DALOMIS: A DATA TRANSMISSION AND LOCALISATION SYSTEM FOR MICROPROBES SWARMS

André Schiele[1*], J. Laycock[2], A.W. Ballard[2], M. Cosby[2], E. Picardi[3]

[1]ESA/ESTEC, Keplerlaan 1, 2200 AG Noordwijk, Netherlands
[2]Qinetiq, Space Department, Farnborough, Hampshire, GU14 0LX, United Kingdom
[3]Alenia Spazio S.p.A., Laben, S.S. Padana Superiore 290, 20090 Vimodrone, Italy

[*]Corresponding Author; E-mail: Andre.Schiele@esa.int

Abstract

This paper introduces the design of an integrated data transmission and localization system for microprobe swarms, called DALOMIS. The development is performed under ESA contract, together with Qinetiq Space as prime contractor.

DALOMIS aims at localizing free falling miniature scientific Probes that are deployed into a planetary atmosphere from a carrier craft, such as a Balloon. As a reference mission scenario for the development of DALOMIS, a Balloon mission to the middle cloud layer of Venus was chosen.

The proposed system is able to localize and track the tiny probes in the atmosphere at ranges of up to 155 km. DALOMIS is centralized into the Carrier craft, in order to keep the mass of the Probes as low as possible.

1. Introduction

The ESA Science Department recently studied a Entry Probe Mission, aiming at in-situ exploration of the cloud-layer and atmosphere of Venus. The mission scenario foresees of an atmospheric entry Probe, which delivers a long duration balloon into the middle and top cloud layers of Venus. The main goal of the mission is to comprehensively investigate the complex venusian atmospheric dynamic processes and composition.

The balloon targets a nominal lifetime of about 30 days at an average floating altitude of 55 km. It will be inserted at about 20° (N) latitude and is expected to drift to over a range of latitudes. The Balloon gondola comprises a highly integrated payload suite, among which also a swarm of atmospheric descend Probes is contained. These Microprobes will be released in clutches of 1 – 3 at a time, over a period of several days. During their drop, the microprobes will acquire vertical measurement profiles 'in-situ'. The desired vertical resolution is in the order of 100 m, down to an altitude of below 30 km. Because it is desirable to carry as many probes as possible on the Balloon gondola, an extremely light-weight design is required for each Probe. According to the latest mission study results, all Microprobes together must not have a mass higher then 1.7 kg. This leaves only about 113 g per Probe in order to accommodate 15 in total. In addition to having scientific purpose, the Probes will also function as ballast that can be dropped to compensate for gas diffusion of the balloon.

1.1 Scientific purpose of Microprobes

Given the complex behavior of Venus' atmosphere at all times and places, it is, on scientific grounds, desirable to deploy a large number of identical Microprobes. Their measurements can be directly inter-compared and used to understand the structure and variability in space and time of the Venus climate system. Due to the required low mass per Probe, the instrumentation can only be a basic one but aim at following key measurements:

(1) Temperature, which is relatively simply and reliably measured using platinum resistance thermometers or similar.

(2) Pressure, as the vertical co-ordinate, using diaphragm sensors or similar.

(3) Light level, using wide-band sensors (ideally sensitive from the UV out to 4μm to cover 99% of the energy in the spectrum of the Sun). The light level sensors must measure upwards and downwards in order to obtain the flux divergence, from which the solar energy deposited at each level can be determined. Flux divergence measurements can also be interpreted in terms of the cloud density as a function of height at

Proc. of 'The 8th International Symposium on Artifical Intelligence, Robotics and Automation in Space - iSAIRAS', Munich, Germany. 5-8 September 2005, (ESA SP-603, August 2005)

each location. This is a key measurement particularly since cloud density is now known to be highly variable [1].

Furthermore, it is desired to deduce a vertical wind profile at the location of the probes. Correlation of the scientific measurements with the location where they are taken is crucial.

1.2 Goal

Besides the miniaturization of the Probes and integration of the scientific instruments, reliable localization and data transfer from the scientific microprobes to the Balloon was identified as one of the key technology drivers for such a mission [2].

The goal of this paper is to introduce the DALOMIS system, which is currently being developed specifically for localization of and data transfer from multiple Probes in flight.

2. Method

In order to allow a suitable DALOMIS design, first a preliminary Probe design is required. This identifies mass, volume and shape of an instrumented Probe. Integration of appropriate scientific payloads, power supplies and computational infrastructure has to be considered. Materials must be appropriately selected to be compatible with the acidic environment existing in the Venus cloud layer to arrive at a credible mass figure. Furthermore thermal analysis has to be carried out with transient simulations to check feasibility of the proposed design.

Next, the preliminary design is used in aerodynamic descend simulations, to determine critical parameters for DALOMIS, such as descent speed, maximum slant range, slant angle and maximum Probe incidence angle. Sampling and data transmission rates, required for performing the scientific measurements with 100 m vertical resolution are determined thereby. An atmospheric model of the Venus atmosphere is used for the simulations. This model is developed by making use of the "Venus International Reference Atmosphere (VIRA)" tables [4] and other sources [5].

Several different concepts for localization of the probes in the atmosphere are compared next and traded-off to identify the most promising approach.

Only then, the DALOMIS system is designed in detail. In this Paper, after a brief outline of the preliminary steps, the DALOMIS design for the flight microprobes is presented. Furthermore, it is explained how the DALOMIS Breadboard differs from the flight system and how it will be used for system functional and performance verification in a next step.

3. Microprobe Design

The detailed design of the Microprobes is described in more detail in [1] and [3].

The Microprobe has a estimated mass of only 150 g at an cylindrical envelope of 46 mm diameter and 110 mm length. The probe core system is even smaller, however a relatively large aerodynamic outer shell is required for a controlled descent. A conceptual design is shown schematically in Fig. 1.

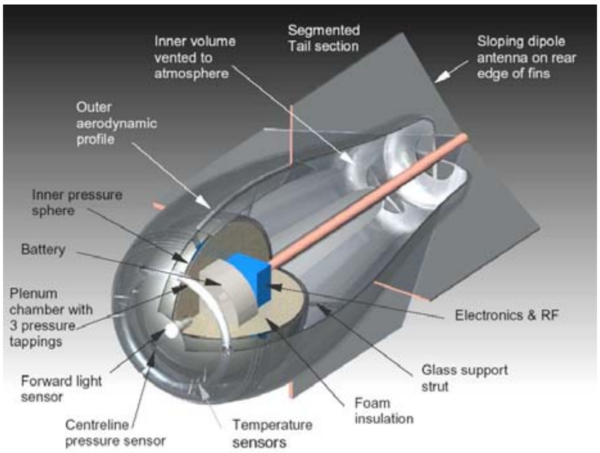

Fig. 1: Graphical Model illustrating the conceptual Design of one Microprobe.

The overall "tear-drop" shape with stabilizing fins is determined from the required aerodynamic performance and is optimized for a drop range from 65 km to below 35 km. It has a very low center of mass, which is good for stability. The required tapering of the aft body shape and the area of the blunt base for the tear-drop body was computed by a semi-empirical boundary layer flow prediction method. In general, the design target is to fall as fast as possible, while just staying below the onset of transonic regime at Mach number 0.52. This avoids the presence of shock waves around the Probe that can create wobble and instability. The design is optimized for a maximum vertical descend speed of about 130 m/s. The Probe shape minimizes sensitivity to the strong horizontal winds occurring at Venus, which reduces slant angle and slant range to about 70° and 155 km respectively. Furthermore, the design ensures Probe incidence angles of below 4°, which is important to keep low drag levels throughout the entire drop.

The probe external material is boro-silicate glass to provide low thermal conductivity, good chemical corrosion resistance and high strength. An inner pressure sphere, also in glass, contains the battery and the electronics. Foam insulation, is used to fill the sphere, providing a thermal barrier to the electronics and mechanical support. The sphere is positioned within the aerodynamic outer shell by 8 glass struts of low thermal conductivity. The rear tail section is segmented to facilitate manufacture and integration.

The established thermal model indicates that the internal Probe temperature will be not greater then ~ 70° C for a probe drop from 65 km to 40 km on Venus. However, the temperature dramatically increases when the altitude is lower then 40 km or when internal electronic power dissipation becomes severe.

Within the instrumentation of the Microprobes, two light-flux sensors are comprised, one facing forward and the other pointing rearward. They are coupled to the atmosphere via a quartz fiber optic light guide and a condensing lens. The sensor heads contain a silicon photodiode and a thermopile sensor to provide spectral coverage from 250 nm up to 4 µm.

Two pressure sensors are included as well. The first measures the probe static pressure and is situated inside a plenum chamber that has three pressure tapings around the hemi-spherical nose section. The tapings are situated about half way around the nose such, that the dynamic pressure induced by the aerodynamic flow acceleration, is minimized. The second sensor is positioned along the center axis of the Probe to measure the total stagnation pressure. By subtracting the static pressure from stagnation pressure, the speed of the probe relative to the atmosphere can be computed 'in-situ'. All sensors are micro-machined silicon diaphragm pressure sensors and each sensor covers a different pressure range.

Two external temperature sensors are furthermore present. Thin-wire thermocouples were chosen, because they allow fast measurements with good time-constants. Both sensors protrude from the Probe, to be outside the boundary layer, away from aerodynamic surface heating. As the boundary layer is thinnest in the laminar region over the nose, the two sensors are located there to reduce required protruding height and thus, mass. The protruding components are moderately streamlined in axial flow direction, not to cause a premature boundary layer transition around the Probe.

Assuming 12 bit resolution for each of the sensors and sample acquisition every 30m, the data rate will easily stay within 100bits/second, including housekeeping data. Thus, data volumes are estimated to be very low, in the order of ~10kbits in total per probe, per drop.

The communications antenna can be built into the rear edge of each stabilizing fin.

4. Key DALOMIS Requirements

The key technical requirements for the DALOMIS system result from the preliminary Microprobe design and the Mission constraints. They are summarized below:

The required DALOMIS mass in the Balloon must be below 1.5 kg.

The DALOMIS mass per Microprobe must be below 50 g maximum.

The DALOMIS system must be able to track the Microprobes with an accuracy of better than 100 m along the line of sight. The resolution must be at least 1% of the line of sight range.

The DALOMIS system must be able to track at least 3 Microprobes at the same time.

The DALOMIS must achieve the required localization accuracy at the maximum slant range of 155 km and maximum slant angle of 70°.

Furthermore, a minimum data rate from the Probes to the balloon of 100bps is required, to avoid on-board storage in the Probe.

5. DALOMIS System Trade-off

The DALOMIS system is distributed in two parts, contained on both, the Balloon gondola, hereafter referenced as Carrier (DALOMIS-C for Carrier part) and on the Microprobe (DALOMIS-M for Microprobe part).

5.1 Concepts

Optical, electromagnetic or in-situ (inertial) methods exist, for localization of free-floating objects in 3 dimensions. The presented work concentrates on electromagnetic and inertial measurement techniques only, because the combination of cloudy atmospheric environment paired with extremely high IR background from the Venus planetary surface is believed to make optical measurement techniques very impracticable.

Each concept is defined in sufficient detail, to allow understanding their relative advantages and disadvantages. Furthermore, for each concept, various sub-options are traded-off, to achieve the best possible implementation. Compared sub-options were, for instance, various Multiple Access Schemes (TDMA, FDMA, CDMA), ranging Methods (Code based, time stamping, Doppler measurements), and direction of arrival methods (Passive Arrays, Active Arrays, etc.) for the electromagnetic localization concepts. However, in order to provide a concise overview, only the finally selected concepts are explained in more detail hereafter.

One-way ‘ timed transmission’ concept

The first analyzed concept is a radio frequency (RF) based one-way transmission scheme.

For obtaining a distance estimate of the Probe from the Carrier, ranging is based on reception of timestamps generated and transmitted by the Probe during descend.

Azimuth and elevation angles are measured on the Carrier with a ‘direction of arrival’ (DOA) measurement system. The proposed DOA system for this (and the next) concept utilizes a compound dual-axis phase interferometer. The phase interferometer system comprises two orthogonal antenna arrays and a multi channel receiver. More detail about the exact functioning of the DOA principle will follow in a later chapter.

Different Probes have unique Identifiers, and are discriminated by a Time Division Multiple Access Scheme (TDMA). Thus, each Probe Data Handling Unit (DHU) has a pre-programmed timeline to determine when a transmission can be made. Other methods such as CDMA and FDMA were assessed, however, mostly resulted in more complex system architectures. They are not outlined in more detail hereafter.

In principle the TDMA based system is very simple and only relies on the accuracy and synchronization of the Carrier and the Probe Clocks for the ranging.

The time of flight of the data (speed of light) is in the order of tens of microseconds, over the time of the drop campaign. To meet the 100m-resolution requirement is difficult, as the following calculation shows:

$$T = \frac{d}{c} \approx \frac{100}{3x10^{8}} \approx 333.3x10^{-9}s \qquad \text{(Eq. 1)}$$

T is time it takes the RF signal to travel 100m. Taking this to be the period of a suitable “resolution” rate, the frequency is given by:

$$f = \frac{1}{T} = \text{ 3 MHz} \qquad \text{(Eq. 2)}$$

This frequency represents the resolution of the clocks required on the Probe and the Carrier. Because in this concept, the major factor influencing the determination of the distance is the stability of the two clocks, the two oscillators (Probe and Carrier) must stay within $333.3x10^{-9}$ s of each other, over the entire drop period. Based on the probe design, the drop period will be in the order of 25 minutes. The stability is then calculated by:

$$stab. = \frac{T}{t_d \cdot 2x10^{-6}} \qquad \text{(Eq. 3)}$$

Where t_d is the drop-time in seconds, multiplied by 2 because 1 clock can run fast while the other runs slow (worst case). This leads to a stability required of about 0.1 ppb, which current technology can just achieve, given the required mass, volume and power. There are also others errors, such as temperature drift, etc., but they will exist in the other three concepts as well, which is why they are not explained in more detail here.

The additional resource required for this scheme to work is thus an ultra highly stable oscillator (OCXO) on the Carrier and Probe. It was estimated that a mass of 53 g could be realistic for the DALOMIS-M part in the Probe. Power consumed would be in the order of 1.9 W. The DALOMIS-C could target at a mass of approximately 1.2 kg and 1 W of electrical power.

Two-way ‘ active echo’ concept

In the second concept a pulsed radar system is used at the Carrier for the ranging. As with conventional radar, a suitably short or equivalent bandwidth coded pulse (e.g. linear FM chirp, PN etc) is needed to provide the required range resolution. On receiving a transmit pulse from the Carrier radar, the Probes actively return this pulse. After removing the known internal Microprobe delay in the signal received at the Carrier, correlation between the transmitted (Tx) and received (Rx) signal pulses determines the 2-way range to the Probe. The resolution of the radar is given by the following equation:

$$\Delta r = 0.8859\frac{c}{2B} \qquad \text{(Eq. 4)}$$

Where c is the speed of light and B is the pulse bandwidth. The resolution of the range measurement is equivalent to the size of the range bin, Δr, which gives a required minimum bandwidth B of approximately 1 MHz for 100 m. As this is not a stringent requirement to meet, the bandwidth was doubled to 2 MHz to provide extra margin.

The ranging accuracy, is influenced by pulse phase errors, Δφ, of the received signal with respect to the reference function, and the receive window timing accuracy δτ.

The typical error E_r can be estimated according:

$$E_r = \left[\left(\frac{c\delta\tau}{2} \right)^2 + \left(\frac{c\Delta\phi}{720B} \right)^2 \right]^{\frac{1}{2}} \qquad \text{(Eq. 5)}$$

This is modified from the across-track localization accuracy of an LFM SAR system. It can be seen that, to keep errors below approx. 5 m, $\Delta\varphi < 20°$ and $\delta\tau < 20$ ns are required, which is considered feasible.

The carrier clock stability specification is dictated by the requirement for the timing error to be within 1 chip at the end of the mission duration i.e.:

$$S_c = \frac{1}{BT} \qquad \text{(Eq. 6)}$$

Where T is the mission duration (~1500 s), and, with a value of $\sim 3.3 \times 10^{-10}$ or 0.3 ppb, the stability can be seen to be of a similar order then the one of the one-way concept. However, an important distinction to the first concept is that here, only one master clock residing within the carrier is required.

The same DOA measurement system as used in the one-way timed transmission concept allows the probe to be localized fully in 3 dimensions.

Thus, concept 2 will not require a stable on board clock in the Probe, but Tx and Rx capability for Probe and Carrier. The assumed mass required for the Probe is about 47 g. The required power estimated for the DALOMIS-M is about 1 W. In the carrier, the system would lead to a mass of about 1.36 kg. The estimated power on the Carrier is higher with respect to Concept one, at about 10 W due to the required Tx systems.

MEMS IMU Concept

The third concept foresees of an inertial navigation system package (INS) within each Probe. The system has to be highly miniaturized such that use of MEMS technology is mandatory. While the overall operating principle keeps the Carrier design extremely simple (only Rx, no DOA), complexity is shifted to the Probes.

An inertial measurement unit (IMU) must contain 3 accelerometers and 3 gyroscopes placed in an orthogonal set. The output of a basic IMU is the acceleration and rate of turn in 3 directions. In order to localize a Probe, the rate and acceleration information has to be integrated twice, to provide position and heading information. Due to measurement drift, the double integration causes a propagation of the errors in the accuracy of the INS as the errors are depending on t^2 or even t^3 (t is the time of flight). The dominant errors are fixed bias uncertainties, scale factor errors, g-dependent biases for the gyro, mounting misalignment and initial offset errors.

In order to achieve the 100 m vertical resolution requirement after only 25 minutes of flight, axial accelerometers with a bias of less than 90mg are required. Furthermore, near navigation grade gyros with a bias of around 0.1°/hr would be needed for the roll gyro. For performance comparison, sensors which are specified today as tactical grade for missile systems have biases of around 10mg and 30°/hr.

A COTS IMU with the necessary performance and size, weight and power characteristics is not available for the microprobe and not currently on any published roadmap of the main MEMS inertial component manufacturers. The estimated mass for a custom developed DALOMIS-M is 52 g. Estimated Power consumption is about 900 mW. The estimated DALOMIS-C mass is in the order of 1 kg only, with a power below 1 W. However, the major concern and most stretching requirement is the performance of the Microprobe IMU, in particular the performance of the gyroscope.

5.2 Selection

The main factors traded-off were the localization performance of the concepts, miniaturization potential in a 5-year timeframe and associated risks of development. Furthermore, the potential to achieve a minimum size for the Probes was assessed.

In all those criteria, concept two, "two-way active echo", is the favorite. This is why it is chosen for further elaboration.

6. DALOMIS Design

A system overall block-diagram of the chosen "two-way" DALOMIS system is provided in Fig. 2.

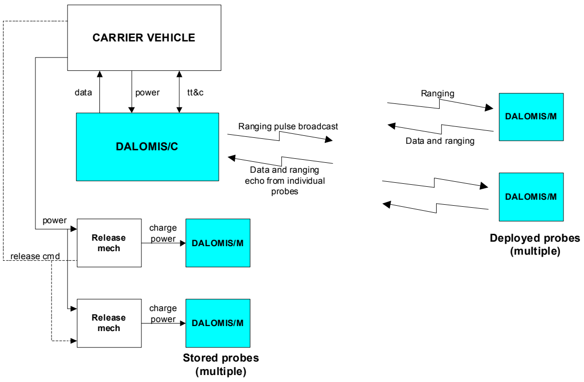

Fig. 2: Overall block-diagram for the DALOMIS system.

6.1 Frequency Allocation

The identified frequency band for DALOMIS is S-band in the region of 2.4 GHz for the following reasons:

The DOA accuracy performance is achievable at this frequency.

The interferometer baseline length can be kept within reasonable limits.

The antenna element size is compatible with the Probe external dimensions.

Free space losses are acceptable at this frequency and atmospheric attenuation is low [7].

High miniaturization potential exists for S-band electronics.

Components and COTS modules for development and testing are widely available.

RF device performance is good at this frequency and reduces at higher frequencies.

Suitable terrestrial frequency allocation is available for breadboard test (ISM band), with sufficient bandwidth to accommodate required Tx / Rx frequency separation.

6.2 Localization Scheme

Ranging Implementation

A pulsed ‘radar’ is located within the carrier. It utilizes a PRBS waveform at 2 Mchips/s. An active responder within the Microprobe returns the ranging signal. Because the maximum round trip delay is in the order of 1ms and therefore, the Tx and Rx pulses will overlap, sufficient frequency translation is required to ensure Tx and Rx isolation in Probe and Carrier.

The baseline for the Probe is to demodulate the received ranging signal with a fixed (plus any offset) local oscillator (LO), re-shape the signal with a comparator and use this demodulated signal to re-modulate a transmit carrier. Modulation format is chosen to be BPSK for best link performance.

Implementation of full ranging signal regeneration within the probe, which would have better performance, was considered difficult within the limited probe resources available.

The ranging bandwidth B is 2 MHz, which according to (Eq. 7) allows a range resolution ρ of 75m to be obtained.

$$\rho = \frac{c}{2 \cdot B} \qquad \text{(Eq. 7)}$$

Ranging is performed sequential to each probe, according to the implemented TDMA multiple access scheme.

Direction of Arrival (DOA) Measurement

Interferometry is used as a principle to detect the direction of arrival. At S-band, the 2 axis compound interferometer has a nominal long baseline of 0.625m, allowing DOA estimates to be made with accuracies in the order of ±0.5° rms.

A short, second interferometer baseline of $\lambda/2$ in each axis provides ambiguity resolution. To minimize DOA receiver hardware, it is possible to multiplex between both X and Y axes and the phase centers (antennas) along each axis. This reduces the receiver requirement to 2 channels minimum, which must phase track to preserve DOA accuracy.

It is possible to use both, the data and / or the ranging signal to obtain DOA estimates. The ranging signal will require de-spreading (correlation) prior to phase comparison, while DOA measurements on the data signal do not. Therefore processing requirements as well as accuracy is better when using the data signal, which is why this is the design baseline.

6.3 Multiple Access Scheme

Some form of multiple access scheme is required to support multiple probes in flight. TDMA is chosen for DALOMIS, to ensure minimal hardware complexity in the carrier. It is sufficient to operate the TDMA in open loop, which means that no probe-carrier synchronization is needed, except at probe release. The scheme operates as shown in Fig. 3:

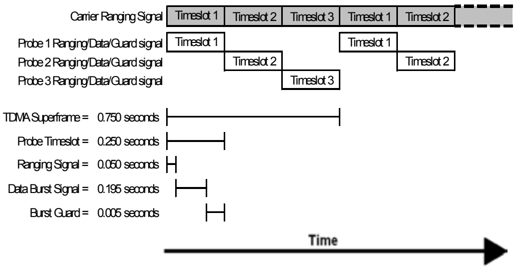

Fig. 3: Exemplary TDMA timeline for DALOMIS

(1) The TDMA schedule is initiated at Probe release from the Carrier. Internal Probe and Carrier clocks maintain the Schedule.

(2) The carrier issues its Tx ranging signal in different time slots, corresponding to a specific Probes. The Probe whose time slot is active during the broadcast, responds by enabling its power amplifier.

(3) The DOA/ ranging subsystem in the Carrier receives the ranging signal from the Probe and processes it to determine the range.

(4) In a second signal burst, the active Probe sends its science data, after a pre-set delay.

(5) The Carrier receives the data burst, acquires and demodulates it to extract science data. Simultaneously, the data burst is processed by the DOA/ ranging subsystem to derive a phase estimate, from which DOA can be derived. The estimates are passed to the DHU.

(6) The Carrier repeats the sequence from step (2) until contact with the Probes is lost.

A simple calculation shows that requirements on the Probe clock are non-demanding. Assuming a ±1.5ppm clock in the Probe (e.g. TCXO) and a maximum drop time of 40 min., gives an uncertainty in TDMA burst position of 7.2 ms. TDMA bursts are therefore long enough, in the order of 200 ms with guard times of 50 ms, to guarantee unambiguous localization.

6.4 Data Transmission Scheme

The same frequency can be used for all Probes, due to the TDMA scheduler. This requires only a single channel data receiver in the carrier and allows for identical RF hardware on each probe.

BPSK modulation format is the baseline for the flight hardware. Given the low data rate (1 or 2 kbps), use of residual carrier (e.g. m=60o ±5%) and Bi-Phase (SP-L) modulation is used to maximize performance and ease receiver design. This is consistent with the CCSDS proximity link standard.

It is proposed to utilize dual data rates. The high rate (2 kbps) will be used in the early stages of the probe drop, when the probes are falling fastest and therefore the update rate needed is the highest. The low data rate will be used later in the descent when the Probes vertical velocity has decreased, to improve the link margin at maximum slant range. Switching between the two rates will occur at a pre-determined time, which is programmed into the TMDA schedule before Microprobe release.

7. DALOMIS Implementation

7.1 Carrier

The carrier is divided into a ranging Tx and data reception subsystem, a DOA and ranging measurement system, a base band or data handling unit (DHU) subsystem, and an antenna subsystem (Fig. 4). The carrier interfaces to the Balloon via a Spacewire 10 Mbit/s TM and TC bus. Power is provided by the 28 V Balloon power-bus and will be regulated locally.

Ranging Tx and data Rx subsystem

The Function of the Ranging transmit system is to directly modulate and convert the baseband ranging sequence from the DHU up to S-band and amplify the waveform to a nominal level of 1W. Modulation is in BPSK format. The baseline is suppressed carrier modulation. The LO will be derived from the master oscillator (MO) reference by a frequency synthesizer (PLL).

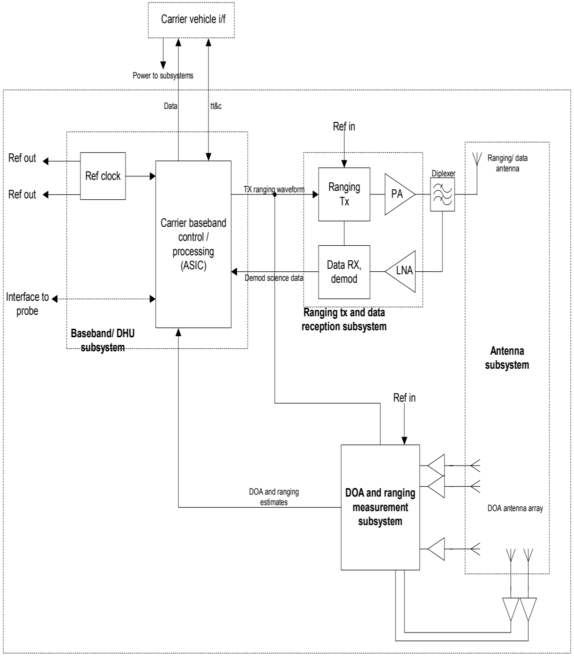

Fig. 4: Block diagram of DALOMIS-C

Furthermore, a Tx enable control, based on drain modulation, is provided on the power amplifier, to disable it when not required. This saves energy.

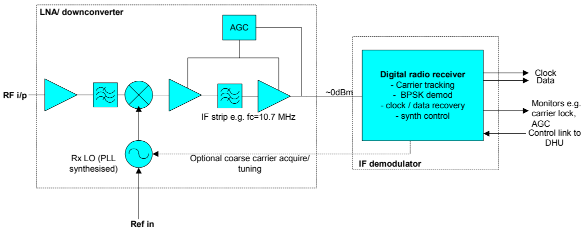

Fig. 5 Block Diagram of Data reception System

The baseline design for the data reception system is centered around a digital ('software defined') radio to maximize integration and to minimize size. The receiver is designed for residual carrier and Bi-phase demodulation. Use of residual carrier eases the carrier tracking loop implementation, with respect to a suppressed carrier approach. All digital functions are to be implemented entirely in an ASIC or FPGA. The analogue LNA and down-converter provide the input to the digital radio (Fig. 5).

The estimated mass required for the entire subsystem is 225 g. The power consumed should stay below 5.2 W.

The implementation for the breadboard is largely driven by the available hardware for the Probe. COTS BPSK transceiver modules suitable for the breadboard have proven impossible to source, hence, BFSK is likely to be adopted for the breadboard. This decision impacts on the ultimate performance achievable, however, builds a safe case for the performance testing, because BPSK would only improve performance.

DOA and ranging measurement subsystem

This subsystem produces the DOA and ranging estimates.

DOA and ranging measurement functions have been combined since both have a common requirement to de-spread (correlate) the received waveform with a replica, which is generated by the DHU. This allows maximum flexibility for later improvements. For instance, ranging and data bursts can be used by the DOA at a later stage, if improved performance is required. A block-diagram of the implementation is shown in Fig. 6.

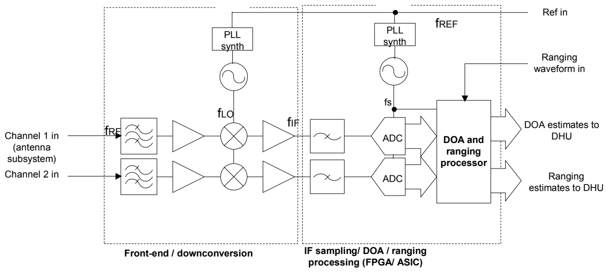

Fig. 6: Block diagram of DOA and ranging measurement subsystem.

The front-end and down-conversion module filters, amplifies, limits and mixes the received signal down to an intermediate frequency (IF), which is suitable to be sampled by the following ADC. A PLL synthesizer locked to the MO enhances stability and avoids the phase noise that could degrade the DOA measurement accuracy.

The IF sampling and processing block digitizes the IF and shifts the samples to an FPGA / ASIC for processing. A sendond PLL locked to the MO derives the ADC sample clock.

DOA is estimated by multiplying the data signal received on one channel by the conjugate of the data signal received on the second channel. Both channels are simultaneously sampled. The complex valued results are then accumulated over the integration time to produce raw phase difference estimates. The DHU will hand those values to the Balloon for further transmission to ground. Ground processing will then convert the estimates into angles.

For the ranging, the received signal on the carrier is demodulated and correlated with the transmitted signal at various delays. The delay of the correlation peak gives the range estimate. The ranging pulse length and integration times will be optimized for a given application. To compensate for occurring frequency offsets (e.g. Doppler, LO frequency errors, etc.), usually, multiple correlators are implemented in parallel, and each compensated for a different frequency offset. This is somewhat inefficient, because if the frequency search range is large, many correlators are needed. This can easily result in a very complex hardware. A strategy to perform frequency compensated correlation more efficiently is to predict frequency offset to narrow the search range. This can be done most simply by always using the last value (recursively updated estimates) after initially locking onto the frequency offset at release. For DALOMIS, an eventually required frequency compensation to the basic 1-bit correlator unit is simple: The accumulators need to be read out and re-zeroed multiple times during the burst. The remaining processing is not intensive and can be carried out by a programmable processor. A schematic of the implemented range correlator is shown below (Fig. 7).

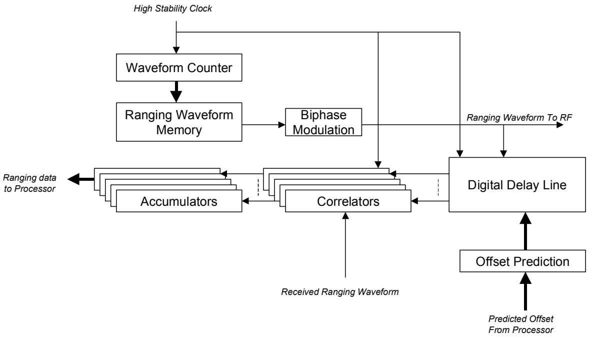

Fig. 7: Schematic of DALOMIS Range Correlator

The waveform is stored in a 1Mbit memory, which is repetitively sent to the RF subsystem. The incoming waveform is correlated (the correlator comprising a simple XNOR function) every 500ns (2 MHz waveform) with delayed versions of the Tx waveform for the ranging pulse duration T. The number of correlators depends on the number of Microprobes to be tracked and the distance the probes travel between measurements. If, for instance, a measurement takes one second and there are 5 probes, then the probes may travel up to 500m between ranging measurements, according to the aerodynamic simulations. This will require 10 correlators and accumulators and 10 delay line outputs to locate the peak to 100 m accuracy.

The estimated mass of the entire subsystem is about 300 g. The power required should stay below 2.6 W, subject to the functional tests with the breadboard.

The breadboard of the DOA and ranging measurement subsystem will be a two-channel version.

Baseband / DHU Subsystem

The DHU for the carrier component of DALOMIS centers on an FPGA hosting a 8031/8051 CPU IP core, that handles the ranging signals, interface to the Balloon and serial communications.

A Boot PROM contains the basic operating software that allows the subsystem to communicate with the Carrier and to load the program EEPROM. The program EEPROM contains the operating software for the processor core. The bootloader code is read from the PROM and then written to RAM by Glue Logic in the FPGA on power up. The boot PROM is not re-programmable in flight but can be re-programmed on ground, prior to flight, using an external interface.

A Spacewire interface allows DALOMIS to exchange data with the balloon systems. The Spacewire interface, CPU and Glue Logic are hosted on the FPGA. The remaining components, RAM, PROM and EEPROM, are external components.

A clocking component generates all operating clocks for the baseband electronics and for the RF subsystem. The range correlator requirements dictate the use of a highly stable oven controlled crystal oscillator (OCXO).

The power conditioning system will be housed next to the DHU and the clock. Its function is to regulate the balloon power bus voltage, nominally 28V, to 5V or 3.3V for the DHU and the secondary voltages for the RF sub-systems. In total, a mass of about 340 g is anticipated for the subsystem. The power will be 6.6 W during operation.

The DHU breadboard will test out the functionality of the architecture design by using commercially available components. The breadboard will center around a PIC-type microcontroller. External RAM and EEPROM are embedded into the PIC as internal RAM and FLASH respectively. The PIC will control a high-speed RS232 link to replace the Spacewire interface. An FPGA will contain the same modules as implemented for flight, except the IP core. Power regulation will be performed by COTS components.

Antenna Subsystem

The Antenna subsystem comprises 6 antenna elements (Fig. 8). Five active antennas (Rx only) feed the DOA subsystem and are mounted on orthogonal (X, Y) CRFP booms. The middle antenna is shared between the X and Y baselines.

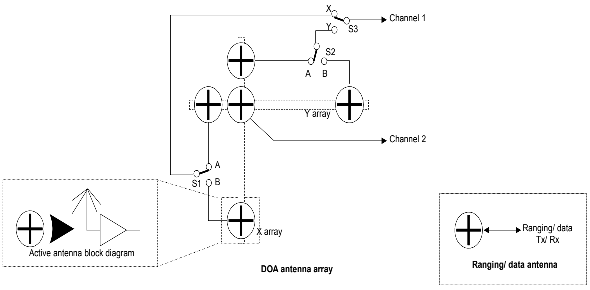

Fig. 8: Block diagram of antenna sub-system.

Amplifiers and Multiplexers are integrated into the antenna subsystem. This minimizes cabling to the DOA receiver and possible calibration errors arising from temperature differentials. The sixth antenna shown, is Tx and Rx in function and feeds the ranging Tx and data Rx subsystem.

All antenna elements are identical in design, featuring a crossed drooping dipole above reflector with a mechanical design following [6], to be extremely lightweight. For S-band, the element is about 6 cm high at an ground plane diameter of 8 cm. The feed network comprises a 3 dB hybrid such as Anaren Xinger, connected to the dipoles via a balun (dual Pawsey stub). The expected dipole feed impedance is 50 Ω. The low noise amplifiers (LNA) integrated with the antenna elements will be PHEMT design for low noise figure. The total antenna sub-system is expected to weight about 548 g only. The consumed power will be in the order of 400 mW.

The breadboard antenna will make use of COTS hardware, thus, the expected weight and power consumption will be accordingly higher.

7.2 Microprobe

The Microprobe design is relatively simple, because the most complex functions have been implemented in the Carrier. A Block-diagram of DALOMIS-M is shown in Fig. 9.

The Microprobe consists of an RF Tx and Rx subsystem, a DHU subsystem with Power Handling Block and a Sensor Sub-system. The Sensor Sub-system will not be explained in more detail hereafter, as it is not strictly a sub-system of DALOMIS.

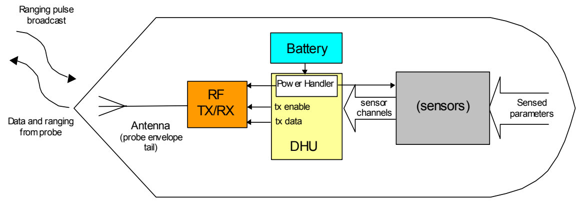

Fig. 9: Microprobe Block Diagram

RF Subsystem

The active radar ranging concept is based on the Probe’s regenerative transceiver. The ranging signal emitted by the Carrier is received, demodulated by the Microprobe and then re-modulated and retransmitted towards the Carrier. The noise power is thereby halved with respect to a transparent repeater design.

In the receiver block, after filtering with a 2nd or 3rd order high-pass filter, the signal is passed via 3 low noise amplifiers to the BPSK demodulator unit. The video ranging pulse-sequence, which is the output, is then fed into a pulse shaper that, by comparison with a threshold, reconstructs a pure square pulse sequence with steep wavefronts.

A dedicated BPSK modulator re-modulates the signals onto the transmit carrier and accepts either the re-shaped ranging pulse sequence or the data bursts sent by the DHU. A power amplifier feeds the signal to the antenna circulator for transmission to the Carrier. Tx and Rx frequencies are separated, for isolation reasons, by at least 50 MHz.

As outlined already above, the Microprobe breadboard will consists of COTS BFSK units instead of BPSK ones, for availability of suitable off the shelf components.

DHU Subsystem

The DHU is time synchronized with the Carrier clock at Probe release and contains the TDMA schedule. Synchronization inside the Balloon Gondola can be performed via Radio Frequency Identification Devices (RFID), contact less.

The DHU will receive, decode and issue commands received from the RFID system, re-synchronize the on-board time, collect and organize data from the sensors and activate and control the RF sub-system.

While for a flight version the DHU will be implemented in a mixed ASIC, the Breadboard will be implemented in COTS components as shown in Fig. 10.

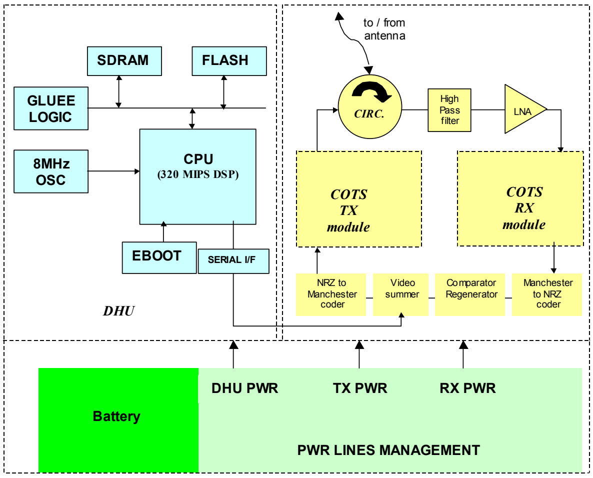

Fig. 10: Breadboard Microprobe Block Diagram.

Power consumption of the Microprobe is strictly dependent on the number of activities the DHU performs. For this reason, some different power request cases are defined. Fig. 11 shows a typical power profile over one TDMA frame.

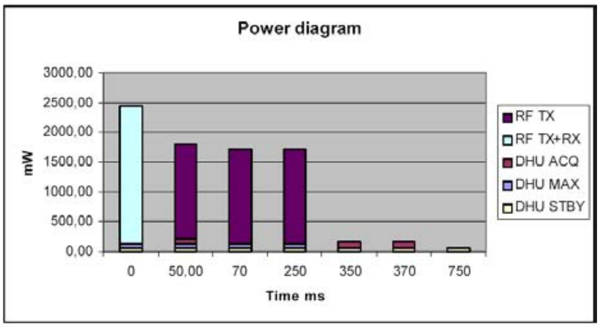

Fig. 11: Microprobe Power required during TDMA frame.

Antenna Subsystem

A turnstile antenna is used for the transceiver, consisting of four quarter-wavelength monopoles (each approximately 32 mm long) fed by a passive network. The baseline implementation foresees of a network including one 90° micro-hybrid and two 180° power splitters, in SMT technology.

The antenna element design is identical to the Carrier antenna elements; with the difference that the ground plane is the crossed structure of the rear fins of the Microprobe shell.

The turnstile antenna is fed by four equal strength signals shifted in phase by 90° each other. This produces a circularly polarized pattern nearly omni directional in azimuth and optimized for the slant angles occurring during atmospheric descent.

8. Discussion and Conclusion

Estimated resources required for DALOMIS-C and DALOMIS-M flight versions are given in Tab. 1. It can be seen that the mass requirements regarding DALOMIS-M and DALOMIS-C seem still accomplishable after a more detailed design. The current estimate of required power for both sub-systems, however, is higher then initially expected in the trade-off analysis. This was found out only during extensive link budget analysis. However, still, the final values are in a range that seems acceptable for the reference Venus Mission.

Element	Mass (g)	Volume (cm^3)	Power (W)
DALOMIS/ C	1420	3152	17.8 (warm up) 14.8 (operating)
DALOMIS/ M	50	100	0.1 / 2.3 Avg/ pk

Tab. 1: Estimated resources required for DALOMIS system.

Regarding the DALOMIS-M required power, it will need to be checked in future analysis, whether thermal dissipation can still be guaranteed in the proposed packaging.

Still, the chosen concept promises good localization performance with a bearing range estimate of better then 75 m and an angular localization accuracy of in the order of 0.5° rms.

A functional breadboard will show feasibility of the proposed design with real hardware under real test conditions in the near future. At the time of writing, the Breadboard versions for both, DALOMIS-C and DALOMIS-M are still being manufactured. Despite the use of commercial components, it is expected that system functionality and localization performance can be analyzed.

Extensive laboratory bench tests are scheduled on sub-system level. Afterwards, a series of out-door tests will be performed. Antenna Test-ranges will be used to measure the gain patterns of all antennas exactly and to verify localization performance of the DOA antenna in a controlled environment. A consecutive long-range test is planned thereafter. For that test, one Breadboard Microprobe (DALOMIS-M) will be fixed to the base of a Meteorological Balloon and launch together with it into earth atmosphere. On ground, the DALOMIS-C will be used to track DALOMIS-M until the signal is lost. In the foreseen set-up, a maximum range of up to 80 km could be tested, if the weather conditions are good. All measured position information with DALOMIS will be compared with reference GPS data that is downlinked from the Meteorological Balloon to ground by default. Scientific sensing as well as multiple probes in flight will be emulated to verify timing performances of the TDMA schedulers.

It was shown that extremely miniaturized Microprobes can be developed, that are able to sense basic scientific parameters in the hazardous atmosphere of Venus during vertical free-fall.

A microprobe with a mass of less then 113g seems achievable that includes basic scientific sensors, data handling electronics, power supply and the required RF infrastructure to submit its collected data to a 155 km distant Carrier craft.

It was furthermore shown that an electromagnetic, RF based system can have superior tracking and localization performance with respect to inertial measurement methods if mass and available power is constrained.

9. References

[1] Nigel Wells, Andrew Ballard, Matt Cosby, John Dotherty, Andrew Eldrige, Fred Taylor, Neil Bowles, Colin Wilson, “Atmospheric Microprobes for Venus: A Preliminary Probe Design and Localisation Method”, Proceedings of the 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation ASTRA, 2004

[2] A. Schiele, “Planetary Microprobes – Data Transmission and Localisation System for Microprobes Swarms”, ESA Statement of Work, TOS-MMA/2003/523, 2003

[3] N. Wells, “DALOMIS Microprobes Requirements Document”, QinetiQ/KI Systems/Space/20/152-RD01, Issue 1, 2004

[4] “Venus International Reference Atmosphere (VIRA) tables”, Advances In Space Research, Vol 5, No 11, 1985

[5] ”VEP Venus Atmosphere Basic Data TN-010 document”, Ångström Space Technology Centre, Issue 1, November 2002, P4/1-208-24 (5.4)

[6] J. Huang, “Mars Rover antenna for solar array integration”, TMO Progress Report 42-136

[7] M. A. Kolodner, P. G. Steffes, “The Microwave Absorption and Abundance of Sulfuric Acid Vapor in the Venus Atmosphere Based on New Laboratory Measurements”, ICARUS 132, 2003, pp. 151 – 169