Chapter 25
BalSAR: A Stratospheric Balloon-Borne SAR System

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Abstract Surveillance systems are continuously employed for both military and civilian applications, including homeland security and border protection, which are two main concerns to NATO and in particular to the Science for Peace and Security (SPS) programme. Several platforms and systems, developed in past years, have turned into surveillance systems that are currently used in such scenarios. This paper describes a high-altitude balloon-borne synthetic aperture radar (BALSAR) system, which is currently under development as part of a NATO funded project within the SPS programme. Such a system will be able to perform surveillance tasks by acquiring radar data, forming SAR images and using them to extract valuable information.

Keywords High-altitude platform · Stratospheric balloon · Airborne surveillance · Synthetic aperture radar

25.1 Introduction

Military and civilian information gathering is an essential part of maintaining security and significant effort and money are spent on systems to enable these functions. Current technologies, which mainly employ satellites, aircraft (both manned and unmanned – UAVs), and drones suffer from a number of shortcomings. Space-borne systems operate from a large distance and, provided careful constellation design, are

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able to cover almost all areas on the surface of the earth. However, space missions are expensive and their use depends on the presence of a satellite over the designated area which can only happen at particular times that are determined by the orbit. Also, they do not offer a rapid and timely response as the ability to repeat measurements over a given area is constrained by the satellite orbit, which may impose intervals of several hours or even days between revisits. Airborne systems operate at much lower altitudes and piloted aircraft missions put the lives of pilots at risk as they are inherently vulnerable to attacks. Their size, and therefore radar cross section, and flight altitude limits make them easier to detect and target from the ground or the air. Moreover, the cost of such aircraft is quite high, justifying the launch of an intelligent missile against them. While UAVs take the pilot out of the equation, they still suffer from all of the other problems associated with piloted aircraft including cost and vulnerability. In fact, all of these systems are not expendable and must be protected.

High altitude platforms (HAPs) [1] have the potential to complement the above two systems and address many of their shortcomings. HAPs have been proposed in military applications for the gathering of surveillance data and are poised to play a key role in the area of national security. The USA, China, Japan and European Union have had military HAPs projects. These platforms enjoy a number of unique advantages with respect to both aircraft and satellites. HAPs operate at altitudes exceeding 20 km, and include certain aircraft, airships and balloons [1]. Their high altitude gives them a higher degree of immunity against attack as compared to aircraft while providing them a wider field of view [2]. On the other hand, they are a cheaper alternative to traditional satellite systems as their development and deployment costs are much lower than those of spacecraft. Their comparatively low altitude, with respect to spacecraft, makes them more versatile and recoverable meaning that they can be maintained and even upgraded. Also for remote sensing applications, they do not suffer from long revisit times that are a drawback of satellite systems.

While some systems employing HAPs exist [1–3] or have been proposed, most tend to be either airships or UAVs, and are large and very expensive. The Zephyr [4] is a solar powered UAV that is developed by Airbus. It is described as a High Altitude Pseudo-satellite (HAPS) as it is designed to hover for an extended period of time over a designated region. Among the intended uses of the Zephyr, Airbus lists maritime and border surveillance, environmental surveillance, missile detection, navigation, and continuous imagery. Lockheed Martin's ISIS [1] and Raytheons Radar Aerostat [5] are two US projects developing high altitude airships. All three systems are manoeuvrable and intended to provide long mission durations (on the order of days, months or even years at a time). Consequently, they are quite expensive and require significant infrastructure for deployment. As an example, the UK Ministry of Defence was reported to have an order for two Zephyr worth USD18 million [1].

Stratospheric balloons have been used for decades for scientific experiments and remote sensing and both NASA [6] and JAXA [7] conduct high altitude balloon missions. These free floating balloons are very large and carry payloads weighing many hundreds of kilograms or even a few tonnes. Stratospheric balloon constellations with trajectory control have also been proposed for communications [8, 9], and scientific missions [10]. Small (sounding) balloons are extremely cheap even in comparison to the large HAPs discussed above. These are mainly used for weather sensing [11], education [12, 13] and amateur activities.

We propose a new high-altitude (in excess of 20 km) balloon-borne Synthetic Aperture Radar (SAR) system that overcomes the shortcomings of existing systems without compromising performance, such as resolution, signal-to-noise ratio and hence target detection and recognition. The new system has a number of significant advantages over the aforementioned solutions. It is very low cost and hence expendable, rapidly deployable, has low probability of intercept (LPI) characteristics and is practically immune to attacks, requiring a very expensive guided missile to intercept it. There are a number of scenarios where airborne/space-borne radar surveillance is needed. Such scenarios include border protection, battlefield surveillance and, in more general terms, critical area surveillance where ground systems cannot be deployed either because the area is far from any logistic support or because of the unacceptably high risks that would be involved in deploying the system. In this paper we describe the proposed architecture and detail various subsystems.

25.2 Proposed Solution

The proposed solution employs a combination of a very light SAR system and a high altitude balloon platform to provide a balloon-borne SAR (BalSAR) system. The BalSAR system would provide the means to fly at a very high altitude, 20 km and above, and therefore operate at a safe distance from the surveillance area. In addition to the BALSAR system, the project will also produce the support systems including the flight prediction and mission planning software, launch (balloon inflation and release) system, telemetry tracking and command (TT&C) system, and HAP recovery system. A high altitude balloon borne SAR has in fact been recently reported in [14], which demonstrates the feasibility of the concept. Our system, however, aims to achieve a number of specific aims including low cost, rapid deployment and standardization of the bus.

The BALSAR system is shown in Fig. 25.1. It comprises a balloon capable of lifting a High-altitude Platform (HAP) weighing around 20 kg, a flight termination system, and a parachute to facilitate the HAP recovery. Capitalizing on the experience in building the UNSW cubesat UNSW-EC0 [15, 16], which formed part of the European QB50 constellation [17, 18], the HAP itself is modeled on the cubesat standard [19, 20]. Platform standardization will enable the use of commercial-off-the-shelf (COTS) components, directly leading to greater flexibility, as well as lower costs and reduced risk. Additionally, as COTS components improve being driven by market competition and pressures, improvements in the HAP will result. Finally a standard bus will greatly facilitate the opportunities of payloads other than the SAR system to be carried by the HAP. This enhances the utility of the proposed HAP

Fig. 25.1 Illustration of the BALSAR system. Note that the radome is not drawn in order to show the antennas

system. Therefore, the standardisation of the HAP is one of the core goals of this project.

The project involves significant challenges both in the SAR and HAP systems. In order to deliver a low-cost and rapidly deployable system, the overall size and complexity must be kept low. The proposed BALSAR system rides on the stratospheric winds and does not include any trajectory control. Therefore, the mission goals are ensured through an innovative architecture that includes the subsystems and support systems described in what follows.

25.3 The Flight Subsystem

The flight subsystem consists of the balloon, termination mechanism and parachute. The balloon is helium-filled and is rated to carry a payload weighing 20 kg up to an altitude of 30 km. As the balloon's trajectory is not controlled, a flight termination subsystem is included in order to terminate the mission in case it diverges significantly from the set flight plan. The termination subsystem is positioned between the parachute and balloon and receives the termination commands from ground control. Flight termination is achieved by burning a nichrome wire to separate the parachute and HAP from the balloon. The termination subsystem can also be used if a desired landing site is specified. The mission is then terminated at the point that results in the HAP landing at the designated site. Also note that automatic flight monitoring may be programmed into the on-board computer (OBC) which can then command the termination mechanism to activate if a pre-specified mission envelope is exceeded.

The parachute ensures that the HAP descends at a rate that prevents damage if it is to be recovered. Thus the parachute is located below the termination device and is sized to provide the desired descent rate, which is typically between 5 and 10 m/s. During the descent phase of the flight, the parachute automatically opens when the atmospheric density becomes high enough (typically at altitudes higher than 15 km).

25.4 The HAP Subsystem

The proposed HAP architecture is shown in Fig. 25.2. As alluded to earlier, it is modelled on a spacecraft bus, and in particular on a cubesat design. Therefore, the HAP comprises an OBC, an electrical power subsystem (EPS) and associated batteries, a communications module (comms), inertial measurements units (IMUs), and various positioning units to provide tracking of the platform. The HAP subsystem also houses the payload, that is the SAR subsystem. Micro-controller Units (MCUs) are employed as intermediaries between the OBC and a number of other subsystems in order to perform specific tasks associated with these subsystems. This philosophy ensures that critical tasks are handled by their decidated MCUs which ensure the reliable operation of the HAP. The main subsystems of the proposed HAP architecture are described below:

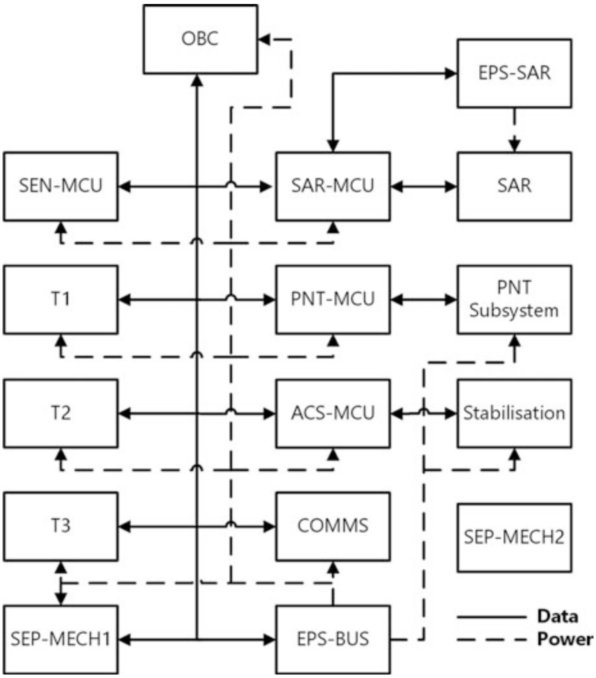

Fig. 25.2 Architecture of the HAP bus showing the data and power interconnections

- OBC: the OBC manages the flight, executes the schedule, and monitors the various subsystems. Upon powering the bus, the OBC will first initialise the other subsystems and load the flight parameters to the SAR and stabilization microcontroller units (SAR-MCU and S-MCU respectively). The OBC will then periodically query the other subsystems to check the health of the HAP. Deviations from the nominal flight envelope will lead to termination of the flight. Finally, if requested by ground control, the OBC will gather relevant information on the HAP subsystems and communicate it to the ground via the comms subsystem.
- EPS: the HAP carries two electrical power subsystems, one for the bus (EPS-BUS in Fig. 25.2) and another for the SAR payload (EPS-SAR in Fig. 25.2). Each EPS includes its own battery pack and is fully controllable allowing various rails to be switched on and off. The use of a separate EPS for the payload is dictated by the power requirement of the radar.
- COMMS: the COMMS module operates at UHF in the amateur band. It provides communications with ground control in order to monitor the HAP health and track it. It also permits critical commands, such as flight termination to be uplinked to the HAP. Note that the SAR data is stored onboard and is not downlinked to the ground during the flight.
- SAR-MCU: This microcontroller interfaces the SAR payload to the HAP bus and performs two primary functions: firstly, it controls the operation of the radar by first turning it on at the right point of the flight, instructing it to start the acquisition and then stopping and turning it off. Secondly, it stores the position tags for the radar snapshots. To this end, the SAR-MCU receives an interrupt from the radar every time the latter acquires a snapshot and then fetches the position data, tags it and stores it in the positioning file.
- PNT-MCU: the position, navigation and timing MCU logs the data from the PNT subsystem and then services requests for tracking data from the OBC, SAR-MCU, and ACS-MCU (which drives the antenna stablization system). This configuration allows the PNT-MCU to sample the high precision navigation unit at the maximum rate and then accommodate the different rates at which the various requests are made by each subsystem. The PNT system includes a GPS receiver as well as IMUs (inertial measurements units) comprising accelerometers and gyroscopes.
- ACS-MCU: In order to minimize the weight of the HAP, only the antenna arrays of the radar are stablized. The attitude control and stabilization MCU provides the interface to the stabilization subsystem. The ACS-MCU is present with the required relative pointing direction of the antennas with respect to the direction of motion of the platform. During the acquisition phase, the ACS-MCU will then use the PNT information that it receives from the PNT-MCU to calculate the absolution pointing direction which it will then relay to the controller of the stabilization subsystem.
- SEP-MECH: the separation mechanisms are included primarily to ensure the safety of the flight and control the risk of the mission. The OBC will continually monitor the flight parameters and verify that they are within the acceptable

mission envelope. Should the flight move outside this envelope, the separation mechanisms are activated to terminate the flight. Two independent mechanisms are included to provide redundancy. One of these mechanisms, SEP-MECH2, is an independent system that was mentioned in the previous section. The other, namely SEP-MECH1, is connected to the OBC and forms part of the HAP bus. In addition to the PNT system described above, multiple tracking subsystems, denoted as T1, T2 and T3 in Fig. 25.2, will be used ensure adequate tracking system redundancy at all stages of the flight.

– SEN-MCU: the sensor suite MCU provides the functionality for various HAP environmental sensors, such as temperature and pressure, and other flight information sensors, such as flight dynamics sensors, to be. These are logged by the SEN-MCU and stored on a dedicated SD card. The MCU can also be queried by the OBC if the relevant data is required.

In addition to the subsystems detailed above, the HAP provides environmental protection to the bus and payload. During the flight, the atmospheric temperature can drop as low as $-70°$ and the pressure decreases to approximately 1% of its value at ground level. Foam insulation, combined with the heat generated by the various subsystems, will ensure that the internal temperature of the HAP remains above $-20°$. Furthermore, thermal and vacuum testing will be employed prior to the flight to verify the system performance under the expected environmental conditions.

25.5 The SAR Payload

As the HAP is limited to around 20 kg in total weight, the project requires a miniaturized SAR system. The SAR system is restricted to a total of 10 kg, with the electronics weighing around 7 kg and the antennas 3 kg. Furthermore the SAR draws its power from the HAP, which then places a power consumption requirement on it. The limits on weight and power consumption are particular challenges for the SAR design.

25.5.1 Radar Front-End

The radar front-end is made up of a single board in standard ITX format (17×17 cm) that is stacked and interconnected according to the requirements to other boards (Embedded Digital processor and power supply subsystem) and an external power amplifier. The front end implements an X-band direct-conversion Linear-FMCW radar transceiver architecture. The transmitted waveform is generated by a PLL-based frequency synthesizer. This approach focuses on a compact, low cost and low power consumption solution that allows for the generation of large bandwidth and high chirp rate Linear-FMCW waveforms. The front-end mainly consists of the following sub-sections:

– Waveform generation and transmitter: this consists of a PLL based, X-band, programmable signal generator (phased detector, VCO and loop filter), a RF pre-amplifier, a splitter for the generation of the OL signal, a RF medium power amplifier (MPA) and a digital control interface. The generator is locked to the same low noise reference source that feeds the ADC stages, in order to perform coherent data processing.
– RF receiver: the receiver includes an input limiter, a RF band-pass filter, a low-noise amplifier and a quadrature demodulator. The demodulator is fed by OL signals generated by the aforementioned synthesizer.
– Base-band signal conditioning: down-converted signals are sent to a base-band signal conditioning stage that employs a programmable attenuator and an active band-pass filter. This allows to tune the overall gain and adapt the signal to the input dynamics of the AD converters.
– Power amplifier: the output of the transmitter section is sent to a solid state GaN based linear high power amplifier (HPA), with a maximum output power of 40 dBm.
– Power down-conversion subsystem: this is a multiple output down-conversion subsystem that employs mixed linear and switch-mode topologies in order to fulfill the power requirements of all the previous described sections. Such subsystem down-converts the voltage(s) provided from the HAP and converts them to the rails required by the various SAR subsystems.

The radar front-end specifications are summarized in Table 25.1, and picture of a test board of the radar front-end is shown Fig. 25.3a.

25.5.2 Power Amplifier

The power amplifier is a COTS device by Keylink Microwave. This model is a GaN based high power amplifier operating between 9.1 and 10.1 GHz and offers a wide dynamic Range with 10 W of output power. It has long term reliability and

Table 25.1 Radar front-end specifications

Parameter	Value
Waveform type	Linear-FMCW
Frequency range	9.3 to 9.9 GHz
Chirp rate	up to 1 THz/s
Output power	40 dBm (max)
TX attenuator	0−30 dB (1 dB step)
Minimum detectable signal	−130 dBm
Noise figure	6 dB
IF bandwidth	from 10 to 40 MHz
RX attenuators	0−40 dB (0.5 dB step)

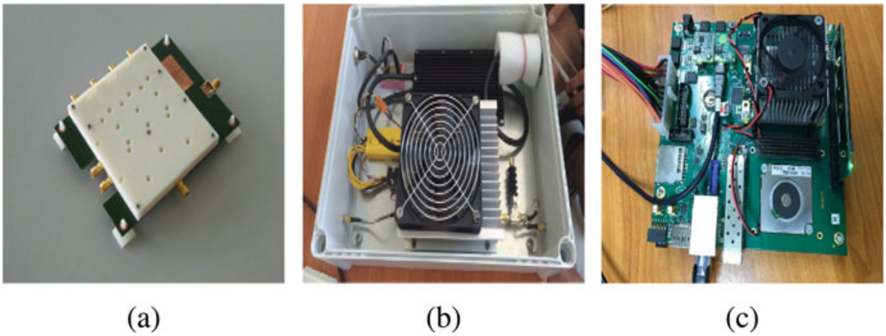

Fig. 25.3 SAR Payload – (**a**) front-end, (**b**) power amplifier, (**c**) embedded digital radar processor

high efficiency and it is ideal for X-Band linear applications. A picture of the same component used for another system is shown in Fig. 25.3b.

25.5.3 Embedded Digital Radar Processor

The Embedded Digital Radar Processor has been designed around the Trenz Electronic TEBF0808 carrier board which is a baseboard for the Xilinx Zynq Ultrascale+ MPSoC modules TE0808 and TE0803. A picture of the developed system is shown in Fig. 25.3c.

The main sub-systems are:

1. Carrier board
2. System on a Module
3. Acquisition board
4. Mass memory storage

25.6 Mission Support Systems

In order to enable the mission execution, a number of supporting subsystems are being developed. These include the flight prediction and planning, inflation and release system, and telemetry tracking and command system. These are described in what follows.

25.6.1 Flight Prediction and Planning

Flight prediction and mission planning are important aspects of the system. Given a launch location, date and time, the flight prediction software uses weather data to determine the expected flight trajectory. This allows the ground track as well as the landing site to be determined. Mission planning, however, can require that a number of waypoints be observed by the balloon. Therefore, when provided with these waypoints, the mission optimization software uses the mission planning program to iteratively determine the balloon inflation and flight parameters in order to give the optimal trajectory that is as close to the desired waypoints as possible.

25.6.2 Inflation and Release System

The balloon will have a pre-launch diameter of approximately 10 m and will display a large area to any light breeze. Therefore, it needs to be anchored to the ground and handled properly during inflation. This requires an inflation and release rig that is being developed as part of the project. The rig is modular to facilitate its transport to the launch site. It is also easy to set up and is able to provide measurement of the neck lift of the balloon to ensure the correct inflation is achieved.

25.6.3 Telemetry Tracking and Command System

Although the SAR data will be stored onboard the HAP and will not be downlinked to the ground during the flight, a TT&C system is being developed to continually track the HAP and monitor its state. The TT&C system, which operates at UHF in the amateur band, comprises a mobile ground station that will enable simple commands to be uplinked to the HAP and health check data to be received from it. Additionally, the TT&C system receives the position data from the HAP and updates the estimated flight path and landing position. This permits the mission to be monitored and decisions to be made on the termination of the flight if required.

25.7 Conclusions

This paper describes a novel balloon-borne synthetic aperture radar that is under development as part of a NATO funded project. The full system realisation is predicted to be completed by 2020 and results in terms of SAR imagery should appear soon after the system completion. The BALSAR system is intended to be low-cost and rapidly deployable in order to provide enhanced surveillance capability in hostile environments. Furthermore, the BALSAR system will find applications in remote sensing and monitoring applications, such as border protection and disaster monitoring.

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