A SINGLE CHANNEL COMMAND DETECTOR FOR DEEP SPACE MISSIONS

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Summary AEG-TELEFUNKEN has developed a Single Channel Command Detector which will be used in the solar probe HELIOS. This command detector demodulates command data, PSK-modulated on a subcarrier with a symbol error-probability of less than $1x10^{-5}$ at an input signal to noise ratio of 13,2 db per symbol-length. The command detector consists of two succeessive second-order phase locked loops and a matched filter. The subcarrier synchronizer loop tracks the 512 Hz subcarrier, the bitsynchronizer loop performs data-synchronisation and in contrast to former space concepts, requires no additional power. The matched filter correlates the input signal and its estimate, generated by the subcarrier synchronizer-loop. The integration over exact dataperiods is dumped by the bitsyncpulse.

This command detector enables the HELIOS Receiver chain to demodulate command data with less than 1 error in 100 000 symbols over a distance of ~ 300 mill. km. Due to sophisticated digital decoding of the HELIOS Decoder, this error-probability results in 1 false command being executed in 64 years.

Introduction In 1970 representatives of NASA and BMWF (Bundesministerium für Wissenschaft und Forschung, Bonn, Germany) signed a memo of understanding to develop and launch a solar satellite HELIOS. The goal of this mission is to obtain special physical data of a region very close to the sun. This solar probe will pass the sun at a distance of 0, 2 AU (1 AU = distance Earth - Sun = 145, 5 mill. km). Commands and scientific data will be transmitted and received over a maximum distance of 2 AU (~ 300 mill. km).

AEG-TELEFUNKEN is responsible for the design and the development of the spacecraft transponder. AEG-TELEFUNKEN have developed the receiver chain and THOMSON-CSF, Paris will be delivering the transmitter chain.

The receiver chain consists of:

- S-Band Preamplifier
- S-Band Receiver
- Command Detector and
- Command Verification and Execution

The S-Band-Signal is received and amplified. The S-Band Receiver tracks and demodulates the carrier. The squarewave subcarrier, which is phase-modulated onto the carrier, is tracked and the PSK-modulated command data are demodulated in the Command Detector. The succeeding Command Decoder accepts the commands and activates their execution. (Lit. 1).

One of the main specifications for this mission is to maintain up-link data transmission at a maximum stance of 2 AU (= 300 mill. km) with a symbol error-probability of $1x10^{-5}$. We need special modes of modulation in order to meet these extraordinary requirements, in order that the system maintains its maximum efficiency at minimum input signal levels.

Two possible modes of modulation are:

- frequency shift keyed modulation (FSK) and
- phase shift keyed modulation (PSK)

Former Investigations prove, that these modes are optimal for deep space applications (Lit 1). The FSK-modulated subcarrier changes its frequency according to the modulated command data, the PSK-modulated subcarrier changes its phase polarity at data transitions. These modes of modulation can be coherent or noncoherent, Coherency means: a fixed phase relationship between subcarrier frequency and data-frequency is maintained. For a fixed input signal to noise ratio, the FSK-system has a higher symbol-error-probability than PSK. Therefore, we decided to use a PSK-modulation system for the Mission HELIOS (Mariner and Pioneer spacecrafts use FSK modulation).

The demodulation of the modulated subcarrier is accomplished by using the correlation technique. Mr. Woodward has shown, that this kind of demodulation is optimal for a binary receiver of minimum symbol error-probability (Lit. 2).

The relationship between the symbol error-probability and the received signal energy per symbol is:

$$P_s = \frac{1}{2} \left(1 - \mathrm{erf}\sqrt{\frac{E\,(1 - C)}{2\,N_o}}\right) \quad \text{(Lit. 3)}$$

where “erf” denotes the errorfunction,

E is the energy per bit

N is the noise power per unit bandwidth

C° is the cross corross correlation coefficient

The cross correlation coefficient of two functions x_1 and x_2 can be computed by using the formula

$$C = \frac{\int_0^T x_1 \cdot x_2 \, dt}{\frac{1}{2}\int_0^T (x_1^2 + x_2^2)\, dt} ; \quad -1 \leq C \leq +1$$

For a minimum symbol error-probability, this coefficient shall be C = -1, this means x_1 must be equal to $-x_2$

The cross correlation coefficient for PSK-modulation is -1, because for a binary ONE: $+\sin(\omega_{sc}t)$ is transmitted and for a binary ZERO $-\sin(\omega_{sc}t)$ is transmitted. (ω_{sc} = subcarrier frequency x 2π).

For demodulation, the noisy splitphase sinusoid (1st harmonic of the square-wave subcarrier) is correlated with a subcarrier estimate, generated in the command detector. To decide if this signal corresponds to a transmitted ONE or ZERO, the product of the input signal and its estimate is integrated over a full symbol period. If the result is positive, the input signal is assumed to be a ONE, if the result is negative, the input signal is demodulated as a ZERO.

The integration and decision is done by a matched filter, an integrator which is dumped according to the symbol period by the bit sync-pulse. The difficulty of this system lies in obtaining the necessary bit sync with sufficient accuracy and stability. Should the detection be off in phase by an angle β , then the efficiency would be degraded by a factor of $\cos^2\beta$. Therefore if the dumping of the integrator is incorrect, the probability of making a correct decision is correspondingly reduced. Further losses result, if any noise is on the signals, i.e. if the time-references possess jitter.

There is another important factor: the requirements for bit synchronisation should not significantly degrade the theoretical system performance. In other words, as only a limited amount of signal energy is available for the transmission of both data and bit-sync, the latter should require a minimum energy in order not to subtract from the data energy. To establish this bit-sync or data synchronisation, former concepts of command detectors used an additional channel to transmit the bit-sync pulse. In other systems, a PN sequence was added to the transmitted data. A bit-synchronizer derived data synchronisation from this PN code, and demodulation of the data was performed with a subcarrier synchronizer and a matched filter.

As you see, all these former systems required additional power only to establish data synchronisation.

The HELIOS-Command Detector is a single channel system, where data-synchronisation is obtained only from the data transitions of the modulated subcarrier. This concept will be used for spacecraft for the first time (see Diagr. 1).

The command detector uses a Costas-loop as subcarrier synchronizer-loop. This second order phase locked loop has a loopbandwidth of $2\ BL_o = 1$ Hz, the subcarrier frequency is 512 Hz squarewave, the voltage controlled Oscillator is a multivibrator with a frequency stability of $\pm\ 2{,}5\text{x}10^{-4}$ over a temperature range from -10°C to +40°C, the loop filter time constant is $z_1 = 100$ sec, the loop-damping factor is 0,707. The loop generates an error signal, if a phase difference between the input frequency and its estimate exists. This signal tunes the frequency of the multivibrator so, that the phase difference becomes minimal.

The bit-sync loop, is an Absolute Value Bit-Synchronizer loop. It is sensitive to the data transistions of the subcarrier: if there are a minimum number of data transitions per time period, the bit-sync loop is able to lock and to generate an exact data synchronisation.

This loop has a loop bandwidth of $2\ BL_o = 0{,}16$ Hz, the data period, to which it -locks, is 125 ms (= 8 symbols per second). It uses the same oscillator as the subcarrier loop. The loopfilter time constant is 100 sec loop damping factor is 0,707 (Lit. 4. 5. 6)

The matched Filter consists of an integrator, which is dumped by the bit-sync pulse, a digital decision stage and a buffer-amplifier. The lock in time to the Command Detector is less than 100 sec.

From theory, we need a signal to noise ratio per symbol-length of 9,6 db to be able to meet a specified symbol error-probability of $1\text{x}10^{-5}$

The HELIOS link Design assumes

- max. subcarriersync. losses of 0,4 db
- bitsync losses of 0,2 db
- losses due to temperature drifts 1,0 db
- losses due to squarewave-subcarrier 0,91 db
  (we only use the 1. harmonic)

Therefore the specified signal to noise ratio per@symbol-length is 13,2 db for a symbol error-probability of 1.10^{-5}. As mentioned above, the bit-synchronizer loop needs a minimum number of transitions per time period. To assure this, the HELIOS command data are Manchester-coded i.e. a “ZERO” is transmitted as ZERO-ONE and “ONE” is transmitted as “ONE-ZERO”. To eliminate the 180° - Phase ambiguity of all PSK-demodulation systems, the HELIOS command sequence has the following structure:

SYNC-COMMAND-SYNC-COMMAND-SYNC.

The command verifier checks if all sync-words have the same polarity, then the two command words must be identical to activate the command execution. The subcarrier sync-loop exhibits, even at its threshold, a minimum phase jitter; therefore, if it is locked once to the subcarrier, the phase of its output signal remains stable with a good probability.

The measured values at various temperatures show, that the HELIOS command detector is able to meet these requirements, even with a margin to spare. We performed verification tests with the first laboratory model in August 71 at JPL, Pasadena and we had a compatibility test with the whole transponder in April 72 at JPL-DSS 71 at Cape Kennedy Air Force Center, Florida and we could verify our test results (see Diagr. 2).

The actual size of the command detector is

- 260 cm x 100 cm x 66 cm,
- its weight is 750 g,
- its power consumption is 1,5 w.

The HELIOS Transponder especially the receiver chain with Preamplifier, S-Band receiver and command detector exhibits one of the extraordinary results of modern data transmission: to establish and maintain radio link over 300 mill. km and to transmitt 100 000 binary simbols with less than 1 error.

This development has been made in cooperation between NASA and GfW (Gesellschaft fuer Weltraumforschung, Bonn - Germany) and with the assistance of the physicists and engineers of Jet Propulsion Laboratory, Pasadena. We would like to express our thanks and obligation to all the people involved in this development and we hope, this mission will be successful.

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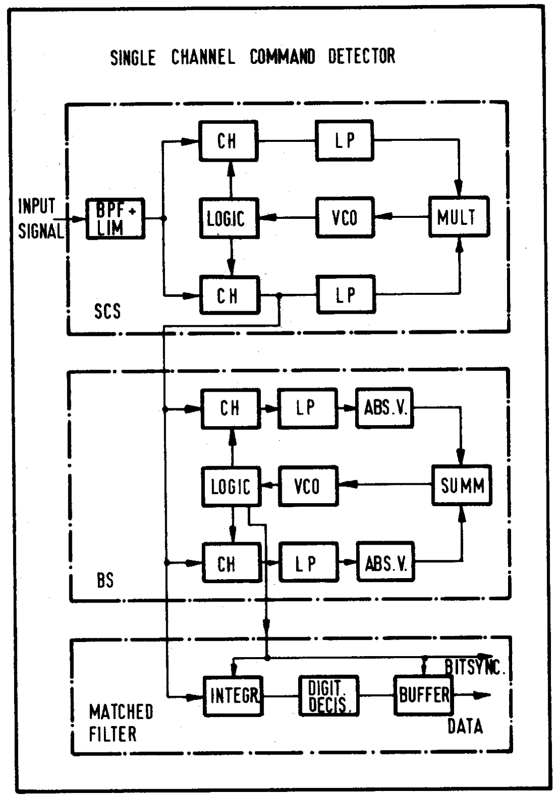
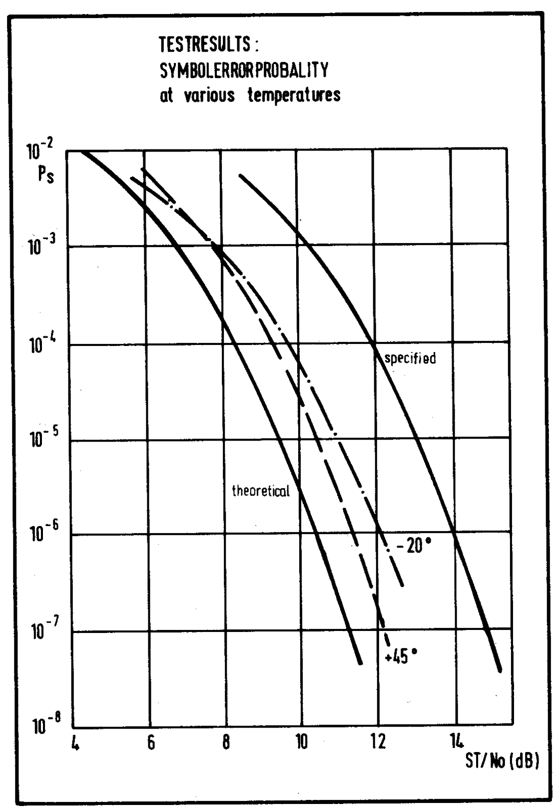


Diagr. 1



Diagr. 2