Trends in Earth Resources Satellites Data Communications Systems

M. Noda*
Hughes Aircraft Company, Culver City, Calif.

The effectiveness of the Earth resources satellite system will depend greatly on the information system which collects the data, relays it to the ground, and then processes it. The amount of data is so great that its transfer from the spacecraft to the ground stations presents several problems which are basically part of one major problem—the reliable transfer of a very large amount of data, in a very short time, using a limited bandwidth. This paper presents some of the more difficult system design problems and offers some feasible solutions, including multiplexing, digitizing, coding and the use of higher frequencies than 10 GHz to avoid frequency-sharing problems. The lack of continuous contact between the satellites and the ground stations may be remedied by deploying data-relay satellites in geostationary orbits.

Introduction

THE Earth resources satellites will realize their maximum potential only when equipped with data communications systems that are able to handle the large quantity of data derived. The amount of survey sensor data is so great that two or more acquisition stations are required for data collection and transmissions. Figure 1 shows satellite passes in a single day and the relationship of the satellite to the ground stations during these passes.[1] The locations of existing and potential stations are shown as circles for three of the stations' reception areas. The bands shown at the equator indicate which satellite orbits fall within the reception areas of particular ground stations. Although the potential for world coverage exists, it should be recognized that in any sequence of orbits, data must be stored for later transmission at a time when the satellite is within the range of an appropriate ground station. This limitation is due to the short read-out time available because of the limited size of the ground station reception areas. The lack of continuous contact between the low altitude (e.g. 500 miles), sun-synchronous satellites and a small number of ground stations is a severe problem. Further, it must be borne in mind that other satellites in the same UHF and S band frequencies will also be using these telemetry receiving stations. Frequency-sharing is becoming a critical problem as more and more satellites are using VHF, UHF, and S bands.

Various bandwidth-reduction or data-compression techniques may be employed to increase the efficiency of digital data transmission for use in sending spacecraft sensor video information to the ground station. Although compression ratios of about 2:1 or power savings of 3 db are all that appear feasible for spacecraft application at present, reductions approaching 10:1 or 10 db may be possible, particularly where time buffering techniques can be used. However, any attempt at digital data compression will certainly increase the complexity of the spacecraft. Analog predeemphasis, on the other hand, adds very little complexity to the FM system, and the additional complexity required for the coherent communications technique is confined entirely to the ground station. However, the artificially-generated analog data-compressed pictures are nothing more than an estimate of the true pictures, and the resultant pictures may not be useful because of lack of high picture quality. For the high resolution pictures required by Earth-resource survey scientists, the picture approximation and quantization-reduction systems must be dropped from consideration because of inherent element brightness reduction and picture distortion. For the data communications system of the Earth-resource technology satellites, the basic problem is the rapid and reliable transfer of a very large amount of data within limited bandwidth and in a limited tracking time.

Flow of Earth-Resources Survey Information

The Earth-resources survey information data originates onboard the satellite in the survey sensors (Fig. 2).[2] Most of the data follows flow paths 1 and 2, in which some storage and a minimum of processing takes place onboard, some processing takes place at the acquisition stations, and final processing occurs at the data processing facility. Real-time information will always be needed in local areas serviced by the system via paths 3 and 4. Command and control signals are sent to the satellites and their sensors through path 5.

The communication subsystem on the Earth-resources survey satellite provides the two-way flow of information between the satellites and Earth bases. It is certain that far more data will be acquired at the satellite that can be transmitted; hence the need for attaining maximum bit rate for accurate transmission and for efficiently selecting the data to be transmitted. The communication link of primary interest is that from the satellite to Earth, both because it

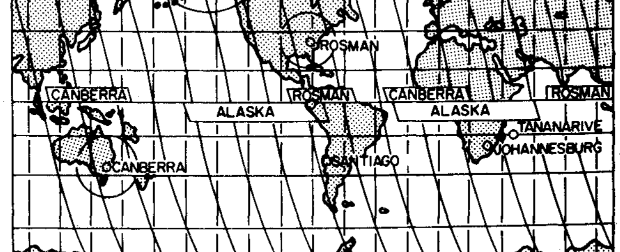

Fig. 1 Ground station coverage.

Presented as Paper 70-325 at the AIAA Earth Resources Observations and Information Systems meeting, Annapolis, Md., March 2–4, 1970 and at the AIAA 3rd Communications Satellite Systems Conference, Los Angeles, Calif., April 6–8, 1970; submitted February 1, 1971; revision received July 29, 1971.

Index category: Data Sensing and Presentation or Transmission Systems.

* Head, Technical Staff, Advanced Projects Laboratory, Data Systems Division, Equipment Engineering Divisions. Associate Fellow AIAA.

represents the more significant direction of data flow and because spacecraft restrictions on weight and available prime power cause this link to be the most critical.

Optical Imagery Transmission Considerations

The distribution of sensing techniques applied by the Earth resource satellite sensors is: optical imagery, 65%; radiometry, 15%; spectrometry, 10%; and active techniques, 10%. When optical imagery techniques are to be the sources of data, a comparison of performance by analog transmission systems and digital transmission systems becomes desirable. When the transmission is from a satellite, the important characteristics to be considered are transmitter power required for a given accuracy and the simplicity of equipment. Thus the pertinent analog and digital systems parameters are rf bandwidth requirements at a given transmitter power. For the analog system, the accuracy is expressed by the output signal-to-noise ratio. For the digital system, the accuracy is described by the probability of error.

Transmitting sinusoidal signal with the analog FM system with a modulation index of m radians will result in the signal-to-thermal noise ratio given by the FM-S/N improvement formula equation, as long as the carrier power is substantially greater than the noise power.

$$(S/N)_A = 3m^2(m + 1)C/N \tag{1}$$

where $(S/N)_A$ = the resultant analog signal-to-thermal noise ratio measured in baseband bandwidth, m = the carrier-to-noise ratio (average power ratio for the analog system measured in the rf transmission bandwidth of $2f_m(m + 1)$, Hz/s), and f_m = the modulating signal of frequency, Hz/s.

For the digital system, there are two sources of noise; quantizing noise and noise caused by making an incorrect decision at the receiver. It is assumed that these noise powers add so that the resultant signal-to-noise ratio is

$$(S/N)_D = S/(N_Q + N_E) = [(N_Q/S) + (N_E/S)]^{-1} \tag{2}$$

where $(S/N)_D$ = the resultant digital signal-to-noise ratio due to the effects of quantization and detection errors, S = signal power, N_Q = quantizing noise power, and N_E = noise power due to errors.

The signal-to-quantization noise ratio, S/N_Q, varies with the number of bits per digital word, n, used to represent each sample, and may be expressed as follows:

$$S/N_Q = (3/2)(4)^n \tag{3}$$

The more n used for each signal sample, the more precisely the information is defined.

The signal-to-error noise ratio, S/N_E, is given in terms of bit error rate as

$$S/N_E = 1/[4P_E(1 - P_E)] - 1 \tag{4}$$

$$S/N_E \simeq 1/4P_E \text{ for } P_E \leq 10^{-2} \tag{5}$$

where P_E = probability of error.

In receiving digital data, we are concerned with ascertaining the presence or absence of a given signal. With nondeterministic waveforms, we must deal with an average power per unit bandwidth or average probability of error as a function of the ratio signal energy/noise power density. Figure 3 (Ref. 3) compares the error performance of PSK, differentially-coherent PSK, PCM-FM, FSK, and ASK systems. According to statistical decision error analysis, it is apparent that the PSK system is superior from the standpoint of susceptibility to white Gaussian noise. The PSK system used for comparison in Fig. 3 is a coherent system with antipodal signals.

Since P_E is known as a function of C/N, the above equations relate $(S/N)_D$ to C/N, with n as a parameter. The C/N ratio is an average power ratio and is referred to the rf bandwidth. Output S/N vs C/N curvers are presented in Fig. 4[3] for the analog and digital systems for various modulation indices and bit numbers.

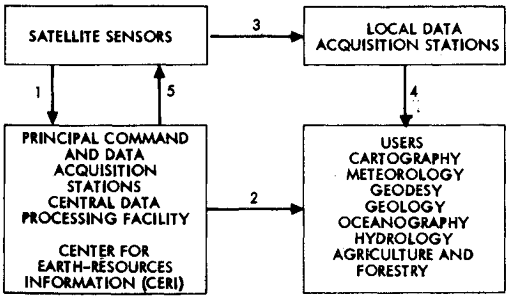

Fig. 2 The flow of Earth survey information.

Analog vs Digital Modulation

Figure 4 indicates that for both digital and analog systems there are threshold effects. If the input C/N falls below the threshold C/N, the output S/N drops rapidly. This threshold represents the minimum C/N required for useful operation of the system. For the digital system, the threshold represents the input C/N below which the transmission bit error rate begins to degrade the S/N available from the quantized signal. In the analog system, the threshold represents the value for which the FM improvement factor cannot be applied. The output S/N at threshold depends upon the system bandwidth (governed by m or n) as shown in Fig. 4. For analog transmission the above threshold value is obtained from the FM-S/N improvement formula (1); and for digital transmission it is given by the quantization formula (3). Since the S/N of the digital system increases exponentially with n and the S/N of the analog system increases with the third power of m, the corresponding output S/N ratio increases much more rapidly in the digital than in the analog system. Sampling the information source at a rate exceeding twice the highest frequency contained in the message waveform is an operation fundamental to all forms of digital mod-

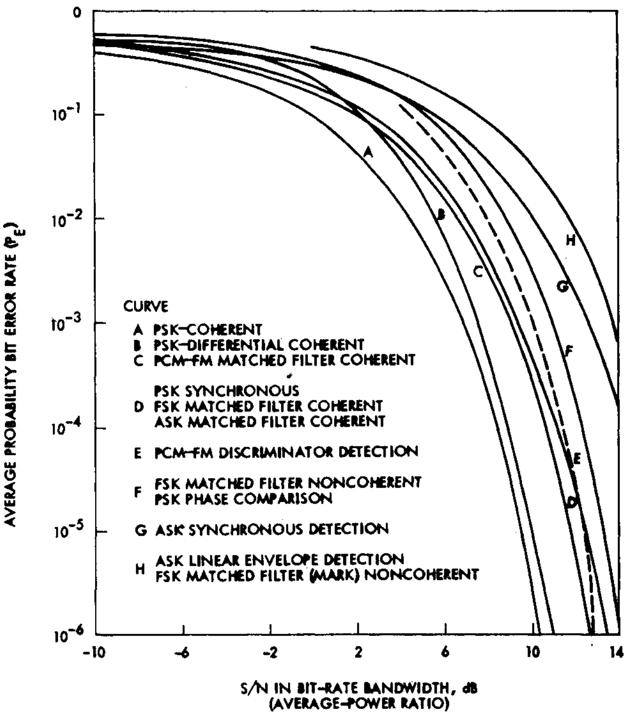

Fig. 3 Comparison of bit error rate vs carrier-to-noise ratio of various modulation systems.

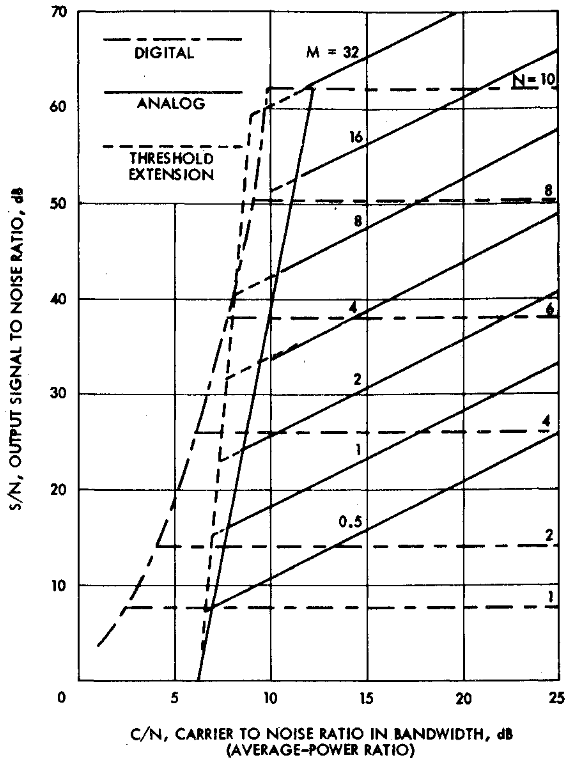

Fig. 4 Output S/N vs input C/N.

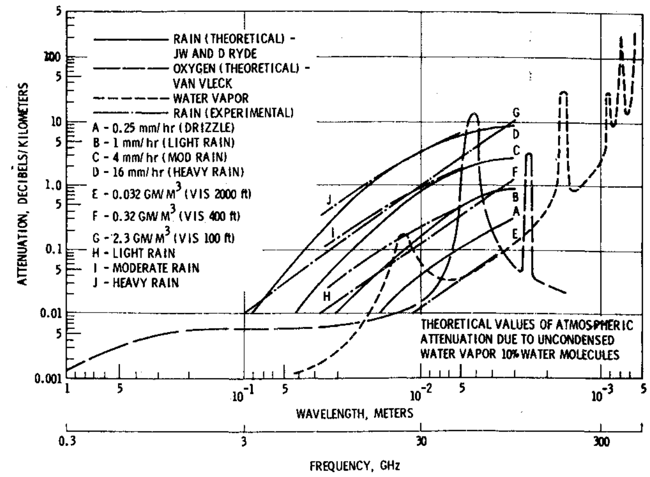

Fig. 5 Atmospheric attenuation summary.

ulation when this is used for conveying analog waveforms. Coding achieves a greater immunity to noise for two principal reasons. First, only a portion of the total information is affected by loss or corruption of one or more of the pulses of a code group Secondly, large amounts of noise and distortion can be tolerated in detecting an individual pulse because the pulse is selected from a small number of possibilities.

In digital transmission systems, analog information is transmitted in a quantized and coded digital form that efficiently trades-off transmission bandwidth for improvements in post-detection SNR, bettering even the performance of wide-band FM. The transmission bandwidth for PCM is n times as great as that required for direct bandwidth transmission of the signal. The code groups can be transmitted either as a time sequence of pulses over the same transmission channel, or in parallel over n separate channels. In either case, the total bandwidth occupied will be the same. A PCM system is, therefore, a coded wideband system in which the coding process purposely widens the transmission bandwidth by a factor of n to gain improved immunity to noise.

The transmission bandwidths for the FM and PCM systems may be expressed as follows:

$$BW_{\mathrm{FM}} = 2f_m(m + 1) \tag{6}$$

$$BW_{\mathrm{PCM}} = 2f_m n \tag{7}$$

where f_m = the maximum baseband frequency in Hz/s. These bandwidths are the minimum that will pass the significant carrier sidebands. In practice, doppler shift, crystal drift and similar frequency instabilities require the use of wider bandwidths, but those used here are based on the nominal rf bandwidth, which is determined by the information modulation. The ratio of the transmission bandwidth required by the analog-to-digital system for various S/N ratio is

$$\frac{BW_{\mathrm{FM}}}{BW_{\mathrm{PCM}}} = \frac{2f_m(m + 1)}{2f_m n} = \frac{m + 1}{n} \tag{8}$$

In high-resolution television (RTV) where primarily the objective is to acquire repetitive frame-type images, the analog system is simpler than the digital and would logically be used.

Although two systems are quite comparable in terms of power in the range of S/N ratios from about 15–35 db, as the value of n increases more than 8, the digital system is capable of greater accuracy. This greater accuracy can be attributed directly to the more efficient tradeoff between S/N ratio and bandwidth in the digital system at high S/N ratios. At very high output S/N ratios, where Earth resource satellite systems produce high-quality optical images, the digital system shown a substantial saving in bandwidth and power as compared to analog systems.

It might appear that a digital system requires more complex equipment than an analog system since a digital system requires sampling, quantizing, and D/A conversion, as well as bit synchronization and provision of a coherent reference at the receiver. However, for a multispectral scanner (MSS) that requires high accuracy, multiplexing, storage of various data transmissions, and automatic data processing capability, the superiority of the digital system becomes more evident. Digital systems are well suited to time-division multiplexing and, in addition, digital systems allow the possibility of combining data with other data collection sensors, automatic classification, automatic identification and further performance improvement with coding.

It should be emphasized, however, that the use of modulation techniques other than PSK for digital data transmission will change the analog vs digital comparison. Four-phase modulation, for example, can permit the doubling of quantizing levels, and hence output signal-to-noise, by increasing the threshold C/N value. Also, coding techniques will modify the comparison in a similar manner.

Considerations Applicable to Systems of the Future

Multispectral scanning in the uv, visible, and infrared regions of the electromagnetic spectrum provides the greatest amount of useful information. For a multispectral scanning camera, the bandwidth per spectral channel may be estimated roughly by

$$B = (2.4 \times 10^8)SW/r^2 \tag{9}$$

where B = the bandwidth per spectral channel in Hz, SW = the swath width in statute miles, and r = the resolution in feet. To obtain better resolution and greater swath width, the data communications system requires more bandwidth.

Systems for the early 1970's are intended to scan a 100 mile swath, imaging six vertical lines across in each of four spectral bands simultaneously. Each instantaneous field of view will have a resolution of about 260 ft. Two 20-MHz channels in the S-band have been allocated for the commu-

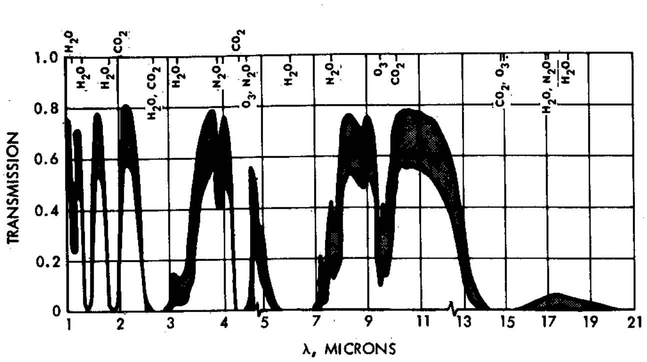

Fig. 6 Atmospheric transmission of infrared at sea level for zenith angles from 20–70°.

nication subsystem. The future communication subsystem may require more bandwidth as the demand for better optical imagery resolution increases.[1,4–7]

Feasibility of Using a Frequency Range of 10 GHz or Higher

The solution of the spectrum problem that faces us lies in effective spectral allocations and comprehensive engineering designed for maximum use of the spectrum. We must have an evolutionary system with changes well thought out and allocations based on complete technical assessments.

One significant consequence is the necessity that frequency allocations for future Earth resource satellite systems be obtained from other than the *S* and *X* bands in order to avoid the frequency-sharing now necessary when a single ground station communicates with more than one satellite system.

Disadvantages are found in possible limitations in the use of higher frequencies more than 10 GHz, such as increased path loss, due to weather conditions. It has been feared that rain and moisture absorption may interrupt service frequently. Every region of the Earth has its own particular weather conditions, and a knowledge of the effectiveness of any frequency higher than *X*-band requires detailed weather statistics. Both the height of the receiving station and the influence of local conditions on the rainfall and cloud pattern will be the prime factors influencing EHF communications performance.

While the use of frequencies more than 10 GHz has its drawbacks, it also has advantages. It should make frequency sharing simpler and even less necessary. The use of higher frequencies would expand the ultimate capacity of the world's satellite communication system. There is also the possibility that, in the future, millimeter or optical waves will be used. Transmission losses in the atmosphere result from absorption of electromagnetic radiation by the constituent gases (especially water vapor); in the optical region these losses are due to aerosol and molecular scattering. Absorption in the millimeter band occurs as shown in Fig. 5.[8] There are several transmission windows in the infrared as indicated in Fig. 6,[8] but roughly half of the spectrum is still blocked by molecular absorption bands. Rain and fog begin to have a serious effect on transmission in the millimeter region; the effect of fog increases at optical frequencies. Fog and cloud cover, of course, block out an optical communication link.

The troposphere varies in depth from an average of 55,000 ft over the equator to 28,000 ft over the poles, the depth in summer being greater than in winter. Thunderstorms may reach heights of over 40,000 ft, but by carefully selecting receiver station locations, their effects on the Earth resource satellite systems can be minimized. For example, thunderstorms rarely occur on the Pacific Coast, the average number of thunderstorms in this region being less than five each year.[9] Thunderstorms will be a function of location, and rainfall statistics can help avoid such locations. Hopefully, only a

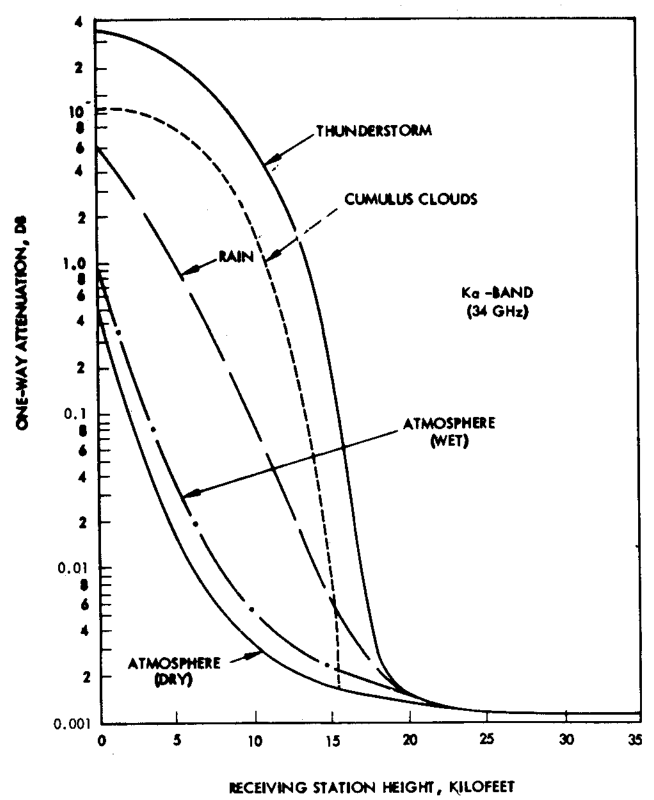

Fig. 7 One-way vertical path attenuation in db vs height at K_a-band for various weather conditions.

certain percentage of the path would be affected by rain, so that for attenuation purposes path length is greater than the actual atmosphere range would indicate. One can also argue that communication is unnecessary or of no concern during thunderstorm conditions because no Earth resources data (except weather) would be made during such weather.

For the use of communication links between a satellite and a receiver station at different altitudes (Fig. 7), the determination of various effective propagation path lengths for wavelengths of K_a-band or less becomes a major consideration. The term effective is used because there is a ceiling to the weather of about 20,000 ft. It can, therefore, be concluded that in normal circumstances, a relay or receiving station at an altitude of 10,000 ft or higher (or in the desert) would be satisfactory. High altitudes will not only avoid clouds and fog, but will also provide longer tracking times for the stations. The emphasis in Fig. 7 is on cumulus cloud and rain conditions because these are predominantly responsible for propagation losses.

Deployment of data relay satellites system in geostationary orbits in conjunction with Earth resources satellites will provide continuous tracking of the lower altitude satellites. Thus direct reading of the sensors can be offered to the ground stations without delay.

Conclusions

We have analyzed the communication problems that wideband, multiple-access satellites used for Earth resource surveying are apt to face in the future and have suggested solutions.

In digital transmission systems, analog information is transmitted in a quantized and coded digital form, trading off transmission bandwidth for improvements in post detection signal-to-noise ratio. To provide sufficient bandwidth and avoid frequency interference, future satellites may use higher frequencies than those in the *S*-band and may have to resort to millimeter or optical waves. To avoid weather-dependent transmission losses, future stations may be located on mountain tops, or in the desert. Continuous contact between the satellites and a small number of ground stations may be achieved by storing the data in the Earth resource satellites, although this would limit sensor collection on a program and selective basis. A promising solution to these problems appears to lie in deployment of a data relay satellite system in geostationary orbits.

References

[1] Space Applications Woods Hole Summer Study Report, "Earth Observations and Resources," Jan. 1968, National Academy of Sciences, Washington, D.C.

[2] Noda, M., "Problems and Suggested Solutions for Earth Resources Satellites Data Communications Systems," AIAA Paper 70-325, Culver City, Calif., 1970.

[3] Noda, M., "Hardware Aspects of Electronics for Manned Planetary Missions," *AIAA Technology for Manned Planetary Mission Meeting*, AIAA, New York, 1968.

[4] Thomas, P. G., "Earth-Resource Survey From Space," *Space-Aeronautics*, July 1968.

[5] "Big Eye in the Sky; Sensors to Monitor Earth," *Electronic Design*, 1 April 1969.

[6] Jaffe, L. and Summers, R. A., "The Earth Resources Survey Program Jells," *Astronautics and Aeronautics*, Vol. 9, No. 4, April 1971, pp. 24–40.

[7] George, T. A., "ERTS A and B—Engineering System," *Astronautics and Aeronautics Journal*, Vol. 9, No. 4, April 1971, pp. 41–51.

[8] Noda, M., "Communications, Instrumentation, and Data Handling for Manned Planetary Missions," *Journal of Spacecraft and Rockets*, Vol. 6, No. 6, June 1969, pp. 673–678.

[9] Federal Aviation Agency and Department of Commerce, *Aviation Weather*, U.S. Government Printing Office, Washington, D.C., 1965.

NOVEMBER 1971 J. SPACECRAFT VOL. 8, NO. 11

Utilization of Jupiter Swingby Trajectories for Comet Exploration

LARRY A. MANNING*
NASA, Moffett Field, Calif.

Jupiter swingby trajectories are investigated for comet flyby and rendezvous missions. The swingby is shown to result in approach velocities between 0.5 and 6 km/sec for 29 of the 37 short period comets considered. A Titan IIID/Centaur/Burner II launch vehicle will provide a flyby payload of over 2000 lb for these flybys. Rendezvous missions are defined for four comets (Honda-Mrkos-Pajdusakova, Tuttle-Giacobini-Kresak, D'Arrest and Daniel). The aforementioned launch vehicle with a 310 sec I_{sp} upper stage will provide at least a 700 lb payload at each of these comets.

Introduction

EARLY studies of comet intercept missions resulted in the determination of generally large approach velocities.[1–3] This meant that rendezvous missions were nearly impossible due to the extremely large propulsion requirements at comet arrival. The arrival velocities were sufficiently high that there was even some question as to the scientific usefulness of flyby missions. Recently, as mission analysts have turned their attention from the planets to other bodies of the solar system, an awareness of the possibility of performing comet missions through use of other trajectory modes (broken plane transfers, gravity assist, or low thrust) has renewed interest in such missions.

Much of the recent analysis has been directed at particular comets of interest due to either unique features (Halley's) or near term opportunity (D'Arrest), as well as low-thrust missions.[4–6] This paper presents a general survey of the mission requirements for comet flyby and rendezvous missions where a Jupiter swingby trajectory is used. The paper first presents the comet apparitions selected for analysis, and then discusses the trajectory characteristics and resulting payloads available.

Presented as Paper 70-1074 at the AAS/AIAA Astrodynamics Conference, Santa Barbara, Calif., August 19–21, 1970; submitted February 1, 1971; revision received August 9, 1971.

Index category: Lunar and Planetary Trajectories.

* Research Scientist, Advanced Concepts and Missions Division, Office of Advanced Research and Technology. Member AIAA.

Comet Selection

One of the outputs of this study is a listing of the comet opportunities which have the lowest energy requirements for both flyby and rendezvous missions. With these data, the mission planner can determine the tradeoffs which exist when sighting, flight time, or other constraints are applied to comet missions.

For this study all short-period comets which have perihelion passages between 1976 and 2000 and which have been or could be observed at three or more perihelion passages previous to launch are considered. The multiple observations are necessary to allow a reasonable degree of confidence in predicting future perihelion passages and the associated orbital elements. This approach retains for consideration 37 out of 94 short-period comets.[7,8] These comets, with perihelion passage dates in the time period of interest, are delineated in Table 1. Halley's comet was not considered, since missions during its next apparition have been thoroughly discussed by other authors.[4,6] The high-launch energy and arrival velocities they have shown for ballistic gravity assisted trajectories to Halley's comet make a high-thrust rendezvous mission impractical.

Trajectory Analysis

Several trajectory modes exist which can be utilized for ballistic missions to the comets. Although only the Jupiter swingby trajectory mode was considered in this study as a means of achieving low-energy comet missions, the other