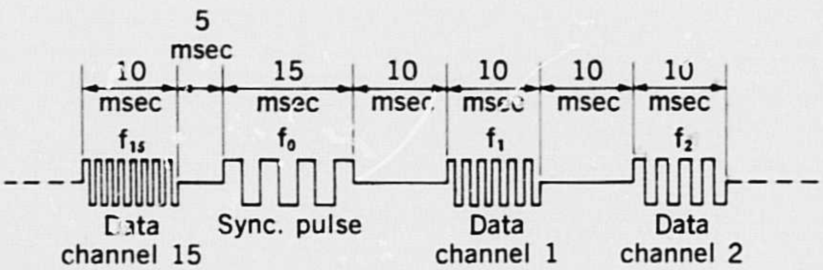
6 *A comparison of several types of telemetry modulation.*

7 *A train of PFM signals. The frequency of the pulses in each channel carries the desired data. The channels are time-division multiplexed. The sync pulse synchronizes the communication circuits.*



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can also report its switch positions to the mission controller; pulse for ON, no-pulse for OFF. Spacecraft temperature readings are easily transmitted as binary words.

The trend in NASA today is to convert most spacecraft transmissions into strings of pulses and no-pulses on both downlink and uplink parts of the space data system. There are exceptions; astronaut voice transmissions are not converted into the binary language, though they could be in principle. The binary language is often called machine language because it is the language of computers and most data processing equipment.

While many NASA spacecraft discourse with ground stations in machine language, different dialects exist. The differences come about as a result of the various ways information can be added to the transmitter's carrier waves; that is, the constant-frequency electromagnetic waves it emits when no information is being transmitted. The easiest and most primitive way to add information to (modulate) a carrier is simply to turn it off and on in Morse code fashion. This is effective but crude. More sophisticated are the amplitude modulation (AM) and frequency modulation (FM) that we receive on ordinary radios. In AM, the information is superimposed by varying the amplitude of the carrier. A 440-cycle/sec note (A on the musical scale) would be represented by a carrier whose amplitude varied between a maximum and a minimum 440 times per second. In frequency modulation, the frequency of the carrier would be varied back and forth between a maximum and a minimum frequency 440 times per second.

The amplitudes, widths, and positions of pulses can carry information, too. For example, pulse-amplitude modulation (PAM) and pulse-width modulation (PWM) have occasionally been used on spacecraft. The object of any form of modulation is to find some property of the carrier and vary it in a way that conveys information to the recipient.

NASA has developed a special type of modulation for its smaller scientific satellites. It is called pulse-frequency modulation or PFM. A data acquisition station listening to PFM from a satellite hears short bursts of pulses. The first burst in a sequence of bursts might come from experiment #1 on the satellite; call this channel #1. The frequency of the pulses in that burst is a measure of the output of experiment #1. If experiment #1 consists of a magnetometer, 1000 pulses per second on channel #1 could correspond to 100 units of magnetic field strength. If 2000 pulses per second are detected, the experimenter knows that the magnetometer is reading 200 units of magnetic field strength, and so on.

The second burst of pulses transmitted by the satellite might represent the output of a voltmeter in the spacecraft power supply, classifying channel #2 as a housekeeping channel. Ten volts might be equivalent to 1000 pulses per second here. So it goes; until all scientific and housekeeping instruments are read as a sequence of pulse bursts. Within each burst of pulses, the frequency of the pulses reveals the instrument reading.

The reading of each spacecraft instrument in sequence one after the other is termed time division multiplexing or commutation. Multiplexing is a general term applied when several channels of information are transmitted on the same carrier. A similar technique is employed when several telephone conversations are sent over the same wire at the same time. In time division multiplexing, each experiment is connected to one terminal of a many-terminal switch (called a commutator). As the arm of the switch rotates, it makes brief connections with each of the spacecraft instruments, thus sampling each instrument once per revolution.

On its bigger satellite and planetary probes, NASA uses pulse code modulation (PCM). PCM is pure machine language; a series of pulses and no-pulses, which are equivalent to a series of 1s and 0s. A 0 might be electromagnetically expressed as the carrier frequency f_0, while a 1 could be frequency f_1. In PCM, some property of the carrier is switched between one value and another; this property may be frequency, amplitude, phase, pulse width, or anything else that the Earth-based receiver can recognize as two-valued.

PCM has several desirable features from NASA's standpoint:

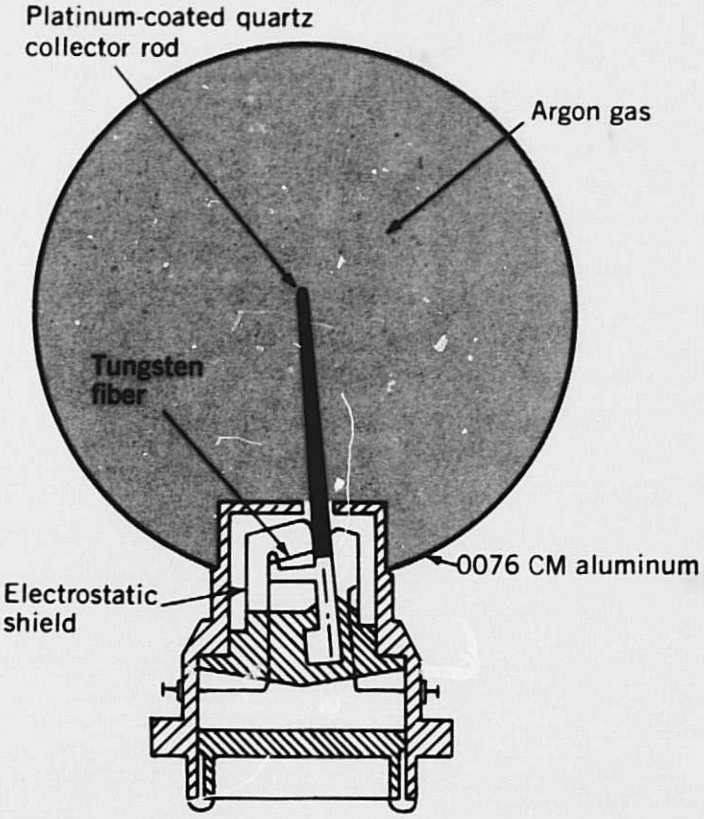
1. It is computer language. NASA's spacecraft can draw upon the immense technology developed by the computer industry.
2. Spacecraft can talk directly to NASA's complex of Earth-based computers, relieving man of the arduous task of translation.
3. All kinds of information can be encoded easily—readings from scientific instruments, commands to spacecraft equipment, etc.
4. If extremely high precision is required for some measurement, say, counting a million Geiger counter discharges, the size of the PCM word can be lengthened accordingly (to 20 bits for decimal 1,000,000). In contrast, it would be almost impossible to accurately distinguish a million different levels in AM and FM.

Spacecraft Sensors

If spacecraft are true extensions of man into space, should they not see, hear, and even extend his sense of touch to the planets? Spacecraft sensors see very well; they see much more of the electromagnetic spectrum than man's eyes. But there is very little to hear or smell in airless space. The sense of touch, however, would be useful when an Earth-based spacecraft controller wishes to manipulate rock and soil specimens on the Moon or some planet by remote control. NASA's Surveyor surface sampler simulated man's hand in a crude way and turned out to be a very effective manipulator of lunar soil. Surveyor's surface sampler had no sense of touch, but the spacecraft's legs were instrumented with strain gauges and other devices that gave engineers data on the properties of the lunar soil during touchdown.

Many spacecraft instruments are nonanthropomorphic; that is, they measure phenomena that man cannot perceive directly. Magnetometers, cosmic-ray detectors, and radio noise monitors are all examples of instruments that permit us to see facets of the universe that would be invisible otherwise.

NASA has flown many hundreds of instruments on its satellites, space probes, and sounding rockets. Just a list would take many pages. However, space instruments can be grouped



8 The Neher ionization chamber produces a single pulse after a specific amount of radiation has passed through the sphere. Radiation causes the chamber to discharge, and the collector rod swings right closing an electrical contact. Most radiation-measuring instruments are counters of some sort.

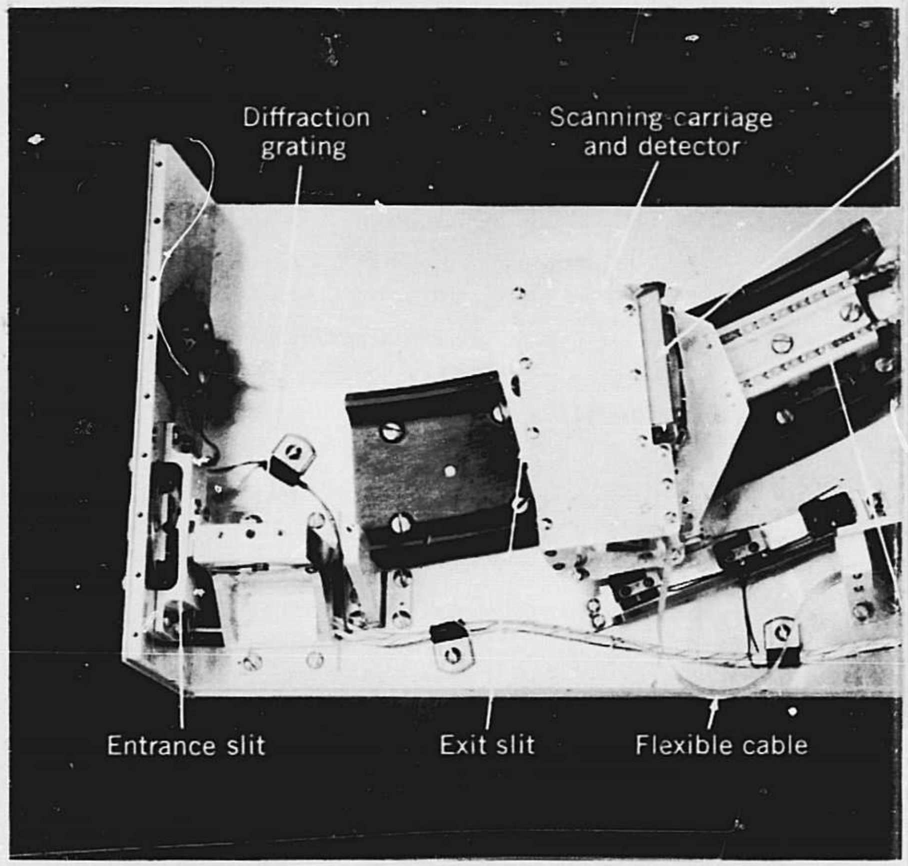
conveniently according to the phenomena they measure:

Class of Phenomena	**Typical Instruments**
Fields and particles	Geiger counters, magnetometers, plasma probes, ionization chambers
Planetary atmospheres	Pressure gauges, thermometers, air-glow photometers
Solar physics	X-ray photometers, ultraviolet spectrometers
Space astronomy	Telescopes (optical and radio wavelengths), gamma-ray detectors
Planetology	Cameras, surface samplers, soil composition experiments
Meteorology	Cameras, infrared radiometers
Bioscience	Astronaut electrocardiographs, life detectors

Many of the instruments just listed are inherently digital; that is, they count events and other

9 This ultraviolet spectrometer was flown on OSO I. To scan the spectrum created by the grating, the detector was moved along the curved track by a motor. This spectrometer generated an analog signal. Compare this spectrometer with the much simpler Neher ionization chamber. Spectrometer is two feet long.

10 A possible command to a satellite includes addresses plus a specific instruction. Shown in digital form is a command to satellite 6, component 14 to perform operation 235. Note the similarity to dialing a telephone number with area code, exchange, and number.



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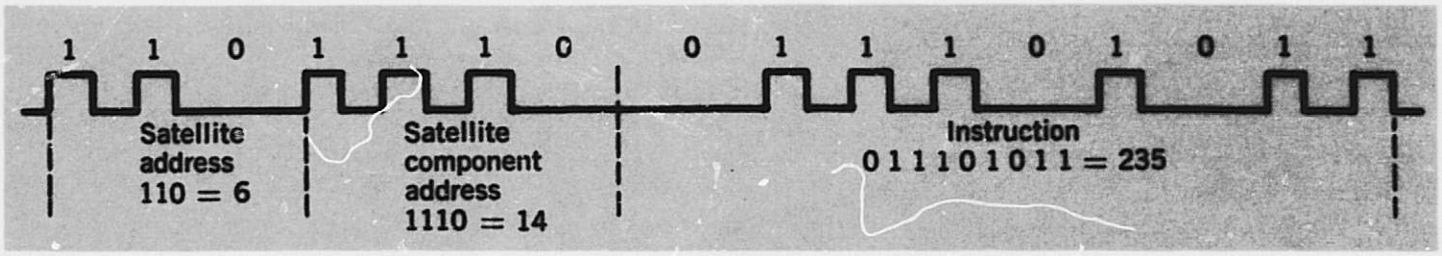
discrete phenomena. For example, the number of Geiger counter discharges per second is an integer; the output of this experiment is already digitized. Housekeeping instruments that indicate switch positions are already digitized, because on and off modes can be described as 1s and 0s. Commands to spacecraft are normally digitized. First, a command must contain an address that picks out the desired satellite from the hundreds in orbit. The address will also have to select the specific part of the satellite that is being commanded. A command's address is similar to a telephone number; and it is digital. The second part of a command gives the order to the addressed piece of equipment. The order might be "turn yourself off" or "read out the tape recorder." These are switching commands that are inherently digital.

Other spacecraft instruments generate analog or continuously varying data. Suppose that the output



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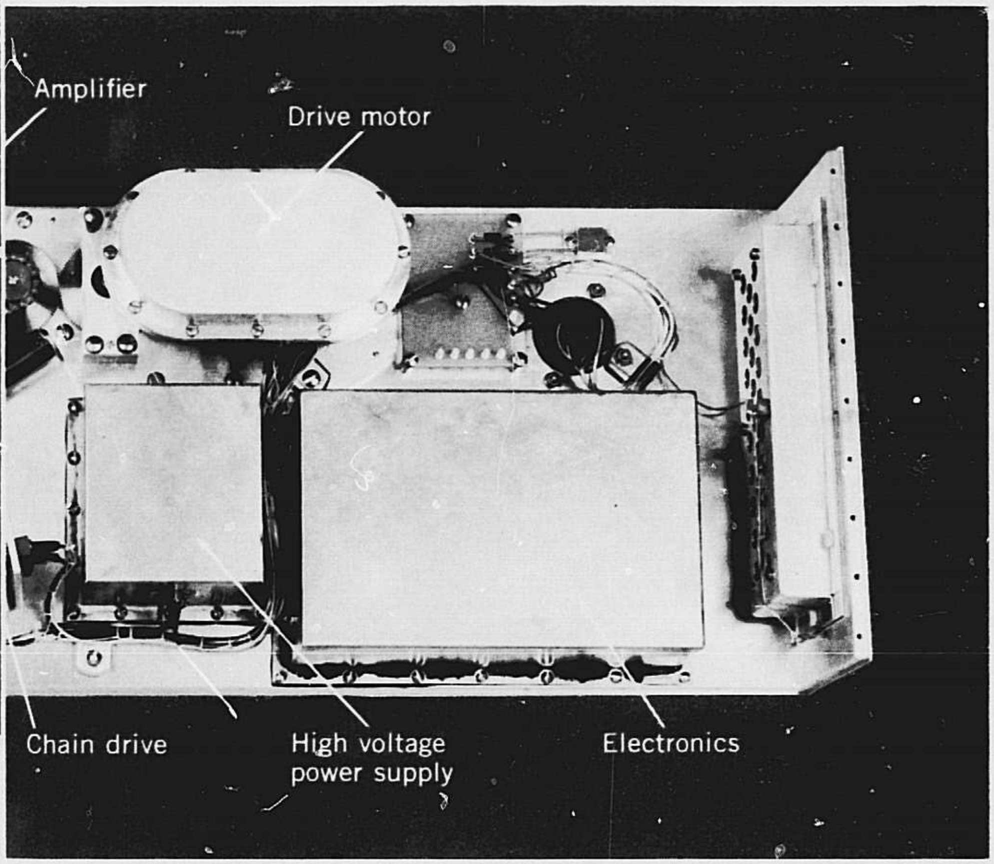


voltage of an instrument varies continuously between 0 and 8 volts (see illustration). This smoothly varying signal can be approximated by reading the instrument once each second and expressing the reading as a 3-bit word. If more precision is desired, a 4-bit word can be substituted. In this way, all analog signals can be digitized and made compatible with the popular digital codes, such as PCM.

Before the data from the various spacecraft instruments can be sent to Earth, they have to be organized into a *format,* a pattern that terrestrial data processing equipment can recognize. As the spacecraft communication equipment scans all the instruments, it assembles the readings into a data frame, which is like a movie film frame in that it is a snapshot of all spacecraft instruments at a specific time. There may be twenty words from twenty sensors in the data frame; all arranged in a specific order. For the sake of the sanity of the computer that will eventually digest millions of these data frames, the words are usually made the same length. The word length and the arrangement of words in the data frame make up the format of the data. In a sense, each spacecraft instrument communicates in a rather stilted machine language and then only when called upon.

Not all space data are so rigidly and thoroughly mechanized. The voice link connecting astronauts with the Earth-based mission controller will usually be analog; that is, the amplitude and pitch of the astronauts' voices will be represented by a continuously varying signal. Television pictures from NASA's weather satellites and planetary probes are often digitized, although they may also be analog in character, like home TV. In general, though, NASA leans toward mechanizing and digitizing its space data systems.

11 *Circular film packs are often mounted on recoverable satellites in order to obtain tracks of ionizing particles at high altitudes.*

Downlink From Space To Earth

So far, the assumption has been that radio waves would carry the torrent of spacecraft data downlink to data acquisition stations on the Earth. There is another way to gather data from space and the technique is superior to radio in several ways. All one has to do is bring the spacecraft back to Earth and examine what it has recorded. Data from recoverable spacecraft will not be real time data, but this fact is not always critical; in fact, delays are sometimes desirable.

Many of the experiments flown on NASA's Biosatellites must be returned to Earth for detailed study in the laboratory. In some Biosatellite experiments, scientists wish to determine the long-term effects of weightlessness upon specimens placed in orbit. The effects of space radiation may show up weeks later in subsequent generations of insects descended from satellite-traveling ancestors. Satellite film is far superior to television cameras in color rendition and detail. The spectacular colored pictures taken of the Earth by Gemini astronauts prove this point.

Man himself is a recoverable instrument in a sense. A scientist-astronaut can perceive and interpret the unexpected better than remotely controlled experiments. A geologist on the Moon, for example, could examine and collect samples of lunar rocks, explore craters, and track down clues to the Moon's origin better than a machine.

Man, for all his powers of observation and ability to adapt to the unexpected, is expensive to sustain in space. Machines make the more routine measurements for him by proxy, just as unmanned weather stations do here on Earth. Indeed, for the great bulk of space research, automated, unmanned spacecraft make the best instrument carriers.

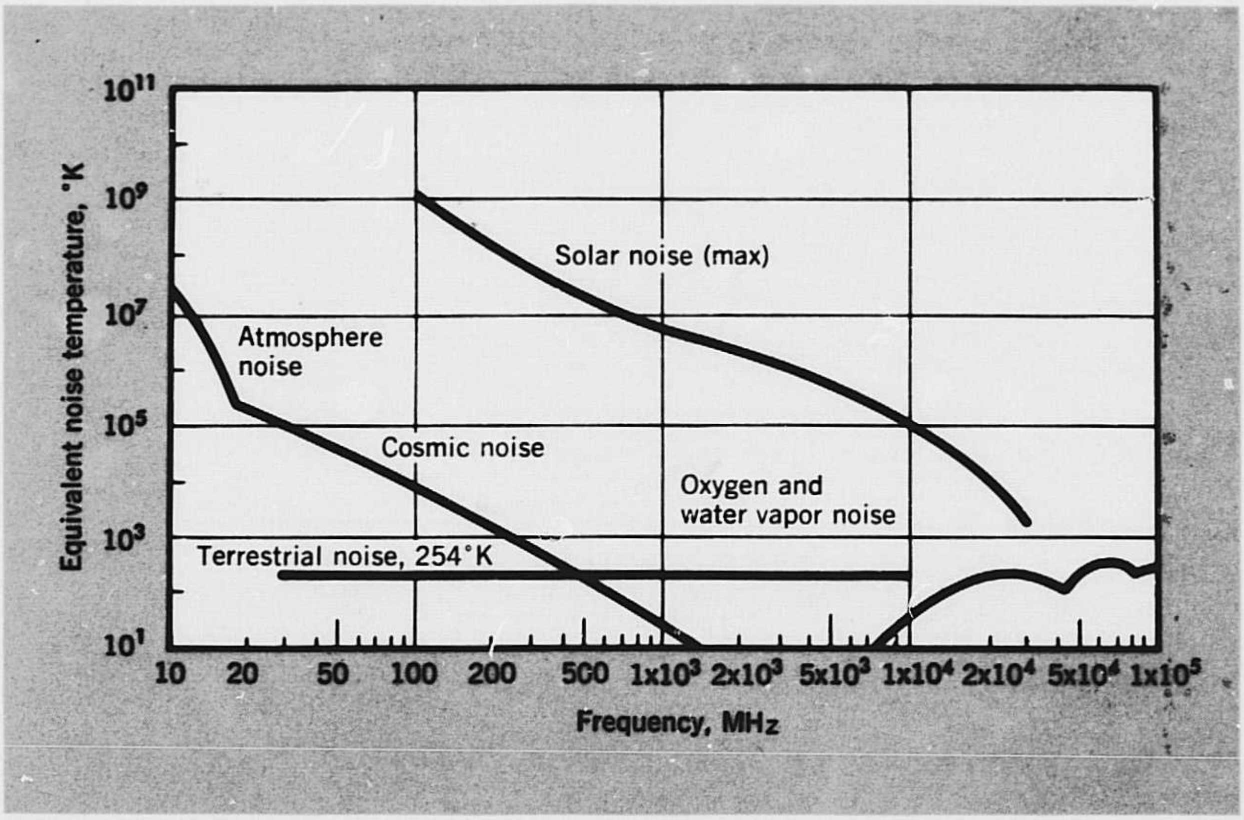
Radio waves represent the only practical way to get the automated spacecraft's instrument readings back to Earth at present. NASA, however, is developing the laser as a communication tool. With the advent of high power lasers and techniques for modulating their thin light beams, engineers have carried out successful short range communication tests on Earth. In theory, lasers can carry considerably more information per second than a radio carrier; primarily because much wider bandwidths are available at the high frequencies generated by lasers. The major problems encountered with laser communication are:
(1) Aiming the thin beams precisely at the receiver, and
(2) The attenuation of light in the atmosphere.

High transmitter power, big antennas, light weight equipment, high reliability; all are key factors in a successful space data system. Unhappily, we cannot have all of these desirables at the same time—compromises are necessary. One area of compromise comes when the carrier frequency is selected.

In choosing the carrier frequency, one looks first for a radio window in the atmosphere; a frequency band where atmospheric absorption is small. A broad radio window occupies the spectrum from 100 MHz to 10 GHz.* The low-frequency edge of this window is created by the Earth's ionosphere which reflects all radio waves below 10 MHz and seriously interferes with transmissions between 10 MHz and 30 MHz at times. The window's upper edge owes its origin to the atoms and molecules in the atmosphere that soak up the radio waves at these higher frequencies. To some degree, the window can be widened at its upper end by placing the terrestrial data acquisition stations in high, arid spots where the attenuation due to water vapor is reduced.

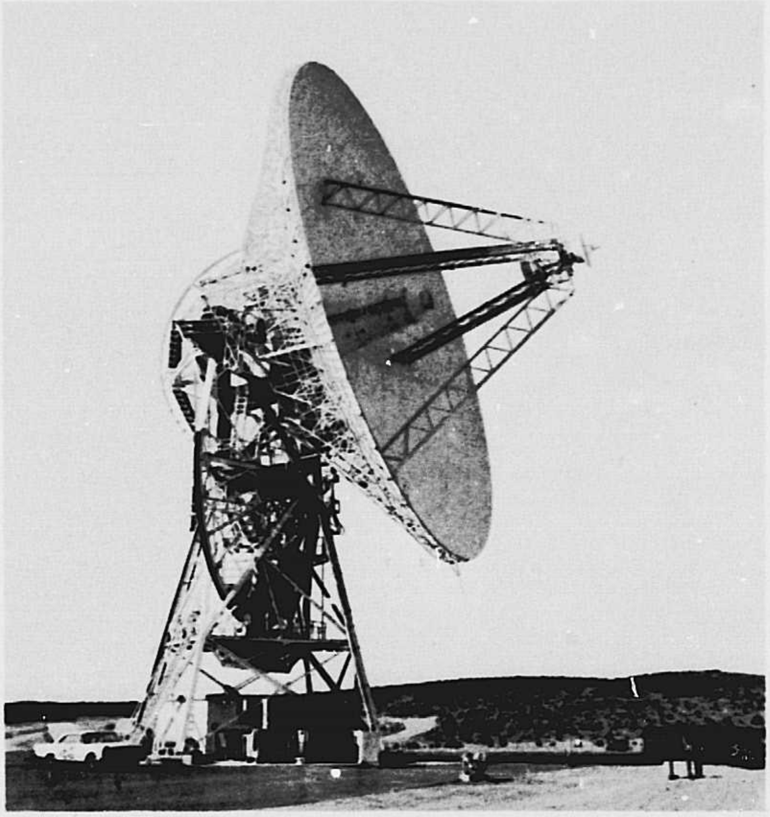
**1 MHz = 1 megahertz = 1,000,000 cycles/sec. 1 GHz = 1,000 MHz = 1 gigahertz.*

12 *Composite profile of noise seen by a receiving antenna.*



Next, noise sources must be avoided. Locating the receiving stations away from urban areas helps, but not all radio noise originates in man's cities. Under 20 MHz, the radio spectrum is burdened with radio noise created by lightning flashes and other atmospheric electrical activity. From 20 to 100 MHz, cosmic radio noise from outside the solar system poses a serious problem. There are many radio stars in the sky, and, of course, our own Sun is a prodigious radio source. Even the Earth, by virtue of its temperature, emits radio noise. A nearby hill caught in a station's antenna pattern introduces radio noise. Above 10,000 MHz, radio noise comes from oscillating oxygen and water molecules in the Earth's atmosphere; each molecule acts like a miniature transmitting antenna. Note that the low-noise region occurs just where the radio transmission window is located: 100 to 10,000 MHz. This is fortunate. Although some cosmic radio noise can be heard in this region of the spectrum, it is the best choice for space communication.

The next hurdle for the data stream is man-made. The spacecraft transmitter must employ a frequency in one of the bands approved for space communication by the International Telecommunication Union. The radio spectrum is so crowded by commercial, amateur, and military stations that space engineers find themselves cramped into narrow frequency bands. Most NASA scientific satellites have transmitted in the 136 to 137 MHz band, but more recently there has been a trend to higher frequency bands where the spectrum is less crowded and where cosmic noise is less of a problem.



13 *A DSN 85-foot paraboloid at Goldstone.*

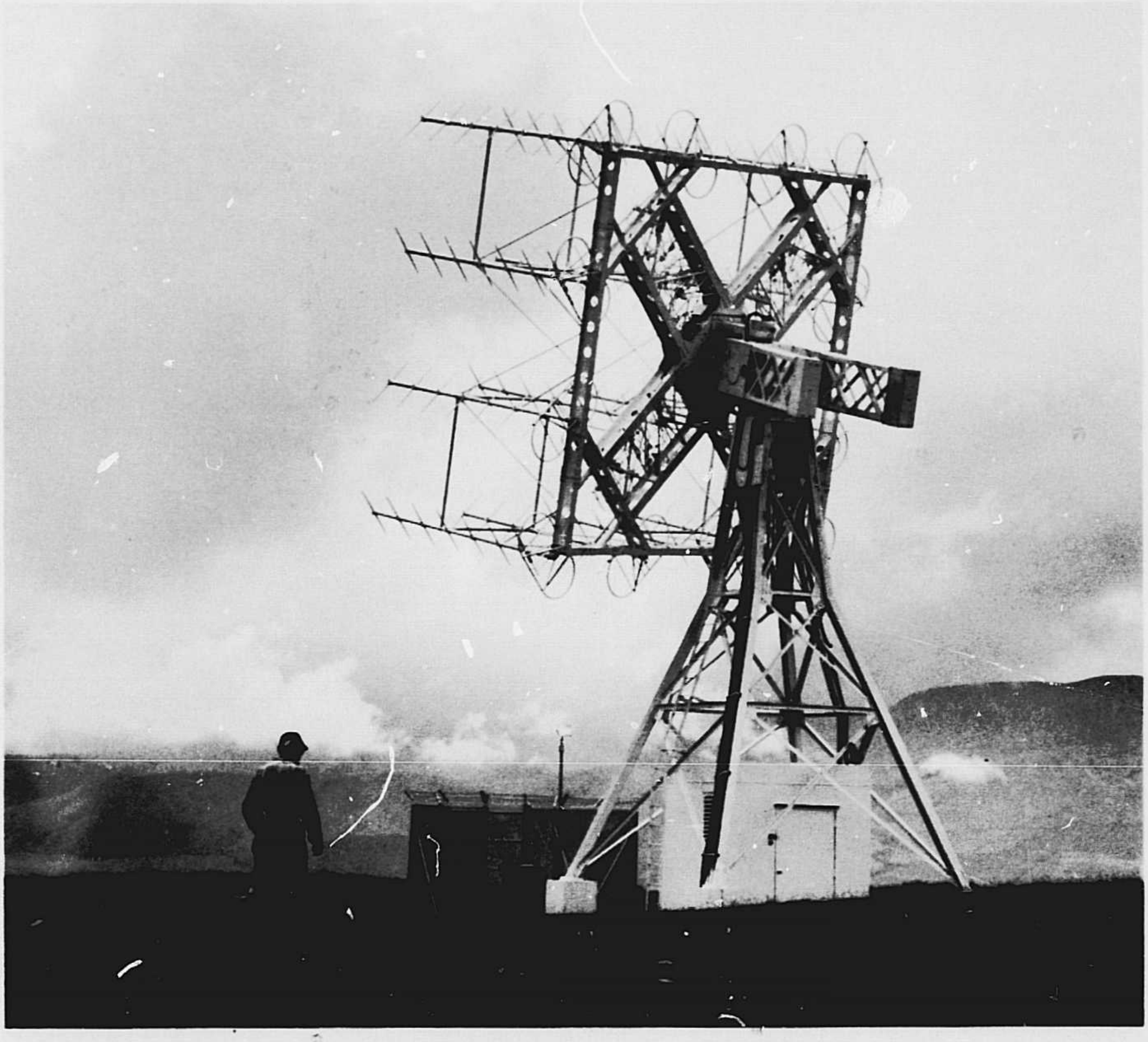
Data Acquisition

Working a spacecraft begins with finding it and then locking the station's receiving antennas on it so they will follow it automatically for the time it is above the horizon. This process is termed spacecraft acquisition. In 1958 and 1959, spacecraft were elusive because they were small and carried weak transmitters; they could easily get lost in the immensity of the sky. Unless a station operator knew exactly where to point his antennas he might never find the spacecraft. Today, the station operator has to select the right satellite from among the hundreds that pass over his site every day.

Suppose that a ground station wishes to work satellite X. A satellite ephemeris—a publication that does for a space tracker what an almanac does for a navigator—will predict when and where the satellite will be. NASA generates such data for its tracking stations from computer orbit analysis. When satellite X is expected on the horizon, tracking and radio receiving antennas are pointed in the direction predicted by the ephemeris. If all is well, the satellite's radio beacon will be detected by the tracking antenna. The tracking antenna will then automatically follow the satellite beacon signal, and the receiving antennas will be slaved to the tracking antenna; that is, they will be driven by motors so that they point in the same direction. Once satellite X is well above the horizon, a command is sent from Earth to read out the contents of its tape recorder. The data it has collected since it was last worked is transmitted (dumped) into the data acquisition antennas waiting below. One of NASA's large observatory-class scientific satellites may transmit several novels' worth of data—millions of bits—in a few minutes.

Acquiring data from a planetary probe is somewhat different. A probe far out in space is always in view for one of NASA's Deep Space Network stations. Seemingly, there is no need for a tape recorder aboard the spacecraft; no need for burst transmissions. In fact, the bit rates, as measured in bits per second, are so low that the probe must transmit continuously to utilize the data-gathering capabilities of its instruments. During planetary encounter, however, several new instruments (cameras, radiometers, etc.) will be turned on to scan the planetary disk. The flood of new data would more than saturate the probe's communication subsystem, so the data are recorded on tape and

14 *An automatic-tracking telemetry antenna used at STADAN sites to work satellites. Each of the sixteen rods is a "yagi" antenna.*



played back slowly after the planet recedes in the wake of the spacecraft.

NASA has built three separate but mutually supporting worldwide networks of stations for tracking and conversing with spacecraft.

STADAN, the Space Tracking and Data Acquisition Network, is used primarily for working unmanned satellites, particularly NASA's many scientific and applications satellites.

MSFN, the Manned Space Flight Network, is applied almost exclusively to tracking and communicating with manned spacecraft, such as the Gemini and Apollo craft. The major stations are concentrated in a belt 40° north and south of the equator.

DSN, the Deep Space Network, is employed in tracking lunar, planetary, and deep space probes (the Surveyors, Mariners, Pioneers, etc.). It also augments the MSFN during the Apollo lunar flights. The DSN stations are spaced around the world so that they will always have all probes in sight.

The major external feature of any tracking and data acquisition station is its complement of large antennas. In STADAN, the smaller satellites are worked by arrays of "yagi" antennas while the bigger, high data rate, observatory-class satellites dump their data into 40 and 85-foot diameter paraboloidal antennas. The MSFN also employs small antenna arrays for listening to the manned satellites. For manned lunar missions, however, the MSFN has added several 30 and 85-foot paraboloids to some of its stations to ensure receiving the weaker signals from the more distant spacecraft. The MSFN 85-foot dishes are located adjacent to like-sized DSN antennas to assure uninterrupted communications and tracking during the critical Apollo lunar operations. The MSFN and DSN paraboloids track as well as communicate, while those assigned to STADAN do not track. The DSN also boasts a 210-foot diameter paraboloid at its Goldstone, California, station for receiving data from distant space probes. This antenna has picked up data from probes over 200 million miles away.

The big antennas are like the tops of icebergs—obvious, but suggestive of much more below the surface. Hidden within the station buildings are great quantities of electronic gear: receivers, transmitters, recording equipment, computers, power supplies, etc. This hardware is necessary to amplify the feeble signals received from the spacecraft and translate them into forms that can be readily transmitted to the network's control center. A network's stations are only temporary stopping points for the streams of data emanating from the several dozen spacecraft that NASA may be working at any one time.

The largest fraction of NASA's data originates on the numerous scientific satellites. Scientific data are usually not needed immediately—realtime transmission via NASCOM, NASA's terrestrial communication network, is unnecessary. Instead, most scientific data are recorded on magnetic tapes, which are then mailed back to Goddard Space Flight Center, Greenbelt, Maryland. Several score miles of magnetic tape are filled each day, depending upon the number of satellites being worked.

Critical, real time data flows through a data acquisition station in only a fraction of a second. Astronaut transmissions and important housekeeping data are amplified and fed into NASCOM's terrestrial communication lines without holdup except for the time it takes electrical circuits to act. NASCOM lines also carry commands from the network control centers to the station working the addressed satellite, thence to the satellite uplink by radio. Tracking data also flow to control center computers on NASCOM circuits. The computers return pointing commands to the next network stations so that they can more easily acquire the spacecraft when their turns come.

One other kind of communication traffic is especially interesting. It is employed primarily by the MSFN, where actual missions are months sometimes years apart. To maintain the MSFN in a high state of readiness, train operators, and check out equipment, network simulations are conducted via NASCOM. During a simulation, signals resembling those occurring during a real mission are sent out over NASCOM to the stations and MSFN control center. The signals simulate equipment failures, human mistakes, and anything else that might go wrong—or right—during a real manned flight. The simulations exercise the network and reveal weak points in human and machine.

Let us take a closer look at NASCOM. It is a global, realtime terrestrial communication network. Signals received from a satellite over Australia cross the Pacific and the U.S. mainland, arriving at Goddard Space Flight Center in less than a second. Goddard is the hub of NASCOM. Most network communications pass through the switching circuits there. In essence, Goddard is the equivalent of a telephone exchange, routing data and voice messages to the proper stations in all of NASA's three networks.

Goddard is aided by numerous relay points plus major overseas switching centers at London and Honolulu. Switching subcenters are located at Madrid and Canberra. All told, well over 100,000 miles of communication lines, undersea cables, and microwave links tie NASA stations together. During the Apollo mission, communication satellites add more circuits to NASCOM for wider geographic coverage.

Some of the points serviced by NASCOM are not network stations; for example, NASA's Ames

Research Center and Marshall Space Flight Center. Some points, such as NORAD and Spacetrack, are not even NASA facilities. Through these points, NASA exchanges tracking data and other information with other governmental agencies. NASCOM is, in fact, an important national resource. As such, it is integrated into a much larger worldwide network called the National Communications System (NCS). NASCOM helps "wire the world" for U.S. government communications.

Where The Brains Are

Each of NASA's networks has its own control center where mission decisions are made. As fast as real time data reach Goddard Space Flight Center on NASCOM lines, they are switched on to circuits leading to the appropriate control centers. These are:

For STADAN: Mission Control Center, Goddard Space Flight Center, Greenbelt, Maryland

For the MSFN: Mission Control Center, Manned Spacecraft Center, Houston, Texas

For the DSN: Space Flight Operations Facility, Jet Propulsion Laboratory, Pasadena, California.

NASCOM might be called the nervous system of these man-machine complexes that join a spacecraft at one end and man at the other. The control centers, which obviously include man, are the brains and decision makers.

In the human body, the functions of the brain include perception, evaluation, decision-making and the dispatch of commands to the appropriate parts of the body. NASA's control centers do the same. Conceivably, a NASA network could run itself without the services of man. A big computer could make all of the decisions if all answers to potential questions were stored in it before the mission. Unfortunately, we do not know all of the questions prior to a mission. Almost all spacecraft missions have presented unexpected situations with which only man, with his unique creative capabilities, could cope. Man has to be in the loop—as control engineers say—because space exploration is not routine.

15 *The Mission Operations Control Room of the Mission Control Center at Houston. The consoles and displays suggest the magnitude of ground support necessary for a manned mission.*

Even though man is in the loop, big computers are needed to control NASA's spacecraft. A computer takes raw tracking data from NASCOM lines and translates them into orbital parameters for the mission controllers. A computer also translates the long strings of pulses representing housekeeping data from the spacecraft back into human language; not necessarily English, more likely some sort of visual *display*. A typical visual display for a manned satellite mission portrays the spacecraft position at all times on a world map.

A computer also helps man cope with the flood of space data by flagging data that deviate too far from normal. The flag may be a red light on an electronic console in the control center. To illustrate, if the spacecraft power supply voltage drops below a specified level, on goes a red light. The human operator then makes a decision and takes action.

Sometimes man may be completely bypassed by his machines. For example, the atmosphere and temperature of a manned spacecraft cabin may be maintained by decision-making machines, just as a home thermostat turns on the furnace when it is needed. Another illustration: during the launch of a large rocket, computers monitor and evaluate engine pressures, temperatures, and fuel flows. They can evaluate much more data than man during this short but very critical period. Things may happen so fast that only a computer can make decisions fast enough to prevent a disaster, say, by shutting off the engine.

Suppose that a manned satellite has just fired its retrorocket and is curving down for a splashdown in

16 Real time computer complex at the Goddard Space Flight Center. Manned orbital and lunar flights are supported by this equipment.

the Atlantic. Just where will it hit? A man could work through the mathematics using data from the MSFN tracking radars, but it would take far too long. The computer comes to his aid by predicting the splashdown point and by displaying this information visually on a screen for the mission controller.

Summarizing, man's machine partner can make routine and certain emergency decisions by itself. Where man must be in the loop, the machine translates data into terms he can understand readily and then displays them for him. Further, a computer can predict consequences of potential actions. Man is reserved for creative decisions—a function in which he surpasses the machine.

Data Processing And Archiving

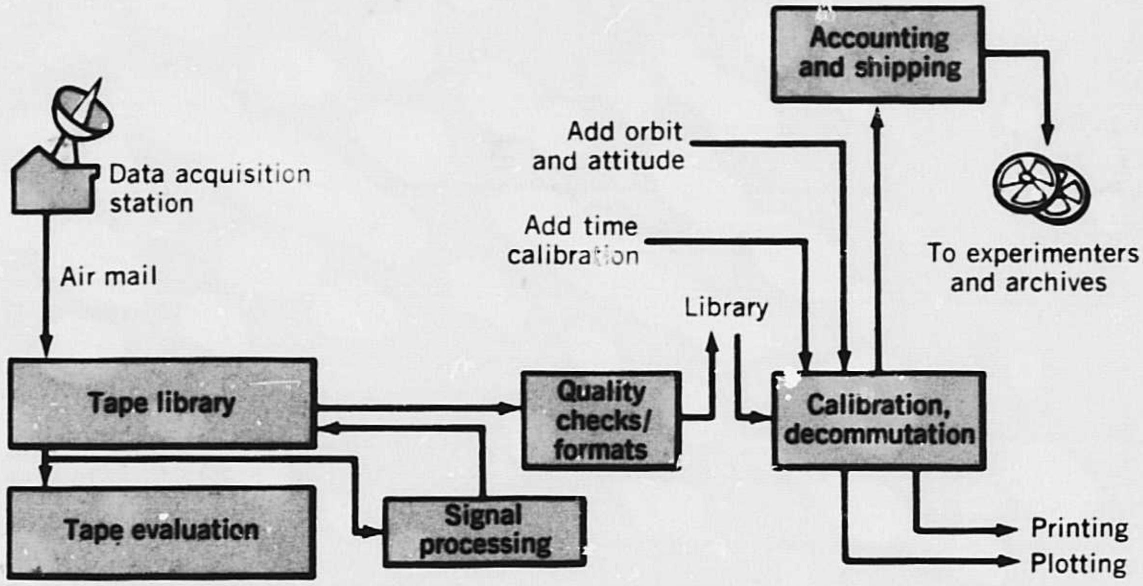
Spacecraft, especially the scientific satellites, are so prolific as data gatherers that it is hard to describe the data deluge in easily comprehended terms. To say that an observatory-class satellite may dump 100 billion data points into STADAN antennas during its lifetime gives little physical feel for the situation. Equating 100 billion data points to a half million library books is a graspable statistic. Few libraries have this many volumes on their shelves. Add to sheer quantity the things that NASA has to do to each data point and you will understand why the processing of space data is a job for big computers.

NASA has evolved procedures for turning the data flood into a well-organized stream of information that is highly useful to space scientists. Each datum arriving at Goddard Space Flight Center from a scientific satellite is edited, cataloged, indexed, and archived. All NASA-produced data are retrievable upon demand from the thousands of reels of magnetic tape stored at NASA tape libraries. Also processed are the data generated by NASA weather satellites.

In practice, data handling is not so formal and formidable. Satellite and probe experiments are usually built by individual scientists and groups of scientists. As the reels of magnetic tape pass through Goddard's data processing lines, a computer sorts out each scientist's data and, if he so desires, edits and partially digests it for him. A scientist with an experiment on one of Goddard's satellites can get his data quickly and tailored to his needs. The data must, however, be preserved in NASA's data archives for future reference.

Upon opening a magnetic tape mailing carton, we find a half-inch-wide tape filled with data in the form of tiny magnetized spots. A tape from a STADAN station will contain data from the scientific experiments on the satellite being worked by the station when the tape was made, plus housekeeping data that tell the scientist which way the satellite was pointing when the data were taken. The STADAN station will also add time signals and other reference data that help the scientist interpret his data. Usually, the data on STADAN tapes are still multiplexed and must be decommutated; that is, sorted out experiment by experiment. Different satellites employ different modulation schemes and

17 *Typical flow of data during processing.*



different data formats. Goddard has built data processing lines, similar to industrial production lines, that make order from the diversity of the data collected by STADAN stations.

At Goddard, a facility called STARS (Satellite Telemetry Automatic Reduction System) digests magnetic tapes and begins the task of data organization and processing. First, the taped data are decommutated and, if they are still in analog form, digitized. STARS computers can often recognize and flag errors that may have crept into the data; some telemetry codes (notably PCM) have self-checking features. The STARS production line also adds universal time to the data points. Satellite position and orientation are inserted where needed. The products are termed *experimenter tapes.* If the scientist desires, his tapes can be processed further. The computer will draw graphs, tabulate data, and even direct the scientist's attention to particularly interesting developments.

Several data processing lines are always in operation at Goddard and the other spacecraft control centers. There is a steady flow of edited, processed, indexed tapes to data libraries, where they will be available to anyone who may wish to see them ten or twenty years hence. To illustrate the potential of such scientific data, old astronomical photographic plates have proven immensely valuable in checking to see if a newly discovered comet was ever recorded before, or if the spot where a nova now flames was occupied before.

Archiving infers long-term data storage. NASA has created the Space Science Data Center at Goddard Space Flight Center for this purpose. The Center is responsible for storing, retrieving, and disseminating NASA's space data. On the international level, World Data Centers have been established in Washington, Moscow, and other locations. All countries send copies of their important space data to the World Centers, where they are indexed and stored for future use.

The data archives represent the terrestrial end of the link tieing spacecraft sensors to man. The link may be only a few score miles long in the case of sounding rockets, but it stretches across the solar system for deep space probes. For the first time, man has extended himself beyond the Earth's atmosphere into outer space. For the first time, he is seeing, touching, and directly measuring the cosmos. Without radio communication, computers, data acquisition antennas, and the rest of the space data system, this would be impossible.

Additional Reading

For titles of books and teaching aids related to the subjects discussed in this booklet, see NASA's educational publication EP-48, Aerospace Bibliography, Fourth Edition.

Information concerning other educational publications of the National Aeronautics and Space Administration may be obtained from the Educational Programs Division, Code FE, Office of Public Affairs, NASA, Washington, D. C., 20546.

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