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COMMUNICATIONS SYSTEMS UTILIZING
PASSIVE SATELLITES

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Summary

The era of communications systems utilizing passive satellites was inaugurated by the launch of Echo I in 1960. This was followed by Echo II in 1964. These preliminary experiments have proven system feasibility and indicated deficiencies of the satellite materials and configurations. Echo III will be launched in the spring of 1966 to test the latest available materials.

This paper outlines the history of the passive satellite communications experiments to date and offers solutions to the deficiencies that have been indicated. The solutions include a preview of studies of new materials and satellite configurations. Communications system capability utilizing the proposed satellites is detailed for conventional and specialized networks.

The Echo I Satellite

The Echo I satellite, launched in August, 1960, is a 90-foot-diameter sphere composed of aluminum foil and mylar plastic. It has been in orbit for almost six years without any significant changes in its surface characteristics after the first few months. The inflation system produced a good sphere; however, after the first few months the surface of the satellite became wrinkled, causing severe scintillation of the reflected radio signals.

Tests on the reflective characteristics of Echo I have been conducted throughout its lifetime to determine the effects of the space environment. Immediately following orbital insertion and inflation, the Collins Radio Company successfully transmitted a facsimile picture between Dallas, Texas, and Cedar Rapids, Iowa, via the Echo I satellite.

The Echo II Satellite

The success of Echo I initiated a program for improved materials and inflation techniques; and the resultant launch of Echo II in June, 1964. In preparation for the launch, the Goddard Space Flight Center of NASA had organized a network of ground stations to study, during its first year in orbit, the communications capability of the Echo II satellite. The network consisted of the U.S. Naval Research Laboratory station near Washington, D.C.; the Ohio State University Research Foundation station at Columbus, Ohio; and the Collins Radio Company experimental station near Dallas, Texas. The geographical locations of the stations permitted mutual visibility on many passes with the satellite at an orbital height of approximately 700 miles. Operational frequencies in the S-band region were chosen for maximum radio reflectivity of the satellite consistent with available equipment in the ground station complex.

A set of disappointing circumstances caused the Echo II satellite to be less than a perfect radio reflector, primarily due to ejection of the balloon from the canister. One of the two clam shells failed to open, imparting a sideways velocity to the satellite. The material used was similar to that in Echo I—mylar plastic and aluminum foil. This material has the property of becoming rigid in a vacuum after the pressurization system stresses the material to the yield point. Before the material had rigidized completely, the satellite lost pressurization prematurely. As a result, the satellite's shape is somewhat like that of a "prune". The tumbling motion of the sphere due to improper ejection from the canister and the rough surface causes severe scintillation of the reflected radio signals. The sphere is made in a segmented configuration using many gores with two polar caps. Several times during the test program the satellite was oriented in such a manner that the axis of rotation coincided with the reflecting surface and scintillation was reduced to almost zero. The characteristics of the Echo satellites are illustrated in figures 1, 2, and 3.

Description of Experimental Stations

Before discussing the tests and results of the experimental program on the Echo I and Echo II satellites, the ground station equipment should be described in brief.

The U.S. Naval Research Laboratory station employed a 60-foot-diameter antenna, low-noise TWT receiving preamplifier, and a phase-lock receiver utilizing special provisions to yield analog data. Data was taken at 2380 MHz, 2260 MHz, and 2190 MHz. Also, a 10-kilowatt transmitter at the station was utilized in the communications experiments. The NRL antenna was pointed by means of a programmed track using predicted look angle tapes, corrected by optical sighting when possible and by peaking the signal return when the satellite was not optically visible.

It should be noted that all experiments by this network were communications oriented and NASA provided
all satellite ephemeris data. Each station received a set of weekly predictions. While the predictions were adequate for the communications program, they were poor in comparison to ephemeris data on other satellites; the limited use of Echo I and Echo II not justifying expenditures for high accuracy satellite orbit prediction programs.

The Ohio State University Research Foundation (OSU) station has four 30-foot dishes and parametric amplifiers feeding phase-lock receivers with phase-locked demodulators for deriving analog signal strength measurements. The station employs monopulse tracking for the pointing of the four antennas.

The Collins Radio Company (CRC) experimental station employs a 60-foot and a 28-foot antenna. This station was used primarily for transmitting to the other two stations on each of the three frequencies involved, but was also used to receive the 2380 MHz signal from NRL at each of the two antennas, for a space diversity experiment. In the normal mode of operation a 10-kilowatt transmitter operating on a 50-percent duty cycle was used in the 28-foot dish to illuminate the satellites. The 60-foot dish and receiver tracked the reflected signals and completed the radar loop. Simultaneously, on one of the other two frequencies, a 10-kilowatt transmitter in the 60-foot dish illuminated the satellites for the other stations.

Data from the Collins station and from the NRL station was reduced and processed by Collins, and the data from the OSU station was reduced and processed by OSU.

The data obtained from the program is unclassified and may be made available by Collins Radio Company with the permission of NASA to interested parties. While the complete program cannot be detailed here, some of the more interesting aspects are included.

**Typical Communication Experiments**

In general, the interest centered on the effective radar reflection cross section of the satellites (Echo I and Echo II), the characteristics of the scintillation of the reflected signals, and the effects of these two parameters on the communications link.

**Average Cross Section**

Perhaps the most important single characteristic of the Echo II satellite as it relates to communications is its effective reflection cross section. This parameter was determined by measuring the received signal level as a function of time and comparing the level to that expected for a perfect sphere at the predicted range. The data indicated that the satellite characteristics did not change significantly with time, and that the Echo II exhibits a cross section average of 1060 square meters as compared to the physical cross section of 1320 square meters. The Echo I exhibits a cross section of about 3 db less than Echo II, which is approximately equal to the ratio of their physical cross sections. Analog recordings of received signal level are shown in figures 4 and 5.

**Time and Amplitude Distribution of Fades**

Another item of extreme interest concerning the reflected signal is its variability. The signal returns are characterized by strong lobes persisting for a second or so, and short deep nulls between lobes. The depth of the nulls is normally about 20 db.

As was previously indicated, the scintillations virtually disappeared on several occasions. We believe this was due to the line-of-sight coinciding with the axis of rotation of the satellite.

Essentially all of the power fluctuations occur at frequencies below 3 or 4 cycles. By removing the variations due to change in range between the satellite and the ground stations, it was found that the amplitude fades could be approximated by the Rayleigh distribution curve. The characteristics of the reflected signals are indicated in figures 6 through 10.

**Bandwidth and Diversity Measurements**

An item of importance in the evaluation of a communication medium is the coherent bandwidth of the medium. It is also of interest, if the medium produces scintillations, to discover what sort of spacings will provide for satisfactory diversity operation. The coherent bandwidth in this case is defined as that bandwidth over which the fading is highly correlated. Frequency diversity measurements were first attempted by modulating the carrier with 6 MHz to produce sidebands with 12-MHz spacing. This was also tried at 70 and 190 MHz. Due to equipment limitations, the wider spacings combined space and frequency diversity. From the data it can be concluded that both Echo I and Echo II have a coherent bandwidth in excess of 12 MHz; frequency diversity operation could be successful at 190 MHz or greater; and space diversity would not normally improve the system. The effects of diversity operation are indicated in figures 11 and 12.
Digital Data Experiment

As a part of the program it was felt desirable to obtain an indication as to the quality of transmission of digital data over the Echo II path. The experiment was performed by transmitting an audio frequency square wave, or a string of alternate ones and zeros. Appropriate equipment was constructed to drive a standard counter when a bit was missing and the subsequent recordings indicated that an average of one bit was lost for each thousand transmitted. As might be expected with Rayleigh fading, the bit errors are by no means uniformly distributed in time. As a result, the word error rate would be considerably better than would be calculated if uniform bit error distribution were assumed. The results of the digital data experiment are indicated in figures 13 and 14.

Facsimile Experiment

As was previously stated, a facsimile picture was transmitted between Dallas, Texas, and Cedar Rapids, Iowa, following the launch of Echo I in 1960. In 1964, a picture was transmitted between Dallas, Texas, and Stumpneck, Maryland. In the Echo II experiment, the facsimile signals were recorded on magnetic tape and then played into the Collins transmitter at four times the recording speed. The transmission utilized frequency modulation onto the carrier and the reception was with a standard frequency discriminator. Reproductions of the facsimile tests are shown in figures 15 and 16.

Audio Transmission

A number of audio tests were made on both satellites and, as a graphic illustration of the transmission path utilizing passive satellites, we offer for your consideration a portion of one transmission made from the Collins station to the NRL station. We hope you will notice that while there are occasional bursts of noise during deep fading, in between these bursts the transmission is clear and virtually free of noise, and at no time is selective fading evident. The results of similar tests utilizing Echo I are comparable. By reducing the transmitter power 10 db on the Echo II path, good communications were still obtainable.

Experimental Program Summary

Each of the tests mentioned was designed as a foundation for passive satellite communications systems. We feel that the knowledge gained will be applicable to future satellite systems. Please note that in each test the scintillation characteristics of the reflected signal are the governing factors for transmission quality. Degradation of signal level due to the wrinkled shape of the spheres is relatively minor. Had Echo II achieved the proper orbit without tumbling, there would be essentially no fading.

Proposed Satellites

Bearing in mind the background already presented, consider now the future aspects of passive satellite communications systems. For a number of years Goodyear Aerospace Corporation has conducted extensive research on new materials and techniques that could be applied to passive satellites, which coupled with the advances in the rocket program enhances the bright future in this field.

New materials have been developed which offer larger-diameter spheres for a given weight, with a subsequent effective satellite gain. In addition, a photolyzable film bonded to a wire grid has been developed. The film would be utilized to shape the wire grid to proper form in space and then evaporate due to solar radiation. The remaining wire grid would then become a stable satellite, unaffected in its orbit by solar pressures as are Echo I and Echo II. The wire grid would be small enough to be a good reflector at microwave frequencies. Meteor impact would penetrate the screen without disturbing the overall shape. Many other materials with unique properties are also being investigated.

In conjunction with the new material developments, new satellite shapes are being investigated. One of the more promising is called a lenticular satellite (figure 17). Notice on the illustration that only that portion of a sphere visible to ground stations serves a useful purpose. The remainder of the sphere may be removed without loss in effective radar cross section. Thus, the effective cross section may be increased by using the same material to form a lens. The curvature of the lens would be dictated by satellite height and required coverage. Typically, for a synchronous orbit at 21,500 nautical miles, a weight reduction of almost 1000:1 can be achieved with a lens, compared to a sphere. The deployment of the lens is illustrated in figure 18. Notice that the lens is surrounded by a torus to insure circularity. The lens itself is caused to take the proper shape by inflating the volume contained by the lens and an associated membrane. The satellite must be earth oriented to achieve usefulness and this may be done simply by attaching a mass at the apex of booms under the satellite. Similar booms on top of the satellite are attached to a mass through a helical spring. The spring and mass constants are chosen to damp the system during the initial orbits of the satellite and to
maintain gravity gradient stabilization. Initial studies have indicated that this simple arrangement can maintain lenticular satellite orientation to the local earth vertical with a nominal accuracy of 3 degrees and all but eliminate the turning motion. This would essentially eliminate any scintillation, should the lens take an irregular shape. Hence, any deformation would result in loss of gain but would not degrade communications quality.

An additional stabilization force may be derived by a loop of wire through the booms carrying a current derived from solar cells. This system would essentially remove the turning component by aligning the satellite with respect to the earth's magnetic field. The torque produced by this "compass" effect has been investigated by other satellite systems.

The station-keeping facilities for the satellites to maintain their position over a given point above the equator are being investigated. Feasibility studies have indicated that a technique called "solar sailing" may be used. Special coating on portions of the satellite to absorb or reflect solar energy could produce the required torque vectors to maintain a given position relative to earth as the earth and satellite rotate with respect to the sun.

The development of the Saturn C-5 launch vehicle has given us the capability to place a 25,000-pound satellite in synchronous orbit. Using the lenticular concept with materials already available, a satellite with a diameter of 1120 feet could be placed in orbit. At synchronous altitude the radius of curvature could be 3200 feet, or an effective diameter of 6400 feet, to correspond to an included angle of 20° for horizon-to-horizon coverage. Based on the radar equation, the satellite would exhibit a gain of

\[ G = \frac{4 \pi^2 \rho^2}{\lambda^2} \]

with \( \lambda \) expressed in feet. For the weight expressed and the diameter indicated, the material utilized has a weight of less than 0.02 pounds per square foot. The actual material available has exhibited a weight reduction of approximately 100:1 compared to that used on the Echo I and Echo II satellites.

Typical Proposed Communications Systems

General

Isotropically reflecting passive communication satellites, such as Echo I and Echo II, have not been seriously considered for synchronous orbit altitudes, because the associated communication system suffers a fourth power transmission loss with respect to path distance to the satellite.

However, for a fixed-weight lenticular satellite, the effective overall system path loss reduces in effect to that of approximately the square of the distance to the satellite. This is because the satellite's lenticular angle is selected to illuminate only the region near the earth rather than reflecting isotropically like a complete sphere. This fact can also be deduced by noting that the equivalent reflected power is independent of orbital altitude if the lens angle is varied as a function of height.

Synchronous orbit passive communication satellite systems will be considered to show the potential of this concept. In the case of either active or passive satellites in synchronous orbit, only three satellites are required for world coverage.

Communication System for Passive Satellites in Synchronous Orbit

Several system configurations which may be used are indicated in figure 19. Note that if a Saturn C-5 rocket were utilized to place a lenticular satellite in synchronous orbit, presently available materials would allow the satellite to have an effective diameter of 6400 feet (3200 feet radius of curvature). The gain of the satellite is plotted as a function of frequency, relative to a one-square-meter reflector. Path loss is also indicated as a function of frequency for synchronous altitude.

The other two curves indicate the relative size of antennas required to communicate for a given transmitter power. In the case of voice transmissions, assuming a 6 kHz bandwidth and a transmitter power of 1 kw, 34-foot-diameter antennas would be required at 10 GHz. A 10 MHz bandwidth would be available with antennas less than 100 feet in diameter if 50 kw transmitters were utilized. This represents a system capability of approximately 10 db below that of an active satellite. This ratio could be reduced considerably as newer materials are introduced or through the use of larger launch vehicles.

One of the outstanding assets of the passive satellite is the unlimited bandwidth and access to all users. As an example, if the 1000-foot-diameter antenna at Arecibo, Puerto Rico, and associated 150-kw, 400 MHz transmitters were used to illuminate the satellite, voice broadcast reception could be achieved via a receiving antenna with only 15 db gain. This would correspond to a 6-foot dish. Since the 6-foot dish would have a beamwidth of
30 degrees, it could be permanently mounted.

Notice that the received signal is a direct function of transmitter power. Many types of ground stations could simultaneously use the satellite for special purpose network requirements as they are conceived either prior to or following orbital insertion. The satellite concept discussed is expected to have a lifetime on the order of tens of years.

Communications System for Low Orbit Passive Satellites

The lenticular satellite concept is not restricted to any given orbital height. For a given height the curvature of the lens may be set for horizon-to-horizon coverage. As an example, if we utilize the lens at an altitude of 2000 nautical miles, the effective diameter would be 1296 feet and a single Saturn C-5 rocket could orbit 40 satellites. To give an effective continuous coverage, two vehicles would be required with the satellites launched in two planes.

Based on an effective diameter of 1296 feet, figure 20 indicates the required antenna sizes for a single voice channel and for television. Note that for the same transmitter power the antennas on the ground have been reduced in size by a ratio of approximately 2:3 for the smaller satellites in a 2000-mile orbit, as opposed to the large satellite in a synchronous orbit. Also, only two Saturn rockets would be required to orbit all the low orbit satellites as opposed to three rockets required for synchronous orbit. Although the ground stations would require an antenna that would be capable of following the satellites through their orbits, the required velocity of the antenna motion would be small.

In effect, the communication system improvement is approximately 6 dB when using the low orbit satellites as opposed to the synchronous orbit, although smaller satellites are used. The lower orbit satellites also restrict communications range due to a lesser horizon for mutual visibility between two stations.

Again, multiple access to the passive satellites is available throughout the frequency range of 0.1 GHz to 10 GHz for special applications and satellite lifetime is on the order of tens of years.

Specialized Systems

With the advent of the Manned Orbiting Laboratories, it is conceivable that very large passive satellites could be assembled in space at a medium altitude and, after assembly, be injected in a synchronous orbit. To reiterate, I would like to point out that presently available rockets and materials can inject into synchronous orbits passive satellites that would allow communications systems to be established with overall system gains approximately 10 dB below that of present active satellites. This difference can be easily achieved through an increase in transmitter power in the ground terminals. One further possible system configuration may be explored. For a given satellite weight using the lenticular concept, the ratio of the effective diameter, that is, the curvature of the lens and increased diameter, is proportional to the square of the intercept angle. As an example, consider a synchronous satellite for hemispherical coverage with an effective radius of curvature of 3200 feet and an intercept angle of 20 degrees. The same weight may be utilized for a satellite with an intercept angle of 3 degrees and an effective radius of curvature of 120,000 feet. This narrow beamwidth would be adequate to completely illuminate the United States. If the 1000-foot-diameter antenna at Aricebe, Puerto Rico, utilized a 150-kw transmitter at 400 MHz to illuminate the satellite, nation-wide television reception would be available to every home owner using conventional television antennas and inexpensive frequency converters. This would put stringent requirements on the stabilization system, as well as requiring accurate position keeping; but the concept does warrant serious consideration.

Conclusions

The proposed systems shown in this paper are within the realm of possibility using available materials, techniques, and presently available launch vehicles. Experience gained from the Echo I and Echo II satellites has verified communication system parameters and the pending trials on new satellites will verify the new material concepts.

Passive communication satellites show great promise and present research may enhance the technology in the areas of proving and implementing satellite system capabilities. All of the research is directed to providing economical communications systems.

Lenticular gravity-gradient satellites, because of their inherent long life, capability to provide broad communications bandwidths, and ability to operate with an unlimited number of users, offer the promise of providing passive satellite communications systems for global coverage.
In conclusion, I would like to express my appreciation to Mr. John Ford of Collins Radio Company and Mr. Charles Kelly of Goodyear Aerospace Corporation for their assistance in the preparation of this paper.

List of References

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2. FORD, John L. (Space Systems Division, Collins Radio Company; Dallas, Texas), Some Communications Results of Echo II Experiments, (Published by Collins Radio Company; Dallas, Texas), Presented to the 17th Annual SWIEEECO, Dallas, Texas, April 1965.


ECHO II TEST SPHERES AT LAKEHURST, NEW JERSEY
CLOSE UP VIEW OF ECHO II TEST SPHERE
AT LAKEHURST, NEW JERSEY
CROSS-SECTIONS OF ECHO I AND ECHO II MATERIAL

Echo I
- 0.5 mil MYLAR
- 2200Å VAPOR DEPOSITED ALUMINUM
- AL FOIL 0.18 mil

Echo II
- MYLAR 0.35 mil
- AL FOIL 0.18 mil

SAMPLE SIGNAL RETURNS-PASS 3001 - ECHO II

receiver input

DBM

-110
-115
-120
-125
-130
-135
-140

ELAPSED TIME, SECONDS

0 5 10 15 20 25 30 35 40 45
SAMPLE SIGNAL RETURNS - PASS 3483 - ECHO II

RELATIVE AMPLITUDE SPECTRUM OF RECEIVED POWER - ECHO I

FREQUENCY - CPS

RELATIVE POWER - WATTS

ELAPSED TIME, SECONDS

RECEIVER INPUT DBM
DENSITY HISTOGRAM - PASS #1170

ECHO II PASS #1170
1978 DATA POINTS
1/4 SEC SAMPLING PERIOD
MEAN = 1110 SQUARE METERS
DATE: 640423.01

DENSITY HISTOGRAM - PASS #2310

ECHO II PASS #2310
1076 DATA POINTS
1/4 SEC SAMPLING PERIOD
MEAN = 1406 SQUARE METERS
DATE: 640718.03
AMPLITUDE CORRELATION MEASUREMENT
ECHO II PASS 1533

CROSS CORRELATION
EXPERIMENT RESULTS

<table>
<thead>
<tr>
<th>SPACING (MC)</th>
<th>ECHO II</th>
<th>ECHO I</th>
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<tr>
<td>12</td>
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DIGITAL DATA
EXPERIMENT
ECHO PASS 1730

EXPERIMENTED: 1730

EXPECTED ERROR RATE FOR AVERAGE SIGNAL
RECEIVED ASSUMING RAYLEIGH FADING AND
LINEAR DETECTION

EXPECTED ERROR RATE FOR AVERAGE SIGNAL
RECEIVED MINUS 3 DB

ACTUAL ERROR RATE AVERAGE OVER 15,000 BITS

TIME IN SECONDS

10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}

120 160 200 240 280 320 360 400 440 480
COPY OF PHOTOGRAPH TRANSMITTED BY FACSIMILE

COPY OF PHOTOGRAPH RECEIVED VIA ECHO I
COPY OF PHOTOGRAPH TRANSMITTED BY FACSIMILE

COPY OF PHOTOGRAPH RECEIVED VIA ECHO II
LENTICULAR SATELLITE CONCEPT

FOR HORIZON TO HORIZON COVERAGE \( \theta = 2 \sin^{-1} \frac{R_o}{R_o + H} \)

\( 6 = \pi P_o^2 \)

FOR CONSTANT WEIGHT

\( \frac{6}{6_o} = \frac{\theta_o^2}{\theta^2} \)

WHERE \( \theta_o = 20 \text{ DEGREES} \)

AT SYNCHRONOUS HEIGHT
LENTICULAR SATELLITE
SYSTEM REQUIREMENTS FOR PASSIVE SATELLITE IN SYNCHRONOUS ORBIT

- SATELLITE GAIN + DB
- SATURN C/D
- ONE WAY PATH LOSS FOR SYNCHRONOUS ALTITUDE

ANTENNA DIAMETER FOR 1 VOICE CHANNEL TELEVISION
(10MC) C/N=16DB
TRANSMITTER = 50KW

NOISE TEMPERATURE
1000° = 100°
TRANSMITTER POWER
10KW = 1KW
C/N=16DB IN 6KC RF BANDWIDTH
SYSTEM REQUIREMENTS FOR PASSIVE SATELLITE IN 2000 MILE ORBIT

ANTENNA DIAMETER FOR TELEVISION (10MC) C/N=16DB
TRANSMITTER = 50KW

ANTENNA DIAMETER FOR 1 VOICE

NOISE TEMPERATURE
1000° <-> 100°
TRANSMITTER POWER
10KW <-> 1KW
C/N = 16DB IN 6KC RF BANDWIDTH