Ground-Based Array for Tomographic Imaging of the Tropical Forest in P-Band

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Abstract—In this paper we discuss the design concepts and preliminary results relating to the European Space Agency’s ground-based campaign TropiScat, whose main goal is to evaluate temporal coherence at P-band in a tropical forest in quadrupolarization, considering temporal lags ranging from hours to months and at different heights within the vegetation layer. The experiment has been successfully set up and operated since October 2011 at the Paracou field station, French Guiana, where the equipment was installed on top of the 55-m high Guaflux Tower to illuminate the forest below. The system consists of a vector network analyzer connected to 20 antennas through a switchbox, which allows the use of any of them either as a transmitter or as a receiver. Vertical imaging and fully polarimetric capabilities are achieved by operating the 20 antennas in a multistatic fashion, resulting in an equivalent monostatic array consisting of 15 phase centers displaced along the vertical direction in each polarization. Such a design allows unambiguous imaging of the vegetation while yielding a minimum distance between nearby antennas on the order of 0.8 m, so as to minimize coupling effects. The equipment allows the gathering of signals with the tomographic array within a few minutes, resulting in the possibility to produce a tomographic image of the forest with a temporal sampling of 15 min. System calibration and validation was performed by employing a 2-m trihedral reflector and a rotating dihedral reflector. This allowed the evaluation of the system pulse response in all polarizations and also assessment of the extent of tower motions. As a result, tomographic images have been generated from 500 (P-band) to 900 MHz in all polarizations. Results from real data acquired in Fall 2011 confirm the feasibility of carrying out reliable coherence measurements for the whole duration of the campaign.

Index Terms—Array design, BIOMASS mission, forest vertical structure, ground based radar, multistatic processing, P-band forest tomography, TropiScat tomography mode, virtual array.

I. INTRODUCTION

TROPICAL forest biomass plays a key role in the global carbon cycle and hence in the global climate [2]–[5].

Despite their importance, however, tropical forests remain poorly characterized compared to other ecosystems on the planet [6], [7]. A significant attempt to fill this gap is represented by the candidate Earth Explorer Core Mission, BIOMASS [8], [9]. The BIOMASS mission would employ the first spaceborne synthetic aperture radar (SAR) operated at P-band (435 MHz), thereby providing unprecedented capabilities for the investigation of densely forested areas. Four airborne campaigns have so far been carried out in the frame of phase-A BIOMASS activities [10]–[13], resulting in a number of studies on forest scattering and biomass retrieval at P-band [14]–[18]. Roughly speaking, these studies can be grouped in two classes, depending on whether the information from multiple passes is processed incoherently, involving intensity-based methods using amplitude and polarimetric signature [19]–[21], or coherently, involving techniques such as polarimetric SAR interferometry (PolInSAR) and SAR tomography (TomoSAR) [22]–[25]. Concerning tropical forest areas, the TropiSAR campaign was carried out in 2009 in the area of Paracou, French Guiana [12]. Data from this campaign have been analyzed by means of TomoSAR techniques in a number of recent studies, which showed that the forest vertical structure represents a key element to characterize scattering from a tropical forest and provides a more direct link to forest biomass than the intensity-based methods [18], [26]–[28]. Clearly, the availability of multiple passes is a necessary condition for TomoSAR, from which it follows that the replicability of the results above based on spaceborne data is strictly connected to the stability of forest scattering over time. The BIOMASS mission is planned to be operated in a tomographic phase with a revisit time of a few days during approximately the first 2 months of mission lifetime, after which the revisit time would be increased to between 17 and 27 days to allow single- or dual-baseline PolInSAR measurements [8]. Accordingly, evaluating the impact of temporal decorrelation in forested areas is a crucial issue [29]. Current figures have been derived from the campaigns BIOSAR 2007 and TropiSAR 2009, in which, at P-band, the temporal coherence was observed to stay high even after 20–30 days [10], [12]. These figures, however, do not fully account for the forest vertical structure. In other words, it is still not clear whether the observed coherence is due to the whole forest structure staying coherent, or rather to a single stable phase center within an environment that changes over time.

The TropiScat ground-based experiment has been planned to give an answer to this question, by investigating temporal coherence at short and long term in all polarizations and at
different heights within the vegetation layer. The experiment was chosen to be set up at the Paracou field station, which is the same site investigated during the TropiSAR campaign. The equipment was installed on top of the Guyaflux Tower (55 m), to radiate from 500 (P-band) to 900 MHz signals to the forest below. A preliminary test was carried out in October 2010 using a vector network analyzer (VNA) connected to two P-band antennas [30]. The vertical aperture for tomographic imaging was then formed by progressively moving downward the couple of antennas. The first successful test results provided input to the implementation of a stable configuration, which was designed to ensure the quality of the results of the experiments over a 1-year acquisition campaign. The aim of this paper reported in this paper is to: 1) illustrate the leading design concepts that made it possible to achieve vertical imaging capabilities; 2) discuss system calibration and validation; and 3) comment on the experiment capability to produce reliable coherence measurements at short and long temporal lags.

The rest of this paper is organized as follows. The TropiScat experiment is briefly introduced in Section II. In Section III, a mathematical model for the received signal is introduced and tomographic signal processing is described. The design of the tomographic array is illustrated in Section IV. Results from real data are presented in Section V. Section VI concluded this paper.

II. TropiScat Experiment Overview

The major objectives of the experiment are the temporal survey of the variation of the measurements in timescales ranging from daily, weekly, monthly, and up to 9 months of observation and possibly beyond [30]. The observables that have to be tracked are as follows:

1) the interferometric complex coherence in HH, VV, and HV, at a very short rate in the order of 15 min, covering daily and monthly scale;
2) intensity in all scales of time;
3) 2-D vertical imaging through tomographic focusing;
4) the vertical distribution of temporal coherence, as obtained by comparing tomographic data taken at different times, covering timescales of minutes, days, and months.

Complementary to electromagnetic scattering measurements, ancillary \textit{in situ} data are collected on the same area, which includes air temperature and humidity, rainfall, wind direction and speed, incident and reflected photosynthetic photon flux density, and atmospheric pressure.

A. Paracou Field Station

The 55-m-high Guyaflux Tower located at Paracou, French Guiana, [39] has been selected to support this experiment. The Paracou site is situated in a lowland tropical rain forest near Sinnamary, French Guiana. The forest in Paracou is classified as lowland moist forest with 140–200 species per ha, as specified in the forest census of all trees with diameter at breast height >10 cm. In 2003, the metallic tower was built in the westernmost part of the Guyaflux area in an existing natural 100 m² gap, thus with a minimum of disturbance to the upper canopy. This location was selected to cover a range of more than 1 km of undisturbed forest in the direction of the prevailing winds. The top of the tower is about 20 m higher than the overall canopy, and meteorological and eddy flux sensors were mounted 3 m above the tower. The distance from the base of the tower to the nearest trunks of the forest is about 7 m. The ground slope is close to 0° in the N–S directions and approximately 7–10° in the E–W directions. The radar instruments are set up within the only available space toward E–W directions. It is important to note that, due to sloping terrain, this setup results in the absence of scattering contributions from ground–trunk interactions [31], [32]. This constitutes a relevant difference with respect to the TropiSAR airborne dataset, which was observed to be characterized by relevant double–bounce scattering contributions on all flat areas [26].

B. System Architecture

The TropiScat architecture is depicted in Fig. 1. The main TropiScat hardware is composed of a VNA, a tropicalized industrial PC, a set of wide-band antennas, a radio frequency (RF) switching Box, and a command unit. The PC is programmed in such a way as to manage all instruments in a fully automatic fashion. The VNA and PC are situated in a shelter at the foot of the tower. The VNA is connected to the transmitting and receiving antennas with four 70-m low-loss cables. Losses in each cable are approximately 3 dB at 400 MHz and 5 dB at 1 GHz. The RF switch box allows RF signal to be routed between the VNA and the antennas. For measurements, each pair of antennas is automatically selected before starting RF acquisition as well as the calibration loop. Due to the long duration of the TropiScat experiment, an internal calibration of the VNA is made before every measurement.

C. Antennas

The TropiScat equipment comprises 20 wide-band antennas, four of which have been tested in field trial experiments in October 2010 [30]. In detail, the antennas are log-periodical antennas, useable from 400 to 1000 MHz (SATIMO LP
400 model). The radiation pattern is relatively similar in the horizontal (H) and elevation (E) planes, with a 3-dB aperture of $65^\circ$ in the H-plane, and $50^\circ$ in the E-plane. The polarization isolation is better than 20 dB, with very low sidelobes, and backward radiation less than $-23$ dB. Moreover, each antenna weighs about 1 kg and can be easily fixed to the Guyaflex Tower with different orientations.

D. Vector Network Analyzer

The radiated signals are generated by a stepped-frequency continuous-wave VNA (Agilent A5061B). The output power of the VNA is from $-45$ to $10$ dB. The VNA was operated with an intermediate frequency bandwidth of 10 kHz with 1601 frequency values, resulting in a final dynamic range of approximately 105 dB and a sweep time close to 1 s. As a result, the frequency resolution is 0.375 MHz. The unambiguous range is 400 m when covering the full bandwidth (i.e., 400–1000 MHz), and 1200 m when covering only 200 MHz bandwidth (i.e., 400–600 MHz). One convenient option is to cover separately the three bands 400–600 (Band 1), 600–800 (Band 2), and 800–1000 MHz (Band 3). So, Band 1 will correspond to P-band, whereas Band 3 will be close to L-band. The aggregation of the three frequency bands will be used to obtain ultrabandwidth data. For the 200 and 600 MHz bandwidth, the theoretical range resolutions are 0.75 and 0.25 m, respectively.

The fundamental requirement is that the frequency band has to cover the 432–438 MHz band of BIOMASS, providing input for the mission assessment. Therefore, the experiment was tailored to operate at P-band, which is the top priority. Yet, the possibility for it to work at higher frequencies is also very valuable.

III. MATHEMATICAL DATA MODEL

In this section we derive the mathematical data model for a signal at a received antenna from a transmitted antenna by using the general concept of diffraction tomography that is widely exploited in seismic processing [33].

A. Scattering Model

We consider a plane wave incident on an object in a homogeneous infinite medium. Suppose the receiver is far from the object so that the scattered wave from the object can be treated as a plane wave at the receiving point. Considering scattering from stationary targets, we derive the signal model at a receiver from a waveform transmitted by an antenna.

For further simplification, we consider the case of the wave equation with constant density. The object is described by the velocity distribution $C(r)$, where $r$ is the position vector. The host medium has a velocity $c_0$, which is the speed of light in vacuum. In the time domain, the scalar wave equation in the source-free region is [33]

$$
\nabla^2 \epsilon^{tot}(t, r) + \frac{\omega^2}{c^2(r)} \epsilon^{tot}(t, r) = 0
$$

where $\epsilon^{tot}(t, r)$ is the scalar quantity of the field such as the total electric field, $\omega$ is the angular frequency, and $\nabla^2$ is the Laplacian operator.

When a scatterer is present, the wave speed is no longer constant and it will change when the wave interacts with the object. We may refer to this as a perturbation in the wave speed. We have

$$
S(r) = 1 - \frac{c_0^2}{c^2(r)}
$$

where $S(r)$ is known as the reflectivity function or the object function.

Substituting $C(r)$ into (1) results in the following expression:

$$
\nabla^2 \epsilon^{tot}(t, r) + k^2 \epsilon^{tot}(t, r) = k^2 S(r) \epsilon^{tot}(t, r)
$$

where $k = \omega/c_0$ is the wavenumber of the field in the host medium. Let

$$
\epsilon^{tot} = \epsilon^{in} + \epsilon^{sc}
$$

where $\epsilon^{in}$ and $\epsilon^{sc}$ are the incident and scattered field, respectively. Substituting in (3), we have

$$
\nabla^2 \epsilon^{sc}(t, r) + k^2 \epsilon^{sc}(t, r) = k^2 S(r) \epsilon^{tot}(t, r).
$$

By using the free-space Green’s function $g(t, r)$ solution [34], we obtain $\epsilon^{sc}(t, r)$ from (5) as

$$
\epsilon^{sc}(t, r) = -\int \int g(t-t’, r-r’)k^2 S(r’) \epsilon^{tot}(t’, r’) d\tau d\tau’
$$

where

$$
g(t, r) = \frac{\delta(t-|r|/c_0)}{4\pi |r|}.
$$

In the frequency domain, the equation corresponding to (7) is

$$
G(\omega, r) = \frac{\exp(jk|r|)}{4\pi |r|}.
$$

Assuming that the object is a weak inhomogeneity, the Born approximation ($\epsilon^{tot} \simeq \epsilon^{in}$) applies [35] and (6) becomes

$$
\epsilon^{sc}(t, r) \simeq \epsilon B(t, r) = -\int \int g(t-t’, r-r’)k^2 S(r’) \times \epsilon^{in}(t’, r’) d\tau d\tau’.
$$

Taking the Fourier transform of (9), we obtain the frequency domain

$$
E_B(\omega, r) = -\int \int \epsilon B(\omega, |r-r’|) \omega^2 S(r’) E^{in}(\omega, r’) d\tau’.
$$

Assuming that the incident wave is a plane wave with a waveform transmitted by an antenna at a location $r^{Tx}$, we have [34]

$$
E^{in}(\omega, r’) \simeq \frac{\exp(jk|r’-r^{Tx}|)}{4\pi |r’-r^{Tx}|} F_{pat}(k, r’-r^{Tx})
$$

where $F_{pat}$ is the scalar analog of the radiation vector, representing the antenna beam patterns and transmitted waveform and $r’-r^{Tx}$ is the unit vector in the direction of $r’-r^{Tx}$.
B. Received Signal Model

To obtain the expression for the data received at location \( r_{Rx} \), we substitute (8) and (11) into (10) and include a second factor corresponding to the radiation vector of receiver. Then we get

\[
Y(\omega, r^T, r_{Rx}) = \int \exp(jk(|r^T - r'| + |r_{Rx} - r'|)) \times A(r^T, r_{Rx}, r', \omega) S(r')d'r'
\]

where

\[
A(r^T, r_{Rx}, r', \omega) = \frac{\omega^2 F_{pat}(k, r - r^T) F_{pat}(k, r - r_{Rx})}{(4\pi)^2 |r^T - r'| |r_{Rx} - r'|}
\]

incorporates the geometrical spreading factors, transmitted waveform, and antenna beam patterns.

Finally, in the time domain we have

\[
y(t, r^T, r_{Rx}) = \int \exp(-j\omega(t - R_c/c_0)) A(r^T, r_{Rx}, r', \omega) \times S(r')d'r'
\]

where

\[
R_c = |r^T - r'| + |r_{Rx} - r'|
\]

is the bistatic distance of the transmitter–receiver pair at target position \( r' \). \( S \) can be determined from the data \( y \) by a focusing procedure.

C. Tomographic Coherent Focusing

To form the image at a certain point in the spatial domain, we aim to invert (14) by applying an imaging backprojection operator to the collected data. The imaging operator takes the form

\[
I(p) = \sum_{n=1}^{N} \int \exp(j\omega(t - R^N_p/c_0)) y(t, r^T_n, r_{Rx}^N) dt
\]

where \( y(t, r^T_n, r_{Rx}^N) \) is the data of the transmitter–receiver pair \( n \), \( N \) is the total number of transmitter–receiver pairs, \( p \) represents a certain point in the (or slant) range and height plane, and

\[
R^N_p = |r^T_n - p| + |r_{Rx}^N - p|
\]

is the bistatic distance of the transmitter–receiver pair \( n \) at target position \( p \).

We can carry out the \( t \) integration in (16) to obtain

\[
I(p) = \sum_{n=1}^{N} y(t_n, r^T_n, r_{Rx}^N)
\]

where \( t_n = R^N_p/c_0 \) is the bistatic time delay of the transmitter–receiver pair \( n \) at the target position \( p \).

The target \( I(p) \) is then focused by superposition of all the backprojected data from all transmitter–receiver pairs.

Such a focusing approach provides resolution capabilities consistent with the well-known Rayleigh limit [24], [36]. Another approach would be to resort to super-resolution algorithms such as MUSIC, CAPON filtering, RELAX, or even compressive sensing algorithms [36]–[38]. Such algorithms, however, are mostly suited for the problem of detecting and localizing a collection of a few point targets, whereas they could easily produce processing artifacts while imaging distributed media.

IV. TropiScat Tomographic Array Design

The system is intended to accomplish three requirements as follows.

Requirement 1: Provide fully polarimetric vertical resolution capabilities, while ensuring unambiguous imaging of the whole vegetation layer.

Requirement 2: Gather data continuously for about a year with a conveniently short time, so as to study both the short-term temporal coherence and its seasonal variations.

Requirement 3: Provide a sufficient number of looks to allow reliable coherence evaluation at every fixed height by averaging independent and homogeneous samples.

It follows from Requirement 1 that the system needs to have sufficient aperture along the vertical direction. On the other hand, the antennas have to be closely spaced along the vertical direction to ensure unambiguous imaging. Requirement 2 entails that the system is capable of acquiring data of the same scene for an extended period. Requirement 3 can be fulfilled by using a large bandwidth system\(^1\) and/or by exploiting time averages. As an alternative, Requirement 3 could also be fulfilled by forming a further aperture along the azimuth direction. This option, however, would entail the use of a very large number of antennas or the capability to move the array horizontally, and hence it has been discarded. Finally, the system has to be able to operate at wavelengths compatible with those commonly used for investigations of vegetated scenarios through spaceborne SARs, namely P-band and L-band. However, studying temporal decorrelation at P-band seems to be the most urgent task to be accomplished nowadays, in order to provide input for the quantitative assessment of TomoSAR and PolInSAR results achievable through the exploitation of multipass BIOMASS surveys on tropical forests.

The following constraints have been established.

Constraint 1: 20 antennas have to be employed.

Constraint 2: Each antenna has to be operated either as a transmitter or as a receiver.

Constraint 3: The physical separation between any two antennas has to be equal or larger than 0.8 m.

Constraint 1 is intended to limit the experiment costs. Constraint 2 allows simplifying system installation and improving the overall signal-to-noise ratio by operating a simpler RF switchbox. Constraint 3 has been established in order to minimize electromagnetic coupling effects due to the interaction among different antennas. The value of 0.8 m has been deemed to be a sufficiently safe distance to operate the equipment correctly, as concluded from field trial experiments in October 2010 [30].

\(^1\)At 200-MHz bandwidth, at every fixed height, we expect the number of looks to be greater than 25 if we exploit a window which is 20 m in range.
A. Tomographic Array Design

To satisfy the requirements and constraints above, we considered a multistatic array configuration that was obtained by placing a transmitting and receiving antenna pair in such positions as to illuminate, at least theoretically, the same wavenumbers of the investigated object as a single monostatic (i.e., transmitting and receiving) antenna placed in the middle. In the remainder of this paper, we will refer to such an equivalent monostatic array as a virtual array. The leading concept in the design of the virtual array is to achieve the same imaging performance as a vertical array constituted by closely spaced antennas, even though the physical separation is actually consistent with Constraint 3.

The concept of virtual array greatly facilitates system design, as it allows us to derive the position of each virtual antenna by controlling the vertical resolution and height of ambiguity. Let $\Delta z$ be the vertical spacing between two nearby virtual positions, and $A_z = (N - 1)\Delta z$ be the overall vertical extent of the virtual array. Then, vertical resolution and height of ambiguity can be approximated as

$$\rho_z = \frac{\lambda}{2A_z} R$$  \hspace{1cm} (19)

$$z_{amb} = \frac{\lambda}{2\Delta z} R$$  \hspace{1cm} (20)

where $\rho_z$ is the vertical resolution, $z_{amb}$ is the height of ambiguity, $\lambda$ is the carrier wavelength, and $R$ is the distance from the antenna to the target. System design can then be carried out by finding a particular multistatic configuration that gives rise to a virtual array whose vertical spacing $\Delta z$ and vertical extent $A_z$ provide: 1) a height of ambiguity significantly higher than the forest height, and 2) a vertical resolution significantly lower than the forest height.

We remark that the concept of virtual array is employed for system design only, whereas the focusing processor was implemented by fully taking into account the multistatic nature of the array.

The best solution among those we considered encompasses one vertical array of five antennas for each polarization (i.e., horizontal or vertical) and for each operating mode (i.e., transmit or receive). This simplifies not only the switch boxes but also the system operation. This design has been optimized for a central frequency of 500 MHz. However, the system is expected to provide imaging capabilities at 700 and 900 MHz, so as to cover all cases to be investigated within TropiScat. The system main dimensions are summarized as follows: 1) overall horizontal extent: $< 2.5$ m; 2) overall vertical extent: $< 4.5$ m; and 3) minimum distance between antennas: 0.8 m. The physical antenna positions are shown in Fig. 2, whereas Fig. 3 reports the physical and virtual antenna positions for each polarization. Each virtual array is formed by $N = 15$ positions, corresponding to 15 transmitting and receiving antenna pairs. The virtual arrays for HH and VV are found at the same positions, whereas the virtual arrays for
△ In particular, the resulting virtual array aperture and spacing ensures the same imaging properties in all four polarizations. The position of each virtual antenna is independent, given the wide aperture of the antenna lobe in the horizontal plane. The horizontal and vertical components are, respectively, \( \Delta z = 0.2 \) m; \( A_z = (N-1)\Delta z = 2.8 \) m. This configuration translates into a vertical resolution at \( R = 70 \) m equal to \( \rho_z = 7.5 \) m at 500 MHz; 5.3 m at 700 MHz; and 4.1 m at 900 MHz. The height of ambiguity turns out to be higher than 40 m for \( R > 50 \) m even at 900 MHz.

**B. Numerical Simulations**

Detailed information about the tomographic imaging performance is displayed in Figs. 4 and 5. All panels have been obtained by simulating the presence of random scatterers on the tower and at the ground layer. Scattering from the forest has intentionally not being included, so as to allow evaluation of ambiguous contributions within the vegetation layer. The ground terrain is flat, resulting in no targets appearing at negative height values. The same bandwidth of 50 MHz is used for three different center frequencies, i.e., 500, 700, and 900 MHz. We considered four scenarios, one corresponding to the case of isotropic antennas and the others to the cases of directional antennas pointing at a look angles \( \theta = 30^\circ, 40^\circ, \) and 50\(^\circ\). The latter three cases were simulated using the radiation pattern of antenna LP SATIMO 400.

Some artifacts are visible that are linked to terrain and ground scattering, especially in the isotropic antenna case. Such artifacts are linked to system ambiguity, due to the fact that the vertical spacing between nearby virtual antennas is larger than a quarter of the wavelength. However, ambiguities are set at locations higher than forest height, so that the corresponding responses can be automatically discarded. The situation is clearly improved by accounting for the elevation antenna pattern. The best imaging quality is found, as expected, at 500 MHz. At 900 MHz, spurious contributions appear, which might partly jeopardize the overall imaging quality at near ranges.

The latter three cases were simulated using the radiation pattern of antenna LP SATIMO 400.

**C. Bistatic Effects**

No artifacts are expected to arise from bistatic effects as long as signal focusing is concerned, since the focusing processor explicitly takes into account the multistatic nature of the antenna array. On the other hand, bistatic effects could be relevant in presence of a strong anisotropic behavior of particular targets within the forest volume. It has to be kept in mind, however, that the TropiScat system has no azimuth resolution, meaning that vertical profiles are relative to an average over an azimuth angular sector. It seems reasonable to assume that this angular average makes anisotropy phenomena negligible. Finally, bistatic effects are expected to result in an azimuth-dependent intensity imbalance between different polarizations, due to the fact that transmission and reception antennas are placed at different physical positions. This effect is, however, a systematic bias, which does not impact on the temporal variation of forest scattering as sensed by the TropiScat tomographic system.

**V. Experimental Results**

The TropiScat tomographic mode was implemented in October 2011, by installing the 20 antennas on top of the Guyaflux Tower, see Fig. 6. The temporal sampling for tomographic imaging at P-band is 15 min (96 samples per day), thus allowing this paper of both the short-term and long-term temporal coherence variations within the forest.

The format for the acquisition name assumed in this section is the following: Year–Month (1–12)–Day (1–31) acquisition time (H-min) frequency band (1, 2, 3), polarization (HH, HV, VH, VV).
Fig. 7. Tomographic system pulse response for the trihedral reflector at 500 MHz HH and VV. Top panels are HH and bottom VV. Left panel: With trihedral corner. Middle panel: Without trihedral corner. Right panel: Difference. Data is at Y2011-M10-D09 10H30. The units used are in dB.

Fig. 8. Radiation pattern of antenna LP SATIMO 400 for 0.7 m for H and V planes. 3

A. System Pulse Response

The tomographic responses of a 2-m trihedral and a (rotated) dihedral reflector were derived by taking the difference between the signals acquired with and without the reflectors, so as to remove forest contributions through coherent cancellation. The pulse responses for the trihedral reflector at 500 MHz of HH and VV polarizations are reported in Fig. 7. The trihedral reflector is seen to be very well visible in HH. It is visible in VV polarization as well, even though signal intensity is about 10 dB lower than in HH. In cross-pol HV and VH (not shown here), the trihedral reflector is only partially visible. Instead, the pulse response for cross-pol is well recovered by exploiting the rotated dihedral reflector, for which the signal intensity is observed to be significantly higher than uncompensated forest contributions, see Fig. 9.

3Antenna radiation patterns have been measured in the Compact Antenna Range Test facility in CNES.

4Since the trihedral has to be located very close to the tower, antennas gains are different in HH and VV and it is responsible for a difference of about 6 dB. However, this will not affect to this paper of temporal decorrelation and radiometric stability.

B. System Stability

Tower stability is a fundamental parameter to achieve the aim of this experiment, as unwanted oscillations of the antenna equipment on top of the Guayfluix Tower could be confused with motions within the vegetation layer. The stability analysis reported hereafter is based on data collected in October 2011, when the corner reflector in front of the Guayfluix Tower was available. The area surrounding the tower is not very windy (wind speed < 5 m/s). However, the wind pressure can generate small oscillating movements of the tower top. The amplitude of such movements was roughly estimated to be less than ± 5 cm at worse with a temporal frequency of about 0.5 Hz. Another possible source of errors is represented by changes in the electromagnetic response of the equipment, for example, due to rainfall events.

To assess system stability on an experimental basis, we considered the time series obtained by taking the pixels in the focused tomograms corresponding to the three targets. These are the tomographic array itself, the trihedral corner on the ground (H = 1 m, R = 61 m), and a point within the forest canopy (H = 30 m, R = 85 m). The analysis is carried out based on P-band data, as they provide the finest temporal sampling. Fig. 10 shows the intensity and apparent line-of-sight
LOS displacement has been obtained as starting from midnight Y2011-M10-D07 00H00. The apparent (LOS) displacement for the three considered targets over 35 h,

\[ \text{Intensity} \]  
\[ \text{Time lag [h]} \]  
\[ \text{Displacement VV} \]

\[ \text{dr} \]

5Intensity is normalized by dividing it by the value observed at start-time, so as to appreciate only the variation over time. This is done independently for each polarization and target of interest (array, corner, and forest).

6Due to absence of azimuth discrimination, some forest contribution stays present in the corner reflector response, and also some coupling with foliage. It might be considered also that the forest motion may induce some small movement of the corner through motion of soil and trunks, but this is a second order effect.

The impact of rainfall is even better observed by considering the change of the interferometric phase over time, as shown in Fig. 12.

The fact is that the phase is modified by rain both at the corner and at the array indicates that rainfall affects the electromagnetic response of the equipment. Accordingly, data acquired during rainfalls should be neglected in evaluating the temporal behavior of the forest, unless actions are taken to compensate for this phenomenon.

Excluding the rainfall event, in Figs. 10 and 13, three different phase behaviors are observed concerning the time series associated with the corner and the array:

1) from 4:00 to 6:00, there are two phase peaks both at the corner and at the array. The observed trend is about 2 mm in LOS motion, but no oscillations are observed;  
2) from 9:00 to 16:00, the corner phase is observed to have a trend of about 8 mm plus a number of phase oscillations (< ±1 mm).\(^6\) No relevant change is observed concerning the array phase;  
3) during most night hours, from dusk to dawn, the phase histories at both the array and the corner exhibit excellent stability.

Concerning the motion of the antenna array under the action of the wind, two effects are expected. The first is a rigid translation due to a slight leaning of the tower top under the effect of a constant wind. This motion has no effect on the quality of tomographic imaging, as it would just result in a very slight image translation. The other effect is associated with random horizontal oscillations due to varying wind speed. This kind of motion can potentially degrade image quality due to the fact that tomographic focusing is carried out by processing data acquired by 15 different antenna pairs, the time duration for the entire acquisition being about 30 s. Assuming that the observed oscillations of the corner phase history are entirely due to horizontal motions of the tower, the standard deviation of the latter can be upper-bounded as

\[ \sigma_s = \frac{\sigma_r}{\sin(\theta)} \sqrt{15} \]  

(21)

where \(\sigma_r\) is the standard deviation of LOS motion, \(\theta\) is the incidence angle at the corner position, and the factor \(\sqrt{15}\) accounts for the fact that 15 antenna pairs are used in the tomographic focusing in the late afternoon or at night. As a result, a peak value on the order of 4 cm is found during daytime, when the wind speed is at its maximum (5 m/s), whereas the average value during nighttime is less than 1 cm.

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**Fig. 11.** Weather in situ data corresponding to the measurements. (a) Rainfall. (b) Wind speed. (c) Temperature.

**Fig. 12.** Interferometric phase over time. Right bottom panel: After big rain; the phase is totally disturbed. The units used are in radians.

**Fig. 13.** Zoomed version of Fig. 10. (a) Intensity HH. (b) Intensity VV. (c) Displacement HH. (d) Displacement VV. Two intensity panels have been normalized in such a way that the intensity of the initial time is 0 dB.
To demonstrate that such a motion does not jeopardize the image quality, we simulated the effect of random motion errors about the sensor positions on data focusing. To do this, we consider a real HH data acquired at midnight (Y2011-M12-D15 00H00) and produce two synthetic raw data by injecting a Gaussian random displacement with zero mean and standard deviation equal to 2.5 and 5 cm, respectively. The raw data are then focused in all cases, assuming that the tower is perfectly still. Single-realization imaging results under perturbed conditions are presented in Fig. 14.

It is important to observe that image quality is fully preserved even in the worst case scenario where the tower moves randomly by 5 cm. As discussed above, this value was derived by assuming that the observed corner phase variations are entirely due to tower motions, therefore providing a worst case scenario upper bound for tower motions. It is also worth noting that in the rare case of such a strong wind so as to induce very large tower motions (>5 cm), the forest would be heavily shaken too, unavoidably giving rise to relevant temporal decorrelation phenomena. Based on this analysis, we then conclude that the defocusing phenomena observed during daytime (see Section V-E) can be safely imputed to forest motion under the action of wind. Moreover, the excellent tower stability during night hours confirms the feasibility of yielding accurate measurements of the forest temporal decorrelation, with the one precaution, i.e., to exclude rainfalls from the analysis.

C. Multipolarization Tomograms

P-band tomograms for all polarimetric channels are shown in Fig. 15. It should be noted that the terrain slopes down on moving away from the tower, which is why targets appear at negative height values. The white line denotes the scene average topography, as obtained from in situ measurements.

Up to about 50–70 m away from the tower, the tomographic imaging shows scattering from the ground and from about 30 m above, which clearly reveals the structure of the vegetation in that area. It is interesting to note a substantial gap between the top and the bottom of the scattering layers, which suggests that the densest canopy layer is on top.

Accordingly, the near range area (i.e., up to 120 m away from the array) is certainly the most interesting for present and future analysis. In this area, vertical resolution is on the order of 6–12 m, which allows us to separate different vertical layers within the forest volume. On the contrary, physical interpretation becomes uncertain at far ranges, as vertical resolution gets worse with range. Furthermore, in the near-range area the incidence angle varies from 20’ to 60’, allowing us to combine and investigate the temporal backscatter of airborne or spaceborne P-band SAR data.

D. Multifrequency Tomograms

Fig. 16 reports multifrequency tomograms at VV and also the exploitation of the ultrabandwidth from 400 to 1000 MHz. The best imaging quality is expected at 500 MHz. As expected, at higher frequencies, volume contributions are dominant even at near range due to reduced wave penetration. The best vertical resolution is achieved at 900 MHz due to the shortest wavelength.

The ultrabandwidth tomogram (see the right bottom panel in Fig. 16), is observed to produce the highest range resolution thanks to the 600-MHz bandwidth, showing that the different bands are properly combined.

E. Multitemporal tomograms

Fig. 17 reports a few snapshots from the tomographic movie obtained over time at P-band. In this case, each panel has been generated in slant range–height coordinates, and
flattened so as to bring the terrain level to 0 m, in order to help visualization and interpretation of the results. As can be seen, acquisitions collected during daytime are often characterized by a lower intensity compared to night hours. This phenomenon has been observed to be associated with wind speed, which reaches its peak during day hours and also with rain events, as shown in Fig. 18. Accordingly, the observed intensity drop can be interpreted as being the result of defocusing phenomena arising from the fact that the 15 antenna pairs are operated at different times, hindering coherent integration. As shown in Section V-B, the impact of eventual tower motions is not enough to justify this phenomenon, after which we conclude that it is due to the motion of the forest under the action of wind.

VI. CONCLUSION

In this paper we discussed the design and performance of the 20-element multistatic array employed in the TropiScat campaign, whose main aim is to produce reliable information about temporal coherence in tropical forests at P-band, considering time lags ranging from hours to months. The multistatic array has been designed so as to form an equivalent monostatic array consisting of 15 closely spaced phase centers, which enables unambiguous imaging of the forest volume while yielding a sufficiently large distance between nearby antennas to minimize coupling effects. Nevertheless, the implemented focusing algorithm fully takes into account the multistatic nature of the array. The TropiScat tomographic mode was implemented in October 2011 by installing the designed array on the top of the Guyaflux Tower at the Paracou field station, French Guyana.

The analysis so far focused on instrument calibration and validation. Image quality was checked by using a trihedral and a rotated dihedral reflector, which allowed us to observe that the system pulse response was consistent with the design at all polarizations. Tower and system stability has been discussed based on time series collected over 35 h with a temporal sampling of 15 m, taking advantage of the presence of a trihedral reflector deployed in proximity of the tower. The extent of tower motions under the action of wind was upper-bounded by assuming that the observed variations of the corner phase were entirely due to tower motions. Even in this worst case scenario, tower motions were found to be less than 5 cm, in cases where the wind speed approached 5 m/s. Tower motions of such an extent have been shown, through simulations, not to affect image quality in any noticeable way at P-band. During night and early morning hours, the system was observed to exhibit excellent stability, confirming the feasibility of yielding accurate measurements of the forest temporal decorrelation. On the other hand, rainfall events have been observed to affect the electromagnetic response of the equipment. Accordingly, data acquired during rainfall should be disregarded in evaluating the temporal behavior of the forest, unless actions are taken to compensate for this phenomenon. The motion of the forest induced by gusts of wind during the time required for each tomographic acquisition (about 4 min) has been observed to result in defocused images. Such a phenomenon has been observed to occur mainly during daytime, whereas night acquisitions appear to be much more stable. Although this conclusion is to be confirmed through long-term analyses, it already appears to provide very useful input concerning the BIOMASS mission, as it suggests that performance over tropical forest could be optimized by gathering acquisitions at dawn or dusk time. Ongoing research
is focused on a methodical investigation of the data acquired over the whole duration of the experiment, in order to analyze forest temporal coherence at short and long time lags as well as its seasonal variations, and to provide physical interpretations of the observed phenomena.

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REFERENCES


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