DSN VHF Transmitting Array Backup Command Uplink for Voyager 2

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As a result of the failure of the Voyager 2 primary S-band receiver and the failed component in the remaining receiver, JPL is evaluating the feasibility and cost of an alternate command uplink in the low VHF band around 40 MHz, by utilizing the planetary radio astronomy experiment receiver aboard the spacecraft. The design considerations, tentative specifications and one preliminary mechanization for the requisite ground transmitting facility are presented. The magnitude of the transmitting requirement is on the order of 120 dBm EIRP, achievable with a 183-m diameter phase steered beam array with 250-kW output power. Preliminary results of tests conducted to date employing the Stanford 46-m diameter steerable parabolic antenna and 300-kW CW VHF transmitter at 46.72 MHz are reviewed.

I. Introduction

The remaining Voyager 2 spacecraft command receiving capability is degraded, and there is concern on the continued operations of the primary S-band receiver even in its degraded mode. In order to enhance completing the assigned mission to Saturn and to, perhaps, preserve the capability of a flyby of Uranus, an investigation was undertaken to evaluate alternate command techniques other than via the normal S-band uplink or stored program capabilities on board the spacecraft for Voyager 2.

The planetary radio astronomy (PRA) experiment instrument was identified as a possible redundant command receiver in September 1973 by the PRA experiment project scientist because the PRA receiver output has a direct connection to the spacecraft Flight Data System (FDS). In concept, the VHF uplink signal to the PRA receiver from the Earth would be suitably modulated, along with having the FDS previously modified so that its software programming would properly interpret the PRA instrument outputs as command logic signals to be routed to the Central Control and Sequencer (CC&S) for ultimate issuance to the appropriate spacecraft subsystem. The data rate would probably not be as high as the existing S-band uplink (16 bps) in order to afford the same bit error probability in the PRA non-phase locked or incoherent receiver, which is basically a broadband (200 kHz) power detector.

Because of the incoherent receiver, the low gain of the experiment antennas, the VHF operating frequencies and the long transmission ranges (Saturn 10 AU, Uranus 20 AU), a new ground-based transmitting facility would be required.

II. Transmitting Array Specifications

For assistance in deriving the approximate requirements of the ground transmitter, it was necessary to estimate the PRA performance characteristics, taking into consideration the configuration and environment aboard the spacecraft. Because of on-board RFI from switching power supply harmonics and other electronics noise, the PRA receiver signal-to-noise ratio (SNR) is better at the upper end (greater than 40 MHz) of the receiver capability. The receiver is limited to less than 50 MHz by amplifier bandpass and image filtering design limitations. Also, from realistic considerations of the chances for obtaining a long term "emergency" RF spectrum uplink frequency assignment at VHF, the higher the frequency, the less the disruption to established users, and thus the greater the chance of obtaining a carrier assignment.

The galactic background noise level in this region of the RF spectrum dominates the receiver input noise, and has a frequency to the minus 2.7 ($f^{-2.7}$) power characteristic that would also favor the upper end of the PRA instrument capability.

The PRA experiment antennas consist of a pair of 10-m long whips that are orthogonal to each other and as orthogonal as possible to the other spacecraft appendages (magnetometer and RTG booms). The resulting placement is such that the plane of the whips is swept back at about 35 degrees to the Earth-spacecraft line. The whip output signals are processed through RF circuitry that results in simultaneous right and left circularly polarized (RCP and LCP) outputs. The degree of crossed polarized discrimination in the actual spacecraft environment is unknown at VHF, but is estimated to be about 8 to 10 dB. The net result is a multilobed antenna pattern at VHF of somewhat unknown polarization characteristics whose spatial disposition, magnitude and frequency sensitivity are also unknown. Nevertheless, for purposes of link analysis, the assumption of a receiving gain equal to that of a simple dipole was selected, with the real state of effective gain to be determined (TBD).

The project scientist and JPL Division 33 personnel performed a preliminary link analysis and determined that the approximately 120-dBm effective isotropic radiated power (EIRP) may yield on the order of 8 bps at Jupiter (5 AU), 1/2 bps at Saturn (10 AU) and 1/32 bps at Uranus (20 AU) with a bit error probability of about 5×10^{-5}. The proposed modulation technique would be to switch between RCP and LCP.

Extensive spacecraft computer reprogramming, along with replanning of command sequences and sequence selection, would be necessary to accommodate the low data rates. It should be pointed out that the reprogramming can only be effected initially via the surviving (hopefully) S-band command uplink. If the S-band link fails before the reprogramming is complete, the PRA outputs will not be accepted as legitimate commands.

It was further assumed for planning purposes that a single VHF ground transmitting facility would be employed, and that it must provide a minimum continuous period of two hours of transmitting time with the power beam pointed in the ecliptic plane.

III. VHF Transmitter Options

A survey of existing VHF high-power transmitters and antenna installations was conducted in order to determine if any current facilities could meet the combined VHF frequency, EIRP, beam pointing and modulation requirements. Table 1 lists the candidates considered and brief notes concerning their technical limitations. All candidates were unsatisfactory on the basis of either EIRP limitations or pointing limitations, and polarization modulation diversity, which was not unexpected. However, it was noted that the Stanford facility was the most satisfactory near-term capability and was strongly recommended to the project to be employed in reducing the uncertainties in link design by conducting initial measurements of the receiving SNR at current range using the interrupted CW (ICW) modulation technique instead of polarization switching.

The longer term transmitter option of modifying or supplementing one of the existing facilities was felt to be not desirable when it was pointed out that dedicated, exclusive use of the facility may be required during track times and for verification testing of performance prior to critical mission phases. This priority or exclusive use (perhaps with configuration control) for upwards of five or more years would not be incompatible with a dedicated DSN facility if it turned out to be the *only* command uplink to the spacecraft.

The above considerations, when taken in connection with the required command verification and transmission elements, led to consideration of a site at Goldstone to make use of existing DSN facilities.

IV. Transmission Facility Configurations

The 120-dBm EIRP capability may be achieved with various combinations of transmitter power and antenna gain. The simplest VHF uplink in concept is a single large transmitter and a steerable paraboloid, as generating large amount of power at these frequencies is not difficult generally. Nevertheless, if an antenna diameter of 100 meters is assumed, then on the order of one megawatt of RF power must be radiated, CW. Feed breakdown and transmission line limitations are serious problems. Thus, in order to reduce the feed problems, an array of elements is desired, with the total radiated power divided between the elements. An obvious tradeoff exists between large, high-gain array elements that are steerable mechanically and electrically phased versus smaller elements that are fixed, requiring only electrical phase steering, at low RF power levels. High-power, continuous phase shifters are to be avoided.

As a result of the uncertainties in the required link performance and in the link location, and in order to provide maximum flexibility in the tracking time beam steering requirement, it was decided to employ simple crossed dipoles as the antenna elements, with solid state RF power amplifier modules at each element. If it were known for certain that only a two-hour tracking capability was required, then higher gain or shaped beam radiating elements could be employed. The ease of added growth and the fail soft character of the many element dipole array were added bonus factors to consider in the overall facility design.

To provide a point design for purposes of establishing the costs of a 120-dBm EIRP, ±15 degree tracking VHF transmitting capability, which was also potentially capable of being implemented in less than a year, the system shown in Fig. 1 and the block diagram of Fig. 2 were selected for detailed consideration.

V. An Array Point Design

A 1000 crossed-dipole element array with 250 W per element employing switched circular polarization modulation was selected to achieve the 120-dBm EIRP at 40 MHz. An unobstructed view to the south on a hillside tilted at latitude for an approximately 183-m (600-ft) diameter flat area with an access road and approximately one megawatt of primary power was desired.

An electrically bonded ground screen was required in order to yield a known and controlled ground plane. Square mesh with openings not much larger than 1/3 meter is desired for the circular polarization capability. The bonds are required to be continuous in both directions, as shown in the subarray drawing of Fig. 3.

Paralleled GaAs FET device output solid state RF power amplifiers of 125 W each, driving each orthogonal pair of dipoles at an element, driven in phase quadrature, would have their input drive signals switched by 180 degrees RF phase to achieve the polarization modulation.

The block diagram of Fig. 2 shows the array element phase shifters located within the proposed (unmanned) local control building. The low level signals would then be routed to the appropriate radiating element via double shielded coaxial lines buried beneath the ground screen or via solid outer conductor coax. Very high quality shielding is necessary to prevent feedback oscillations in the power amplifiers.

To enhance the capability for alternate uses of the facility after project completion or in the event the single remaining S-band receiver continues to successfully operate, a non-simultaneous receiving capability is shown. The receiving function could be employed to verify the transmit beam pointing location via monostatic radar bounces from the moon.

The bandwidth for the transmitter and antenna elements need be only that necessary to pass the modulation of the very low bit rate commands when operating. However, to the degree that there exists any uncertainties in the spacecraft antenna patterns as a function of frequency, and bandwidth may be allocated for any frequency latitude in that event, then added bandwidth capability may be required. Obviously, the alternate uses of the facility are enhanced by having large bandwidths, but at obvious increased expense. The narrow band array should achieve well over 70 percent aperture efficiency.

As it may be desirable to reduce the array antenna pattern sidelobe level during reception, a separate amplitude tapered aperture distribution combiner may be employed, which is switched in only during receiving operations. However, there is no good reason to taper the aperture distribution when transmitting commands, as the maximum on-axis gain that results is desired and simply achieved.

Bent, thinwall electrical conduit stuffed with rope to damp the wind driven vortex shedding oscillations was suggested for the radiating dipole elements. All four conductors could be grounded to the bonded ground screen at the element mounting base. Orthogonal wings of the dipoles could be fed in quadrature phase at the bends to yield circular polarization.

As the second harmonic of the array is near resonance of a standing person, and the site, if at Goldstone, is expected to be unmanned, then a personnel exclusion fence and warning signs and lights were proposed for alerting intruders to the RF hazard. The peak flux density on axis in the power beam is calculated to be about 5 mW/cm^2 at a range of slightly less than a kilometer. The average flux density in the aperture is only about 1.2 mW/cm^2, but the peak, localized density in and around the dipoles with a body present is such as to be avoided if possible.

The threshold for producing instabilities in the ionosphere with the high-power VHF beam was calculated based upon thermal self-focusing. The 183-m diameter, uniformly distributed aperture, 250-kW array beam is about 10 dB below the threshold, and difficulties are not expected, except possibly in conjunction with severe solar activity.

VI. Alternate Utilization

During the survey of existing facilities and in connection with discussions of the array with others, the alternate uses to which the array facility could be employed (listed in Table 2) were encountered. The SPS power beam ionospheric heating simulation application would actually benefit by a higher total flux density in certain regions of the ionosphere. Hence, an even larger area, more powerful facility would be mutually beneficial to DOE and NASA. Close coordination with the radio science and radar astronomy community as well as the National Science Foundation is advised if further detailed consideration of the capability is anticipated.

VII. VHF Uplink Experiments

After the initial array design investigations, Stanford University was requested to participate formally in a test of the uplink in order to gain information for reducing the range of uncertainties in the estimated link performance and to determine if the spacecraft PRA receiver could be successfully commanded to a range of receiving frequencies higher than its nominally designed 40.5 MHz. Also, the on-board RFI environment was to be sampled in and around the compromise 46.72-MHz operating frequency for Stanford, which was recommended by the DSN frequency allocation group after considering the assigned government band edges in the Palo Alto area, while keeping in mind the severe tuning limitations of the quarter wave (at 49.8 MHz) stub-supported open-wire transmission lines on the dish of the Stanford antenna.

The Stanford group restored and retuned the transmitter facility to operational readiness on short notice in order to support the first test on September 13, 1978.

300 kW was transmitted from the 46-m (150 ft) diameter antenna for 6-minute, 24-second periods with a 50 percent transmit duty cycle, time tagged for later correlation by the PRA experiment team at the University of Colorado.

The Stanford signal, because of the greater than minus 25-dB SNR, was detected with difficulty in the PRA experiment output. The experiment provided a greater than 1000 to 1 probability against incorrect detection, but the results were about 4.3 dB down ±2 dB one-sigma variation from the expected signal level. This result was well within the range of the TBD's, however. The on-board RFI appears not to be excessive from 40.5 MHz up to the highest frequency the PRA receiver was commanded to operate at, which was 49.152 MHz. An unresolved issue was that the on-board PRA instrumentation recorded receipt of the sense of circular polarization opposite that which was transmitted from the Stanford antenna.

An attempt was made to repeat the experiment again on November 18, 1978; however, one of the coaxial transmission lines carrying the high-power RF failed.

VIII. Conclusions and Recommendations

The PRA VHF uplink to Voyager 2 is technically feasible given that the FDS can be reprogrammed to interpret the experiment receiver output as legitimate commands when properly interfaced with the spacecraft CC&S. Depending upon the desired bit error probability and bit rate for the commands, a transmitting array larger than 183-m diameter and/or a radiated RF output power of greater than 250 kW may be required.

If the decision is made to pursue this alternate command link, then more detailed studies should be made of the optimum command sequences, stored command selection, the best allowed operating frequency, the spacecraft antenna patterns and polarization, the optimum modulation scheme, and the best location and implementation configuration for the VHF transmit array.

Table 1. 40-MHz uplink capabilities

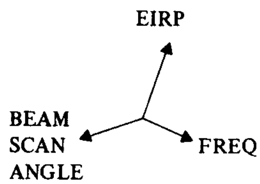
Requirements Summary:

(1) EIRP 120 dBm at ~40 MHz

(2) 2-h tracking, minimum

(3) Switched circular polarization modulation

(4) Capable of ~9 mo implementation, 1985 end of life



Candidates considered	Latitude	Capabilities
Arecibo	18.5°N	92 m (300 ft) useful at 40% η_A = 27 dB (93 dBm = 2 MW, feed, power amplifier and rotary joint required)
Stanford*	37°N	46 m (150 ft) at 50% η_A = 22.7 dB, 300 kW = 84.7 dBm (−12.6 dB and feed) (designed for 49.8 MHz)
Platteville	40.18°N	10-element ring-dot array ≈ 19 dB, 2 MW = 93 dBm (−8 dB, 25-30 MHz)
Sunset	40.18°N	29-dB manual-steerable, linear-polarization, 5-kW average (steering and power limits)
Goldstone DSS 14 mod	35.16°N	64 m at 40% η_A = 24 dB (96 dBm = 4 MW, feed, power amplifier required)
Turnstile array	35.16°N	1000 turnstiles for 36 dB, 250 W per subarray, ±23-1/2° × ±15° scan
Jicamarca	12.5°S	1/2° beam, 6 MW peak, 49.98 MHz, manual phased
Alternative designs:	Shaped beam subarrays, folded dipole radiators, mechanically steered, high-gain subarrays, manually phased declination, high-power phase shifter	

*Recommended to reduce link design uncertainty by measuring SNR at current range.

Table 2. 40-MHz uplink alternate utilization

Solar corona radar
SPS power beam ionospheric heating simulation
Stratosphere-mesosphere coherent scatter radar
Pulsar receiver array
Earth and planetary Faraday rotation effects
Radio astronomy sky mapping

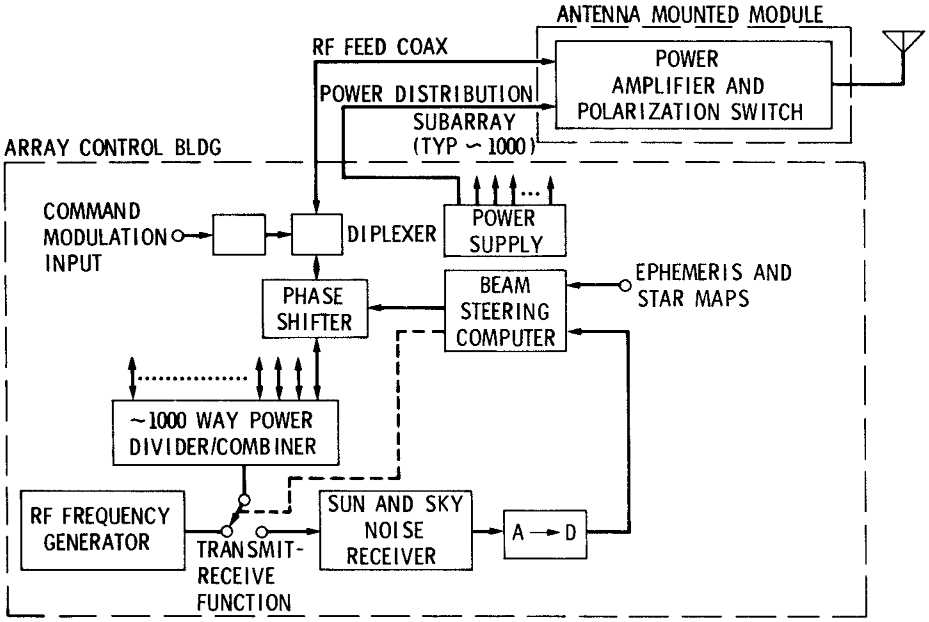


Fig. 1. 40-MHz uplink crossed dipole array

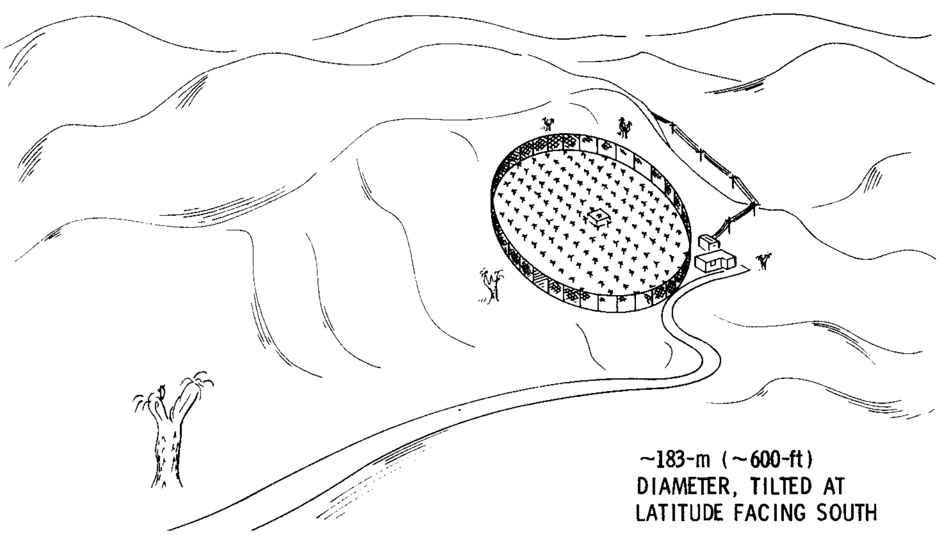


Fig. 2. 40-MHz uplink system block diagram

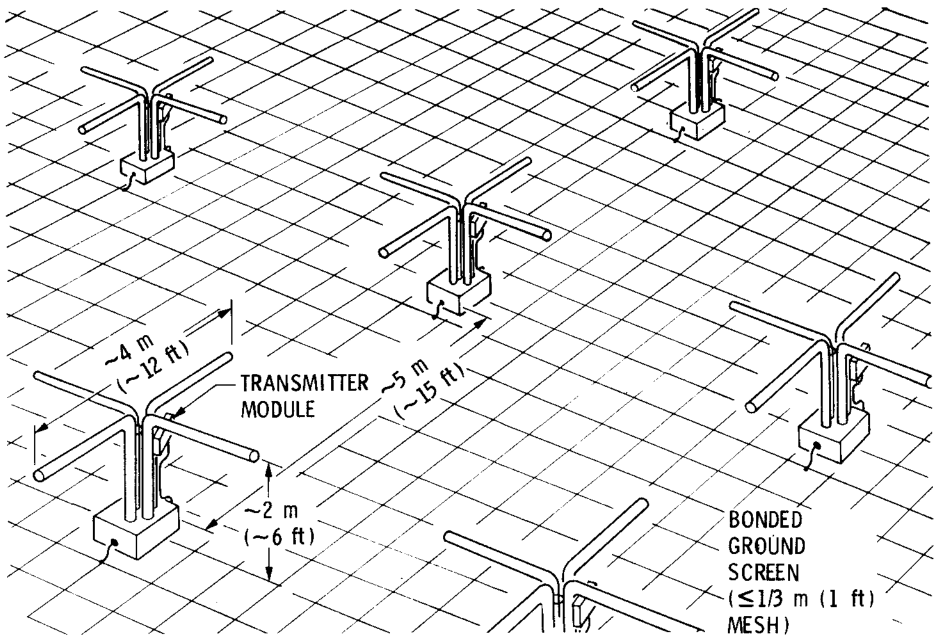


Fig. 3. 40-MHz uplink subarrays