Presentation

FMCW Radars for Entry Probes and Landers: Lessons learned from the Huygens Radar Altimeter

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ABSTRACT

The Huygens probe [1] carried two Frequency Modulation Continuous Wave (FMCW) radars during its successful descent through the atmosphere of Saturn's largest moon Titan [2,3]. Originally these radars were included primarily to provide real time altitude data only, and the original range specification of 10km (20km goal) dictated the design. They were early identified as potential sources of valuable scientific data on Titan's atmosphere and surface. However, improvements were only requested during the Qualification Model test campaign and so design changes had to be minimal. A dedicated Radar Altimeter Extension (RAE), interfacing to the radars, was developed as a part of the Huygens Atmospheric Structure Instrument (HASI) [4]. Altitude and topographic data were acquired by the Permittivity, Wave and Altimetry (PWA) experiment, a subunit of HASI. Radar altitude and AGC data was recorded via the probe housekeeping data. Terrestrial tests of the radars as well as the data acquired by the Huygens probe have identified a number of possible improvements that can significantly enhance the performance of this type of radar, both for the measurement of the probe altitude and for the acquisition of data on the atmosphere and surface of the target body.
The basic design of the radar is introduced. Processing of data by RAE and PWA is explained. Data from terrestrial tests as well as data from Huygens are presented. Radar design features and their impact on the radar performance are discussed, and improvements of the radar design are suggested. The importance of complementary data sources for the interpretation of radar data is explained, and new operations modes for the full exploitation of the capabilities of FMCW radars on planetary probes are suggested.

1. FMCW RADARS / THE HUYGENS RADAR ALTIMETER

FMCW radars have been developed since the 1970's [5] and are often used for applications such as cloud radars, altimeters, velocity measurements, etc. Their concept allows a simple and reliable technical implementation [6], which makes them a good choice for applications where low mass and high reliability are of importance. In FMCW radars, a signal of constant power is emitted continuously. This signal is frequency modulated using a low frequency waveform. In the case of the Huygens Radar Altimeter Unit (RAU) a triangular waveform was selected. The signal propagation time causes a time delay τ_P, corresponding to a frequency shift of the received signal with respect to the emitted frequency. Fig. 1 illustrates the corresponding waveforms. This frequency shift is obtained by mixing the amplified received signal with the transmitter frequency. In the servo type FMCW radar the transmitted frequency f_{TX} is controlled by a circuit, which modifies the waveform ramp rate such that the frequency shift between f_{TX} and the received frequency f_{RX} is constant. Then the ramp rate $\Delta f/\tau_P$ is inversely proportional to the distance D of the reflecting target, and the period of the triangular modulation signal T is proportional to the altitude. For the Huygens radar altimeter the servo loop adjusts the ramp rate such that the Intermediate Frequency (IF) Δf is maintained at 200 kHz. A sweep range of 30 MHz was selected. The sweep ramp rate was chosen such that the modulation signal time constant is 1 msec per km altitude. Two redundant systems (called RAU A and B) are used, with transmitter frequencies of 15.4 and 15.8 GHz, respectively. The maximum gain of the transmit and receive antennas is 26 dBi.

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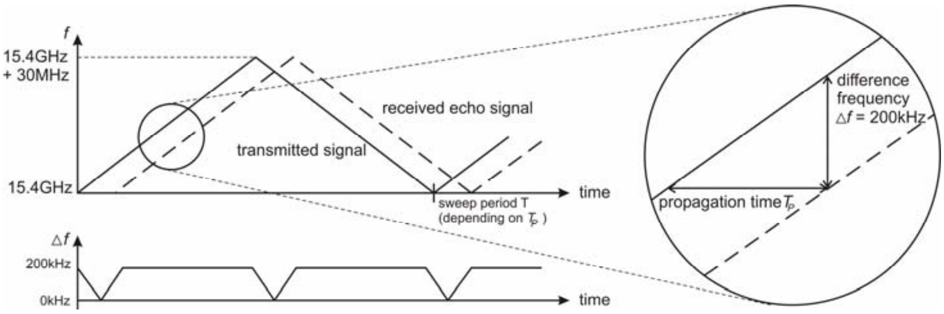

Fig. 1. FMCW modulation waveform for the Huygens Radar Altimeter

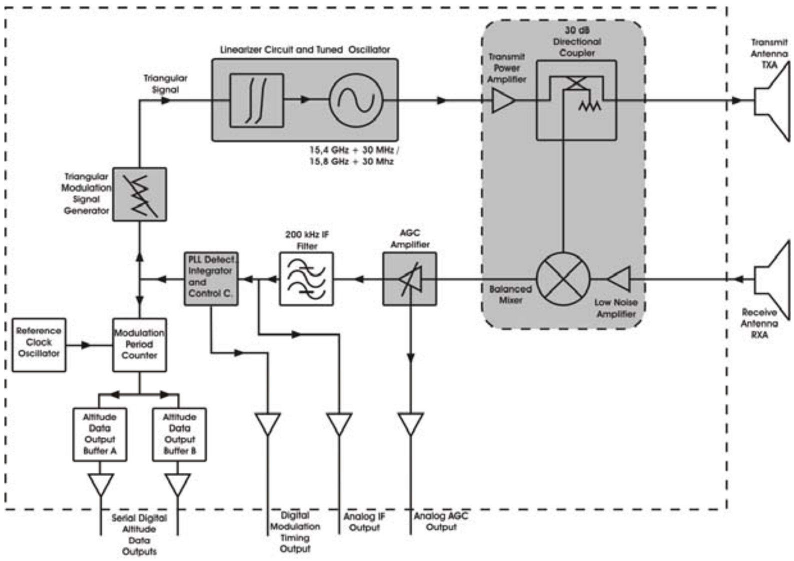

Fig. 2. HRA Architecture

A Phase Locked Loop (PLL) circuit is used to maintain the ramp rate by controlling the triangular wave signal generator. The frequency controlling element, a varactor diode, is fine-tuned using a linearizer network for obtaining an approximately linear ramp slope. The RAU output power P_t is 20 dBm. The digital altitude data is generated using a digital counter with a gate function controlled by the modulation ramp. Lock status is indicated by the PLL circuitry. The input amplifier Automatic Gain Control (AGC) is recorded as part of the probe telemetry, and the 200 kHz intermediate frequency as well as the blanking signal (which indicates the turning points of the triangular signal) are provided to the HASI RAE for scientific data acquisition. Fig. 2 shows the basic architecture of the radar system.

2. PROCESSING OF RADAR DATA ON BOARD THE HUYGENS PROBE

2.1 Digital Altimeter Data

The digital altitude data is read out via a serial interface and transmitted as part of the probe telemetry with a sample rate of 0.5 samples per second. The data is not modified on-board, but taken into account for selection of payload operations modes.

2.2 AGC data

The amplifier gain in the electronics is determined by the AGC circuit. This gain, which can be derived from the AGC voltage signal, is important for both engineering and scientific purposes. The AGC voltage is sampled once per second with a dynamic range of 8 bits, and provided as part of the Huygens housekeeping data stream.

2.3 Intermediate Frequency Data

The received signal, which is down-converted to the IF, contains information that allows deriving a variety of parameters of distinct scientific interest.
The analysis of this signal is done by down-converting the 200 kHz signal to 10 kHz in the RAE unit and by subsequent sampling of the signal by the PWA data acquisition unit. After performing a Fourier transform, the averaged data from multiple IF spectra is provided as part of the HASI science telemetry data. Figure 3 shows the schematic of the RAE unit and the data processing done in PWA.

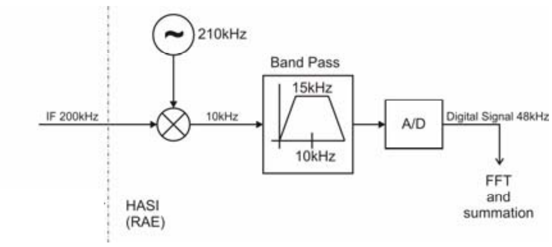

Fig. 3. RAE / PWA processing of IF data

3. HRA DATA PRODUCTS AND SCIENTIFIC RESULTS

3.1 Altimetry and Surface Backscatter Measurements

The reliable measurement of the probe altitude is the primary objective of the Huygens Radar Altimeter. Altitude data is assessed with respect to reliability and consistency by the Huygens onboard computer, and used for the switching of payload operations modes. The altitude is derived directly from the modulation ramp duration and reported in the Huygens housekeeping data. Together with the IF power measured via PWA, the AGC signal allows to derive the input power received by the radar. The backscatter coefficient σ_0 of Titan's surface can be derived from transmitted power, received power and altitude according to the following formula:

$$\sigma_0 = \frac{P_r * (4*\pi)^3 * D^4}{P_t * G^2 * \lambda^2 * A_B} \qquad (1)$$

where P_t and P_r represent respectively the transmitted and the received power, G is the antenna gain, λ is the wavelength, and A_B is the surface area illuminated by the radar beam. The backscatter coefficient varies with the incident angle of the radar beam. In case of Huygens the nominal radar attitude was nadir-pointing, but off-nadir angles up to ~ 10 deg were achieved due to probe motion under the parachute.
In addition to the determination of general surface scattering properties, the profile of backscattered power versus time may also enable the separation of liquid and solid surfaces if specular reflections are observed. This has been confirmed in terrestrial balloon-based tests [7].

3.2 Surface Topography and Spectral Data

For a FMCW radar, any structure of the topography of the terrain reflecting the radar signal causes a modification of the spectral signal distribution in the IF. Without taking into account system nonlinearities, flat terrain would provide narrow band spectra, while large variations in terrain altitude would cause significant spectral spreading of the signal. Therefore the analysis of the IF signals can provide valuable information about the underlying terrain characteristics [8], independently of the ambient illumination conditions and the atmospheric optical properties. For the selected bandwidth of 15kHz, the range of altitude fluctuations that can be measured within the radar footprint is determined (at nadir) by

$$d = \frac{15 * D}{200} \qquad (2)$$

where d is the terrain altitude range covered, and D is the altitude of the probe above the ground. The actual altitude resolution depends on both the spectral resolution and in particular the linearity of the frequency ramp.

3.3 Atmospheric Backscatter Measurements

On Huygens, the sampling of IF spectral data by PWA is independent of the radar lock status. If the radar is out of lock (and the system is scanning all possible altitudes), the backscattered power from a distance interval d at distance D is measured. Both the spectral power and the distance are recorded in the PWA data.The power backscattered by an individual droplet at a distance D from the radar is known to be proportional to $1/D^4$. As the number of droplets N interacting with the impinging wave is proportional to the volume V probed (which is itself proportional to D^3), the total backscattered power measured in the IF bandwidth is ~ $1/D$. If this signal is higher than the system noise level, the volume backscatter parameter Z could be determined. Figure 4 illustrates the concept of the backscatter measurement.

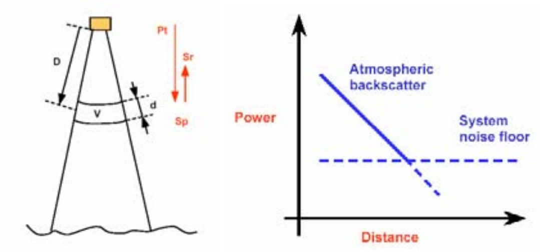

Fig. 4. Atmospheric backscatter measurement

Together with information on the aerosol composition and particle size distribution, parameters such as volume density and particle number density can be derived. The system noise floor of the radar determines the maximum range and sensitivity of the measurement.

4. PROBLEM AREAS AND POSSIBLE IMPROVEMENTS

4.1 Altimetry and Surface Backscatter Measurements

The Huygens altimeter data is affected by a specific problem in the digital electronics, which causes shifts in the bit patterns of the digital link above ~17 km. This led to an erroneous determination of the probe altitude during the Huygens mission because the onboard software trusted the radar data above the tested altitude range of 150m to 10km (extra functionality, including a range extension to 40km, was only requested during the QM test campaign). For the post-landing altitude data analysis the error was corrected. An analysis of the temperature and altitude related effects using data from a terrestrial stratospheric balloon flight [7] and from FM tests [9] revealed significant altitude and temperature dependent errors. The measured altitude A_{meas} can be corrected using the following formula:

$$A_{corr} = A_{meas} * (0.97788 + E_{Temp} * T + E_{Alt} * A_{meas}) \quad (3)$$

The respective altitude and temperature dependent errors are

$$E_{Alt} = 9.966 * 10^{-7} \qquad [1/m] \quad (4)$$

$$E_{Temp} = 0.002305 \qquad [1/K] \quad (5)$$

The impact of these errors can be reduced by an optimized design and accurate calibration. Figure 5 shows the raw, corrected and calibrated altitude data measured by RAU B on the Huygens probe.

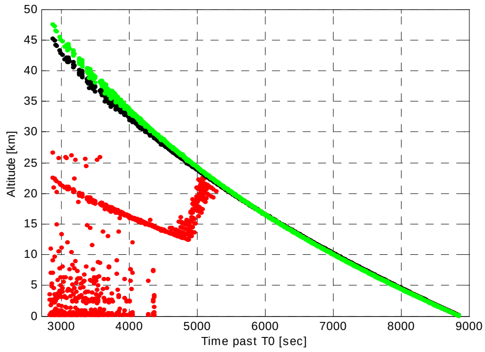

Fig. 5. Raw (red), corrected (black) and calibrated (green) Huygens altitude data (RAU B)

4.2 Surface Topography and Spectral Data

The approximation of the surface altitude distribution requires an accurate knowledge of the properties of the signal processing chain. The most important elements in this chain are the frequency ramp (stability of the 200 kHz IF signal) and the IF filter characteristics. Due to the late consideration of the RAU for scientific utilization there is only limited information available on the characteristics of these elements. The ramp linearity (which is implemented using a diode linearizer network) was improved for the RAU flight models; however there is still a considerable deviation from an ideal linear ramp, which significantly reduces the possibilities for data analysis. Figure 6 shows the frequency ramp (lower graph) and the frequency deviation from an ideal linear slope (upper graph) for RAU B (arbitrary units).

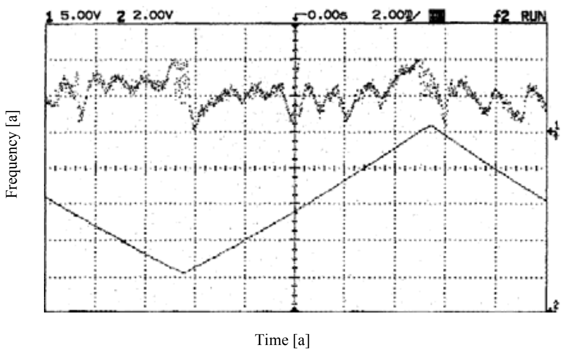

Fig. 6. Frequency ramp (below) and nonlinearity residuals (above) vs. time for RAU B (both parameters in arbitrary units)

This deviation from linearity broadens the IF spectrum and reduces the sensitivity of the measurement with respect to the surface altitude distribution. As far as the scientific performance of the RAU is concerned, a different design approach for the ramp generation, together with accurate calibration of frequency responses and an optimized utilization of the data volume, could lead to significant improvements of the measurement. In addition, as the spectral response may depend on the attitude of the probe, the measurement of the attitude angles would have been an asset for the interpretation of the radar surface echos.

4.3 Atmospheric Backscatter Measurements

The sensitivity of the Huygens radars for backscatter measurements is ultimately defined by the noise level of the overall data acquisition system. The noise contributions of the first stages (antenna input, RF harness, preamplifier, and mixer) have been calculated based on design figures and measurement data corresponding to a noise temperature of ~ 263 K. Noise contributions added at subsequent stages (AGC amplifier, IF filter, RAE amplifiers / attenuators, down-converter, RAE filters / amplifiers / attenuators and PWA signal multiplexer and ADC, as well as unidentified but possibly deterministic noise) cause a significant increase of the system noise temperature resulting in a noise level in the order of 2600 K. The sensitivity of the Huygens radar for the detection of aerosols and droplets is therefore restricted to backscatter levels corresponding to precipitation similar to light drizzle under terrestrial conditions. An effort to minimize the noise temperature of the overall system could therefore significantly enhance the sensitivity for this measurement mode.

4.4 General Hardware Related Improvements

In addition to addressing the problems listed for the individual measurement modes, a number of general improvements should be applied for future space-borne radars of this type:

- All relevant data (IF data, AGC voltage, altitude data) should be sampled by the same acquisition system in order to ensure accurate (identical) sample timing
- In order to support accurate calibration, temperature data should be acquired for the most temperature sensitive devices within the radar circuitry
- Onboard calibration of the altitude data may be supported by implementing a calibration delay line instead of external systems
- Additional data from external systems should be acquired (such as probe attitude and relevant supply voltages) in order to allow a correction of attitude and power supply related errors
- With optimized noise levels, the required transmitter power can be reduced for the required radar range, resulting in lower power consumption levels
- Science data bandwidth should be optimized using adaptive spectral resolution, preprocessed spectral power data, and advanced data fitting / compression as far as applicable.
- In cases where minimized mass is required, an FMICW (frequency modulated interrupted continuous wave) type radar (requiring only one TX/RX antenna) might be beneficial. This variant of the FMCW radar has been tested successfully and provides a performance similar to conventional systems [10].
- The radar system / instrument needs to be tested under conditions representative for the space mission. The data delivered by the system must not be trusted by on-board control and command processes if environmental parameters are outside the tested range.

Obviously any hardware modification has a potential impact on the system reliability and performance. Therefore potential improvements of scientific as well as engineering performance need to be traded against their cost in terms of mass, power and system reliability.

4.5 System Operations and Scientific Requirements

The Huygens radar altimeter is designed to operate in search mode until a significantly strong return signal is detected. In search mode, the ramp rate is continuously modified, which causes the radar to scan a range of distances from 150 m to more than 60 km. As soon as a sufficiently strong return signal is detected, the radar locks to the signal. In locked mode, the ramp rate is stabilized and proportional to 1/D. However, for the measurement of atmospheric backscatter it is required to scan the distance range from minimum to maximum distance. Therefore the Huygens radar does not return atmospheric backscatter data when the surface has been detected and the radar remains in locked mode. For future space-borne radar systems with more emphasis on the science return a

dedicated operations mode might be implemented, for which the radar is forced into scan mode and performs one full atmospheric scan, with a typical duration of a few seconds, before it locks again as soon as the scan range corresponds to the altitude.
If onboard calibration facilities are provided, an auto-calibration cycle may be introduced occasionally, which allows to increase the data accuracy by adding onboard calibration data to the delivered data products.
For the post-landing phase, a surface mode may be considered for which radar operation is optimized for the analysis of subsurface backscatter.
If an imaging capability of the radar is required or desirable for scientific purposes, the antenna hardware can be modified in order to allow control of the antenna beam direction. This would provide detailed information on the topography also under adverse optical visibility conditions, and would allow deriving the surface backscatter coefficient for a range of radar beam incident angles. The independent measurement of co-and cross-polarization would provide additional information on the surface properties. The utilization of individual modes (simple altimeter, atmospheric scan, imaging mode, surface) can be tailored for risk minimization. The implementation of these modes would not have an impact on the safety aspect of the mission assuming basic requirements such as those of the Huygens mission.

5. CONCLUSIONS

FMCW radars are reliable lightweight systems that offer a number of possibilities for scientific data exploitation in addition to the basic altimeter functions. Data on altitude, descent velocity, surface altitude distribution, surface backscatter coefficient and atmospheric backscatter can be acquired. Additional data products may include surface altitude profiles, data on wind velocities, and evidence for particular types of surface features such as liquid surfaces. The Huygens radar altimeter, while designed as a pure probe system, is still providing very useful science data despite the rather limited design optimization and calibration possibilities. The design of this instrument can be improved with respect to both scientific and functional capabilities. Suggested enhancements include reduction and accurate assessment of altitude and temperature related errors, improvement of system linearity, and the reduction of noise levels. Apart from the lessons learned in the technical domain, the Huygens radar altimeter has demonstrated that certain probe sensors may have significant potentials for scientific purposes. Using a combined spacecraft sensor / payload instrument approach, the capabilities of such sensors can be significantly enhanced if their potential for scientific utilization is identified in early stages of the project. Scientific requirements should be taken into account for the development, test and calibration activities of the system. Such an approach would allow adding capabilities of a science instrument to the system at low mass and cost, and would help to maximize the overall scientific and technical output of the mission.

6. ACKNOWLEDGEMENTS

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