A TRANSPONDER FOR DEEP SPACE PROBES-DESIGN AND PERFORMANCE CHARACTERISTICS

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Summary. Deep space probes necessitate the use of coherent ranging transponders. The requirements for this class of transponder can be divided into telemetry, command and ranging requirements. Usually the telemetry requirements are rather straightforward and concern more with hardware design aspects. On the other hand, command requirements generally requires iterative computations to achieve an optimum system design. Ranging requirements are based either on a simple turn-around ranging channel, or on the complex regenerative channel. The design of this transponder is based on the former type of ranging channel.

This paper shows the system design for such a transponder and a comparison with measured performance characteristics. Additionally, spurious signal analysis for the ranging operation is dealt with briefly.

Introduction. In order to maintain a telecommunication link over interplanetary distances, the telecommunication subsystem has to operate as efficiently as possible within the constraints imposed by other spacecraft subsystems while fulfilling the mission requirements. Thus, a phase-locked receiver is needed, which is very sensitive as well as able to track over a wide frequency range. Also, a transmitter with a high power efficiency is required to minimize power consumption.

For the Helios project, a joint U.S.-German deep space mission, telecommunication links until 2 AU ($3x10^8$km) were required.

This requires a transponder containing a receiver with about 3 dB noise figure and a transmitter capable of switching between 10 and 20 W output power. The capability is required due to the possibility, that at 2 AU the solar arrays cannot meet the power demand for 20 W operation.

One year before the start of development date AEG-TELEFUNKEN has performed investigations concerning design problems of a low-noise phase-locked receiver. The results of these investigations has been well documented; for a comprehensive report including test results on an engineering model please refer to ref. [1] and [2]

Unfortunately, at the time when development contracts were awarded, a sufficiently reliable transmitter with high power efficiency in light-weight technology had not reached a stage where it could be incorporated in the Helios program. Therefore we chose a conventional design, containing features proven in other space projects. The manufacturer responsible for the transmitter was Thomson-CSF, Paris, except for the travelling wave tube power amplifiers, which were delivered by Watkins-Johnson, Palo Alto, California.

Although transponders of this type have been built before, the performance characteristics of this transponder might be interesting, as we have utilized integrated circuits to a high degree in building the receiver.

As those chips have more or less inherent temperature compensation circuitry, we achieved low deviations in performance under temperature conditions.

Telemetry performance. The transmitter equipment accepts the data stream from the data handling equipment, which is convolutionally encoded and modulated onto a 32768 Hz subcarrier, and phase-modulates the subcarrier onto a 76 MHz carrier which is then frequency multiplied to the S-band downlink frequency. In the coherent mode a 38 MHz unmodulated signal is derived from the uplink signal and frequency doubled prior to modulation. The non-coherent mode utilizes onboard auxiliary crystal oscillators.

Regardless of whether the non-coherent or coherent mode is selected, only one driver/modulator is activated at one time. The active driver/modulator feeds one of four possible amplifier circuits only one of which is active at a given time. The four power amplifier circuits are composed of redundant modules of two classes of amplifiers:

1. 0.5 W solid-state low power amplifiers whose primary service is during the near-earth phase of the mission when the solar arrays are not yet charged up,

2. 10/20 W dual mode travelling wave tube (TWT) amplifiers used during the main phase of the mission.

Following the power amplifiers is a switching matrix circuit which will permit the downlink to be sent to earth via any one of the three antenna systems described in the next

[1] B. Heynisch, "Recent Development Results on the HELIOS S-Band Command Receiver", International Telemetering Conference Proceedings, pp. 648-661; 1972.

[2] S. Knapp, "A Single Channel Command Detector for Deep Space Missions", International Telemetering Conference Proceedings, pp. 662-667; 1972.

paper to be presented in this conference session. However, for the 0.5 W mode only the low gain antenna can be used. Due to the complex switching circuitry involved, a loss of between 0.9 and 1.7 dB in output power was measured.

Due to temperature compensating devices in the driver/modulator variations on the input power to the TWT could be held to ±0.1 dB. This results in amplifier operation with a high degree of power efficiency. The overall efficiency of modulator, driver and TWTA together is:

1. 31 % at 21.6 W output power

2. 26 % at 11.4 W output power

3. 7 % at 0.6 W output power

The efficiency is so low in the 0.5 W mode because optimization was effected for the main modes.

The output power variation for the TWT was ±0.2 dB for the temperature range of -5 to +65°C.

Another requirement concerns the rise/fall time t_{r1} of the squarewave subcarrier, which may not exceed 0.5 % of the subcarrier period T_{sc}, or 140 ns. Using the equation:

$$B_{r1} = \frac{1}{t_{r1}} - \frac{2}{T_{sc}}$$

the one-sided noise bandwidth B_{r1} for telemetry transmission should be at least 3.3 MHz. However, the 3 dB signal bandwidth of the baseband single-pole lowpass filter in the test receiver used for measurement is 2.5 MHz. The corresponding one-sided noise bandwidth B_{r2} is 2.27 MHz, so that a degradations in rise/fall time between measured and actual rise/fall time:

$$t_{r2} - t_{r1} = t_{r1} \left(\frac{B_{r1}T_{sc} + 2}{B_{r2}T_{sc} + 2}\right) = 60 \text{ ns}$$

is to be expected. Measurement results show rise/fall times of ≤ 200 ns, so that the requirement is fulfilled.

In order to ascertain the rise/fall time independent of any measuring bandwidth, the signal characteristics before any bandwidth limitations are imposed thereon have to be investigated. The best way is to use the spectrum of the transmitted signal. Assuming equal rise and fall times, Fourier series expansion yield the following results:

1. for an unmodulated subcarrier the power ratio d_{sc} between the first harmonic (double the subcarrier frequency) and the second is:

$$d_{sc} = 20 \log \frac{T_{sc}}{\pi t_{r1}} \geq 36 \text{ dB}$$

2. for a subcarrier phase-shift-keyed by a symbol stream of alternating “ones” and “zeroes” with symbol period T_{SY} the power ratio d_{SY} between the first harmonic and any even harmonic is:

$$d_{sy} = 20 \log \frac{T_{sc}^{2}}{2\pi t_{r1} T_{sy}} \geq 18 \text{ dB} \quad \text{for a symbol rate of 8192 symb/s.}$$

Measurements made during the DSN compatibility test serve to confirm the abovementioned values.

Telecommand performance. The transponder presented here contains two actively redundant receiver/command detector chains, which are hard-wired to different antennas. Each chain has a separate command aubcarrier frequency, i.e. 448 versus 512 Hz, thereby permitting ground control to select the chain they desire,even though the 8 symb/sec. command rate is coherent to both subcarrier frequencies.

The receiver equipment accepts the S-band uplink signals, coherently converts them in two stages to 48 and 9.57 MHz respectively. The final frequency is then tracked by a phase-locked loop, which is also used as a phase demodulator for the command signals. A separate coherent phase demodulator is used to extract the baseband ranging signals from the carrier.

During the early phase of the project the following requirements were established:

1. dynamic range for command symbol error probability of $\leq 1 \times 10^{-5}$: from -144 to -70 dBm, with a modulation index of 50.64°

2. acquisition at a sweep range of ±42 kHz centered on the rest frequency,

3. corresponding sweep rates are max. 80 Hz/s at -144 dBm and max 500 Hz/s at -100 dBm or higher,

4. phase errors at transmitter output in coherent mode are max. 0.4 rad rms at -144 dBm and max. 0.05 rad rms at -100 dBm or higher.

According to ref. [3] the theoretical SNR at the command detector input has to be at least 9.6 dB in 8 Hz for a symbol error probability of $\leq 1 x 10^{-5}$ using coherent PSK. However, losses due to imperfect subcarrier and symbol synchronisation, limiter and waveform losses, and non-gaussian phase noise effects have to be considered. Calculations show (ref. [4]) that 13.2 dB in 8 Hz is needed instead of 9.6 dB.

The receiver equipment noise figure referenced at the preamplifier input was assumed to be 3.6 dB and the diplexer losses 1.4 dB, so that assuming a noise contribution of the transmitter power amplifiers of 55°K a total noise figure of 695°K was calculated referenced to the transponder input terminal. Measurements show lower values:

1. a receiver noise figure between 3.2 and 3.4 dB in the temperature range of -10 to 40° C

2. diplexer losses between 1.06 and 1.13 dB in the same temperature range.

The transmitter noise contribution could not be evaluated unequivocally.

In order to obtain the loop design values, the following values at -144 dBm were assumed:

1. loop signal-to-noise ratio SNR_L= 6 dB

2. loop damping ratio z = 0-707

In addition, a limiter loss L_c of 0.66 dB a predetection noise bandwidth B_i of 8 kHz, and a allowable total phase error θ_t of 0-35 rad were assumed.

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[3] J.G. Lawton, "Comparison of lineary data transmission systems", Proc. 2nd National Cowention on Military Electronics, pp-54-61; 1958

[4] F.M. Gardner, G.B. Go, "Criteria to establish receiver equipment noise figure based on uplink performance,"AEG-TELEFUNKEN Helios TN-019/1 Rw.A, pp. 3-33; 1972

Then, using the following equations:

$$a = \left(1 + \frac{4B_i N_o}{\pi P_T}\right)^{-\frac{1}{2}}$$

$$4z^2 = a \cos m_c \; G_{ss} \; T_2^{\,2} \; T_1^{\,-1}$$

$$2B_L = (4z^2 + 1)(2T_2)^{-1}$$

$$SNR_L = \frac{L_c \cos^2 m_c \; P_T}{2B_L N_o}$$

$$\omega_n = 2B_L \cdot 4z(1 + 4z^2)^{-1}$$

$$\theta_t = \frac{\Delta^{\bullet}\omega}{\omega_n^{\,2}} + \frac{\Delta\omega \cos m_c}{a \, G_{ss}}$$

with : a = limiter suppression factor

B_i = double-sided predetection noise bandwidth in Hz

B_L = one-sided loop noise bandwidth in Hz

G_{ss} = strong signal total loop gain in s^{-1}

L_c = limiter loss

m_c = command modulation index in degrees

N_o = noise density referenced at transponder input in W/Hz

P_T = received total signal level in W

θ_t = total phase error during swept acquisition in rad

SNR_L = loop signal-to-noise ratio in the actual loop bandwidth

T_1,T_2 = loop filter time constants in S

$\Delta\omega$ = sweep range in rad/s.

$\Delta\omega$ = sweep rate in rad/s^2

ω_n = loop natural radial frequency in rad/s

z = loop damping ratio

the requirements as stated before can be met using the following loop design parameters:

$G_{ss} = 1.7\text{x}10^7 \; s^{-1}$

T_1 = 1730 s

T_2 = 45 ms

However, excessive phase noise in the data channel occured due to loop cycle slipping at threshold input power levels, resulting in a worse symbol error rate than required. Therefore the following measures were taken:

1. the loop signal-to-noise ratio at command threshold was increased from 6 to 8 dB to minimize loop cycle slipping

2. the command threshold was changed from -144 to -142.5 dBm

3. the command modulation index was changed from 50.64 to 44-52 degrees in order to meet the change in command threshold

4. the strong signal loop gain was changed from $1.7x\ 10^7$ to $2x10^7$ s in order to obtain better trucking performance.

5. the lagging loop filter time constant T_1 was changed from 1730 to 2310 s because of the change in SNR_L and the corresponding change of the loop noise bandwidth 2 B_2 at command threshold

After implementation of these points all requirements could be met. Measurement results for the strong signal loop gain vary from $2.1x10^7$ to $2.4x10^7$ s^{-1} under temperature conditions. This large variation of 13 % was due to the large amount of discrete components involved. Symbol error rate measurements were done mainly at unit level, for test results please refer to ref [2]. Checks made during transponder integration and testing were positive. Acquisition could be made under all conditions. Because it was only intended to check out the equipment, it was not tested at what level the required sweep rate of 80 Hz/s could still be used. The phase error at the transmitter in coherent mode was found to be 0.2 rad at -142.5 dBm and < 0.05 rad at -100 dBm, so that the specification was fulfilled well within margin.

Measurements in the temperature range -10 to +40°C show for 6 receivers (qualification model, 2 flight models) the following peak-to-peak variations:

1. Rest frequency : 10.7 kHz ($5x10^{-6}$ the S-band frequency)

2. Absolute threshold: 2 dB with -156 dBm as nominal value.

Ranging performance. A non-redundant turn-around ranging channel is incorporated in the transponder. Ranging operation can be maintained simultaneously with command and telemetry operation. The ranging signals from the ground station are demodulated in that receiver which is connected to the medium gain antenna. However, these baseband signals are not processed further until a command is given. Upon the reception of the ranging command the transmitter allows the baseband signals to enter the modulator. At the same time the transponder switches over to the coherent mode. The baseband ranging signals together with the telemetry data modulate the coherent carrier.

Ranging delay measurements were performed with a Mark I Ranging Assembly utilizing the lunar code used for the Apollo project. Four different chains were tested:

1. TWT I in the 20 W mode connected to the high gain antenna

2. the same mode however connected to the medium gain antenna

3. TWT I in the 10 W mode connected to the high gain antenna

4. the same mode however connected to the medium gain antenna

The overall peak-to-peak variations for all chains measured on 3 transponders (qualification and flight models) amounted to the following values:

1. between 4 and 31 ns with the input power level varied from -70 to -130 dBm at a constant temperature,

2. between 10 and 47 ns with the temperature varied from -10 to +40°C at a constant input power level.

The absolute ranging delay of the transponder is about 1000 ns. The low variation of ranging delay over the dynamic range can be attributed to the voltage limiting networks in the ranging channel. The somewhat higher values on variation over the temperature range were due to slight offsets of the bandpass filters influenced by the temperature, leading to different phase delays for different temperatures.

The ranging channel frequency response was flat to within 1 dB until 1.5 MHz, and beyond that frequency falling off at a slope of more than 5 dB/octave. Therefore the transponder can be employed for nearly all kinds of ranging systems, e.g. GRARR, ESRO tone ranging, PN ranging systems, Apollo and Mariner ranging systems.

Formerly investigations with regard to spurious signal suppression during ranging operation were effected with the JPL continuous spectrum (PN) ranging system in mind. However, in the midphase of the project it was decided to switch over to the JPL discrete spectrum ranging system due to improved correlation performance. This multi-component, single-correlator system utilizes squarewave signals instead of tones. Their (fundamental) frequency is derived from the carrier frequency. The spectrum is rich in harmonics. Due to doppler effects, one of these frequencies can fall in the command or telemetry channel, or can be near the downlink carrier, thus interfering with command or telemetry demodulation, or interfering with the carrier tracking by the receiver. Therefore investigations are necessary, taking into account the following variable parameters:

1. the command and telemetry channel bandwidth

2. the carrier loop bandwidth

3. the command and telemetry subcarrier frequencies

4. the maximum number of operational waveforms which form the composite ranging signal

5. the maximum doppler offset and doppler rates, positive as well as negative.

A computerized investigation performed for the Helios project did uncover one possibility of interference, i.e. at an instantaneous doppler of 2.9777 km/s and zero doppler rate a line exists at 32283 Hz at a level of -24 dB. As this line is near enough to the telemetry subcarrier frequency of 32768 Hz, and 3 dB above the non-interference level, it will cause interference in the telemetry subcarrier synchronizer. In this case ranging operation will be discontinued when the instantaneous doppler attains the corresponding value. Doppler predictions are obtained from the mission profile.

Conclusions. The coherent ranging transponder presented in this paper contains redundant active receiver chains and redundant transmitters, capable of operating in one of three output power modes, 0.5, 10 and 20 W. The transmitter power efficiency is 31 % at 21.6 W output power. Rise/fall times of the telemetry subcarrier are limited to 0.5 % of the subcarrier period, or 140 ns.

The dynamic range of the receiver is 85 dB for tracking, and more than 70 dB for command operation. The performance variations over the temperature range of -10 to +40°C could be held to low values due to extensive use of integrated circuits.

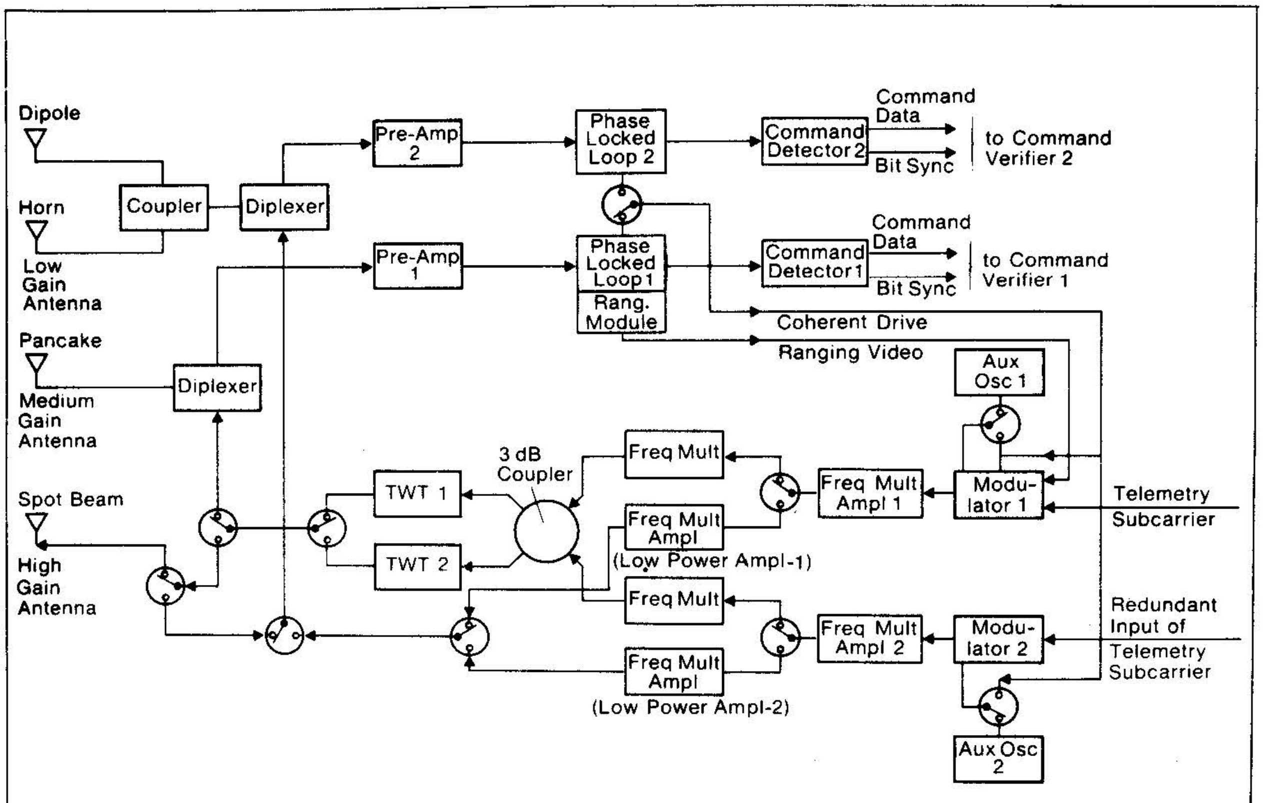

Fig. 1 - Functional block diagram of the transponder

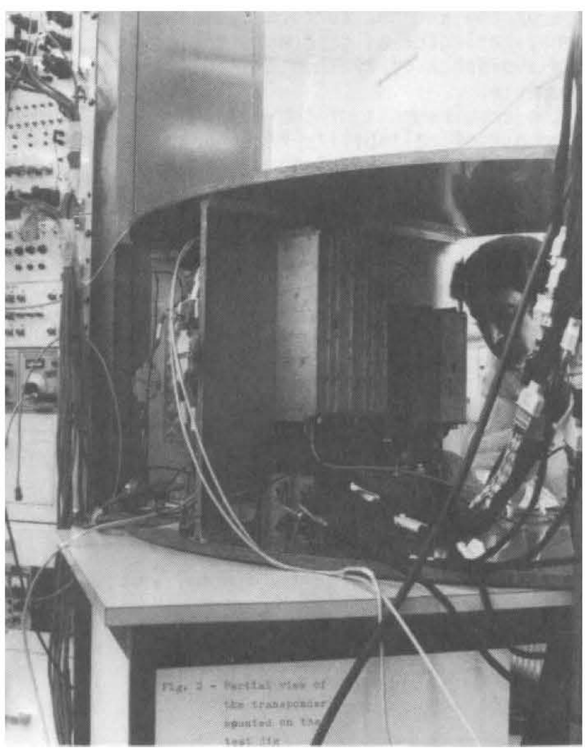

Fig. 2 - Partial view of the transponder mounted on the test jig