

Characterization of the PAZ X band SAR Using the HITCHHIKER Ground Receiver

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Abstract—With the start of the Spanish PAZ system, another earth observation satellite has become available to the scientific community. Following the launch of the PAZ science phase, we performed a number of ground experiments using different modes of the satellites SAR instrument, measuring the transmitted radar signal as well as its ground reflections using the HITCHHIKER receiver. The data acquired in these experiments is analyzed and used in collaboration with the PAZ calibration team at INTA to characterize the PAZ instrument and thus verify the system calibration. Further we obtained bistatic radar images from the data of the HITCHHIKER ground receiver.

Index Terms—PAZ, calibration, bistatic SAR, passive SAR, HITCHHIKER.

I. INTRODUCTION

Since the beginning of the HITCHHIKER project in 2009, a number of bistatic spaceborne/stationary SAR experiments were conducted in cooperation with the TerraSAR-X/TanDEM-X satellites[1], [2]. Additional to the understanding of this bistatic SAR configuration and synchronization in bistatic SAR[3], [4], an extensive amount of information about the transmit chain the antenna and timing etc. of TerraSAR-X/TanDEM-X could be derived from the ground measurements of the transmit signal, using the reference channel of the HITCHHIKER receiver.

In February 2018 the PAZ satellite was launched using the Falcon 9 vehicle of SpaceX on behalf of the spanish MOD and the operator Hisdesat. The PAZ satellite was build by Airbus Defence and Space and is largely based on the TerraSAR-X/TanDEM-X satellite with only minor modifications. Like the TanDEM-X constellation, it can operate in Stripmap, ScanSAR, Sliding Spotlight and Staring Spotlight mode. Since the same operating bandwidth of 300 MHz at a center frequency of 9.65 GHz is used, the HITCHHIKER system is capable of acquiring signals from the PAZ system as well.

At the start of the PAZ science phase, the HITCHHIKER project received a grant under AO-001-010 to perform bistatic SAR acquisitions using PAZ as radar transmitter together with the HITCHHIKER ground receiver. In the course of the first experiments it was proposed to use the HITCHHIKER data to support the validation of the PAZ performance and calibration [5] in cooperation with the PAZ calibration team at INTA.

This paper describes the initial steps of this cooperation, the intended goals and results of the first experiments.

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A. The HITCHHIKER receiver system

Intended for use in bistatic radar experiments, the HITCHHIKER receiver provides four radar channels, each capable of coherently recording 500 MHz bandwidth in X band. For transmitter—receiver synchronization in bistatic operation, the first channel is used to acquire the transmit signal through an antenna directly pointed towards the transmitter platform hereafter referred to as the reference channel. The three remaining radar channels are used either also to record the transmit signal in a similar manner or to simultaneously acquire the reflected signals to create three images of the radar scene in different configurations and are then further denoted as radar imaging channels. Raw data acquired by the HITCHHIKER system is available to other research groups at <https://hitchhiker.zess.uni-siegen.de/request-data/>

II. INSTRUMENT MONITORING USING A GROUND RECEIVER

Continuous monitoring of the status and performance of the instrument is crucial while operating an Earth observation satellite. In order to validate the calibration and system performance, ground receivers have already proven their value during the TerraSAR-X mission [6]. In this paper, the authors will use the HITCHHIKER receiver system to capture the transmitted signals from the satellite and derive information about the azimuth antenna pattern and steering, the stability of the satellites ultra stable oscillator (USO), the along-track timing error and the transmitted waveform.

A. Azimuth Antenna Pattern and Surface Power Density

Since the receiver gain is calibrated, we are able to measure the surface power density at the position of the reference antennas. Using this measurement, we can obtain and verify the azimuth antenna pattern for various SAR acquisition modes. Fig. 1 shows the antenna setup used to acquire these patterns. Three antennas are therefore mounted on a triangular structure and pointed towards the satellite. The first reference channel is used to trigger the system polarized by 45° between the antennas used to record the horizontal and vertical polarization of the transmit signal.

B. Estimation of the USO Frequency

The PAZ RF system is synchronized by an ultra stable oscillator (USO) at a nominal frequency f_{USO} of 59 937 888 Hz. While maintaining coherence within the system, the USO itself is free-running, so its frequency is changing over lifetime and thermal state of the satellite.

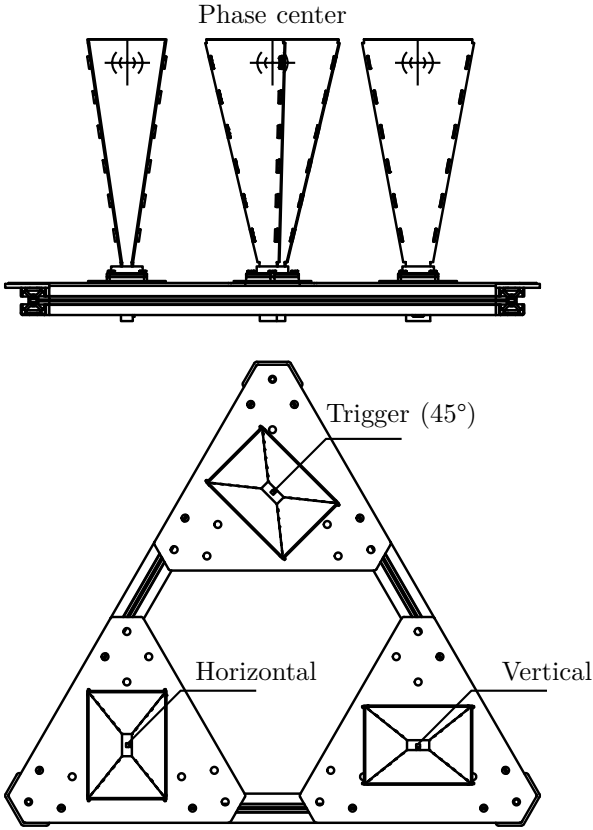


Fig. 1. Antenna setup to measure the transmit antenna pattern.

Measuring the carrier phase and the pulse repetition interval of the transmitted signal on the reference channels of the ground receiver, we can estimate the deviation from the commanded values after modeling and compensating the effects of the signal propagation. By knowing the dependencies of the respective intervals and frequencies from the USO frequency we are able to estimate the error of the USO itself. For this purpose the model of the oscillator/clock system we derived for TerraSAR-X/TanDEM-X is also used for the PAZ system. Using the receive timestamps of the transmit pulses the respective transmission time can accurately be estimated referenced to GPS time/UTC.

There are several sources of error affecting this measurement, starting with the oscillator used as reference in the receiver itself. To maintain long-term stability, the X band local oscillator in the HITCHHIKER system is attached to a Trimble Thunderbolt GPS disciplined oscillator (GPSDO). We could confirm the stability of the system testing the HITCHHIKER receiver using a X band CW transmitter locked to a second GPSDO unit, showing a combined frequency deviation of less than 10^{-11} for observation times $>10^{-2}$ s. The accuracy of the timestamps for the received signal is expected to be better than 50 ns with respect to GPS time.

In Order to compensate for the propagation delay/Doppler-effect, accurate knowledge of the positions of the antenna phase centers (APC) of the transmitter and receiver system are crucial. The transmitter position, determined given alongside the scientific orbit state vectors in the Level1b annotation

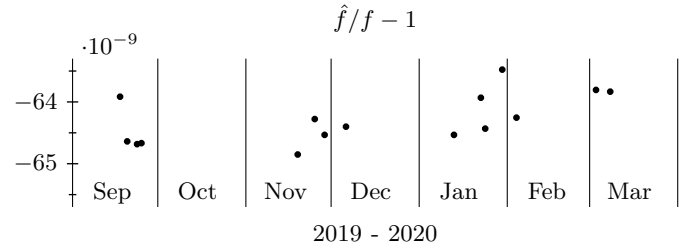


Fig. 2. Estimated frequency deviation of the USO on PAZ.

should result in an overall position accuracy better than 10 cm. Real-time kinematic (RTK) measurements in the german reference station network (SAPOS) are used to determine the position of the receivers APCs which then are transformed to the orbit reference frame. The processing of the position data is described in section III-B. The achieved accuracy is also expected to be within 10 cm. Tidal effects will result in a mainly vertical contribution of ± 30 cm at the receiver position. The sensitivity of the synchronization error with respect to the position error is maximum along the path of the satellite with a typical value of $30 \cdot 10^{-12} \text{ m}^{-1}$ to $50 \cdot 10^{-12} \text{ m}^{-1}$ for the orbit of PAZ.

Further effects [7] resulting from the gravitational potential (general relativity) and orbital velocity (special relativity) are a frequency shift of clocks on the PAZ satellite with a mean of $-268.6 \cdot 10^{-12}$ oscillating along the orbit with $\pm 1.6 \cdot 10^{-12}$. Although these effects are small compared to the observed frequency deviation of the USO, they should be within the sensitivity of the measurement. As we have given the position of transmitter and receiver in an earth-fixed coordinate frame (ECEF) that rotates with the Earth, we cannot assume constant speed of light, meaning that signals observed in this frame are not travelling at straight lines (cf. Sagnac effect). To solve this issue we can define a new coordinate frame coincident with the ECEF at the time of signal reception but not rotating with Earth and this inertial. This is realized by compensating the rotation of the ECEF within the time of flight of the signals. Although resulting in a range error of up to 1 m, the Sagnac effect has only minor influence on the measurement of the clock frequency of $5 \cdot 10^{-12}$ at the receivers position.

At X band frequencies, signal propagation is dominantly affected by the troposphere, mostly by slower propagation in the lower layers of the atmosphere. This results in a one-way range error of 2.5 m to 5 m, depending on the angle of incident. As the synthetic aperture describes only a small angle across the sky, the variation of this effect during the aperture time is small leading to an approximately linear error in the frequency estimation with a rate of $1.5 \cdot 10^{-12} \text{ s}^{-1}$ crossing zero at the time of maximum elevation.

We have estimated the frequency error of the USO from measurements during the experiments, which we have performed from September 2019 to March 2020. These experiments were using several modes, mostly high-resolution spotlight, partly dual-polarization. In Fig. 2 the estimated fractional frequency deviation is given for the USO of the SAR instrument on PAZ.

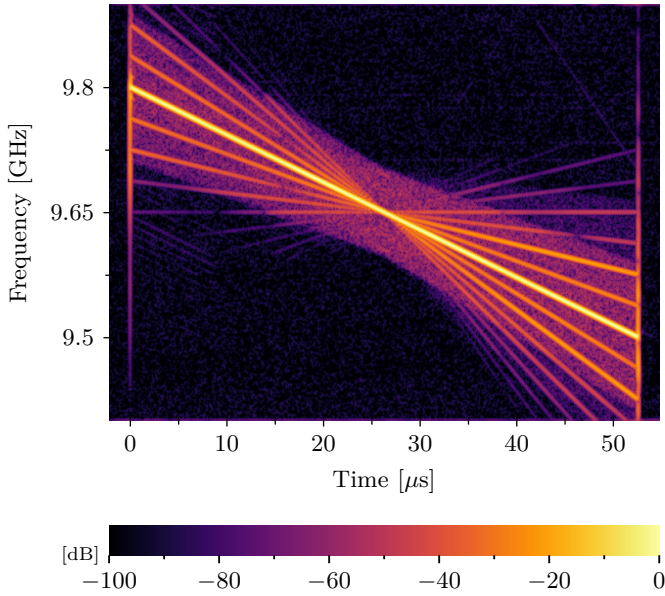


Fig. 3. Spectrogram of the PAZ pulse of a High Resolution Spotlight acquisition.

C. Acquisition of the Transmit Pulse Replica

The reference signal of the ground receiver can further be used to directly measure a replica of the transmit pulse. After estimation and removal of the channel response/doppler and under the assumption that the replica itself is stable, the measured signal might be summed over the measurement to increase the dynamic range of the replica.

Fig. 3 shows the replica of a 300 MHz downchirp pulse during a High-Resolution Spotlight acquisition. It shows consistent effects with the signal of TerraSAR-X and TanDEM-X [8] and is a crucial information needed for pulse compression of the radar return.

III. NOTES ON THE EXPERIMENTS

The HITCHHIKER receiver was mounted on the roof of our laboratory to be able to conduct a series of measurements. Three channels of the receiver systems were used to capture the direct path signal, whereas one channel was used to receive the radar scene response. The purpose of this setup is to measure the transmit signal on both polarizations. The three reference channels were arranged according to Fig. 1. To verify the position accuracy in the bistatic configuration, a radar transponder was placed in the scene.

A. Transponder and the bistatic image

The transponder was designed as an active reference reflector for bistatic experiments as trihedrals are not usable in this configuration. The system has a maximum electronic gain of 45.7 dB with an antenna gain of 19.2 dB at 9.65 GHz for transmit and receive antenna giving an equivalent radar cross section (RCS) of 43.2 dB(m²). The internal delay of 5.8 ns is resulting in an range offset of 1.75 m.

Fig. 4 shows the point spread function (PSF) of the transponder, which was placed at a distance of 4.3 km from the

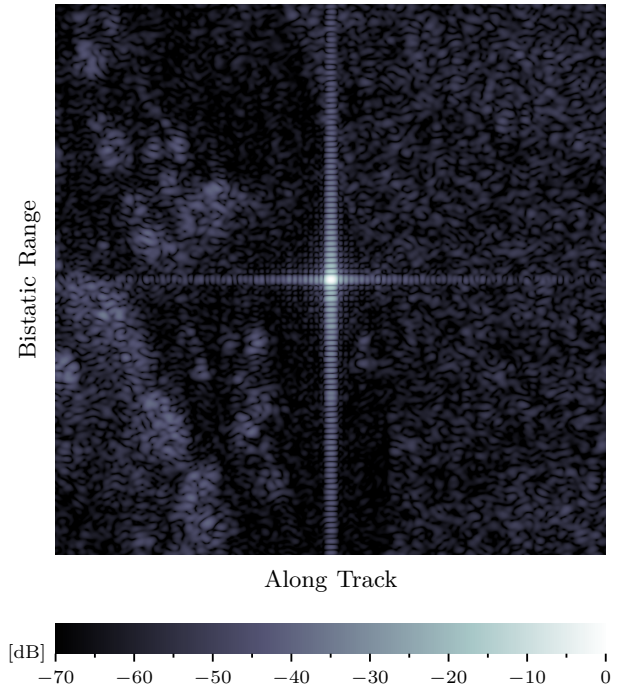


Fig. 4. Point spread function of the transponder in the bistatic measurement.

receiver. Its position was determined using RTK-GNSS. After compensation of the internal delay and the atmospheric delay, the accuracy of the transponder position was within 20 cm (range and cross-range) for this experiment. The tropospheric delay of 1.421 m for the path from the transponder to the receiver was determined using local meteorological measurements. The difference of the atmospheric delay for the path from transmitter to transponder to the path from transmitter to receiver with 5 mm is negligible.

The bistatic SAR imaging result of this experiment is shown in Fig. 5 in radar coordinates, which are the time of minimum bistatic range to a target and the corresponding bistatic range value at that time. The image is processed using the spatial domain algorithm proposed in [4] using a polynomial model to represent the position dependent range history of a target. The monostatic image acquired by PAZ is given for comparison.

B. Position measurement

Positions of the ground equipment like the antenna phase centers of the receive antennas and the transponder are determined using a GNSS receiver. The GNSS raw data is post-processed with RTK using data from a permanent site of the SAPOS network installed on a building of the University of Siegen. The resulting positions given in the ETRS89/DREF91 frame of the reference stations are further transformed to ITRS/ITRF2008 and ITRS/ITRF2014 for processing in combination with the orbit position of the satellite. The attitude of the reference channel setup was further verified optically, taking the bearing and measuring the elevation using an accelerometer.



PAZ satellite image ©Hisdesat Servicios Estratégicos S.A., 2019

Fig. 5. On the left: SAR image processed using the data from the HITCHHIKER imaging channel, given in bistatic radar coordinates. The horizontal dimension is along-track and the vertical bistatic range increasing from top to bottom. On the right side, the corresponding part of the monostatic image acquired by PAZ is given.

C. Surface power density

To measure the transmit pattern of the PAZ satellite, a long, dual polarized stripmap acquisition was commanded by the INTA CALVAL team while the signal was recorded on ground by the HITCHHIKER receiver in horizontal and vertical polarization. In Fig. 6 the received power during this experiment is given. The upper plot shows the estimate for the horizontal transmit antenna, the lower plot gives the vertical pattern. The received power is compensated for the receive antenna gain and the path loss, giving an estimate of the equivalent isotropic radiated power (EIRP) of the satellite. The power is given in dependency of the azimuth angle determined

by the acquisition geometry.

IV. CONCLUSION

We have presented first results from bistatic experiments using the PAZ satellite as transmitter and used a transponder to verify the geometric accuracy of the bistatic imaging.

Further the data recorded by the HITCHHIKER ground receiver during the bistatic experiments is used to validate the performance and the calibration of the spaceborne SAR instrument. This will be pursued in close cooperation with INTA CALVAL.

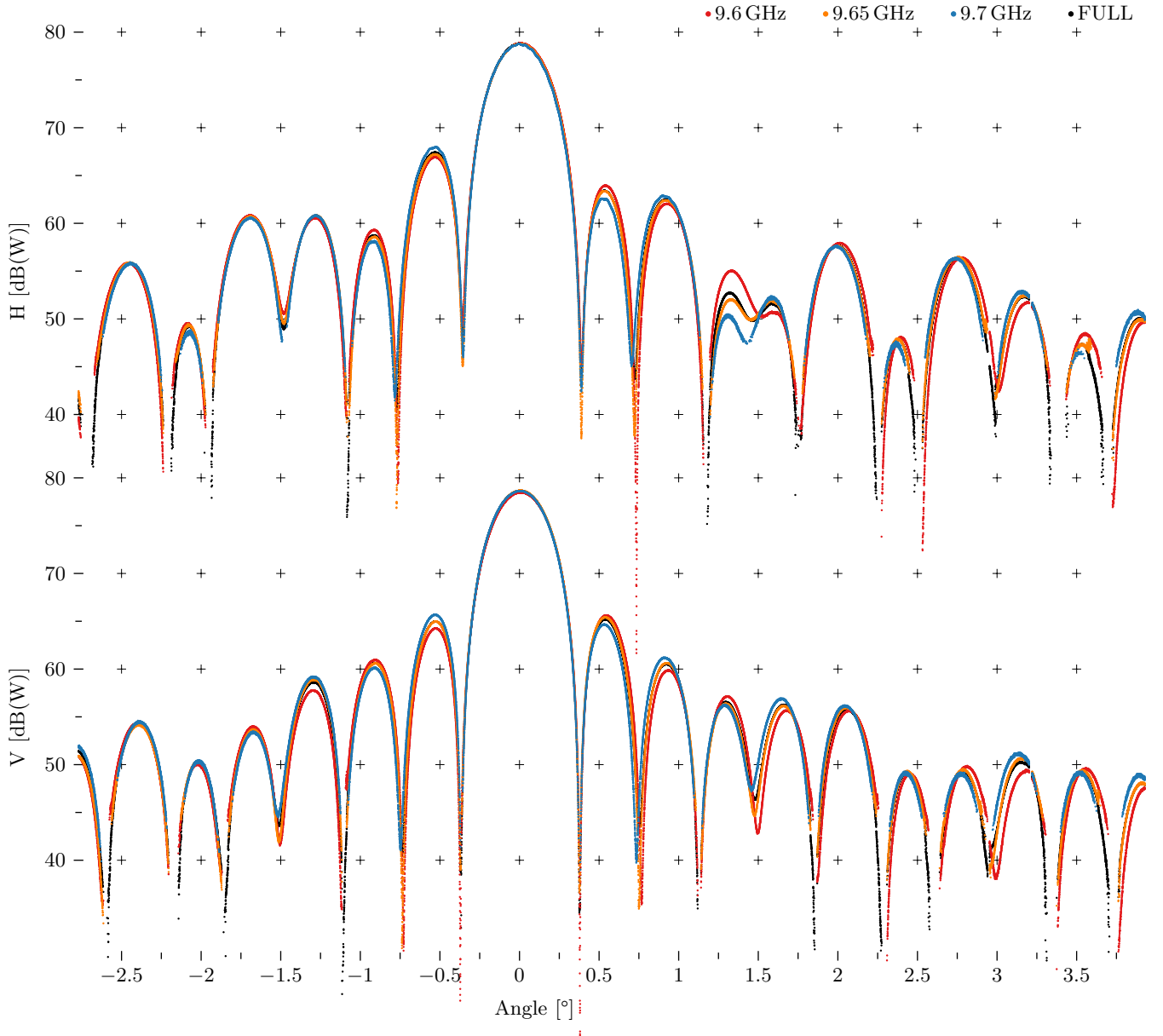


Fig. 6. Estimate of the signal power on the three reference channels, pointed towards the transmitter. The EIRP transmit power estimate is given for 50 MHz subbands at different frequencies as well as for the full bandwidth.

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