Thermal Effects on a 4.2 m Center-Fed Cassegrain Antenna Strut in the Alphasat Ka- and Q/V-band Aldo Paraboni Propagation Measurements

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***Abstract*— Large gateways of future satellite communications (Satcom) systems will likely operate at Q-/V-band frequencies (40-50 GHz) to take advantage of the larger available bandwidth. On the other hand, Q-/V-band Satcom systems suffer from highly variable propagation losses, which must be accurately assessed and modelled. The Alphasat Aldo Paraboni Propagation experiment, conceived and realized by the Italian Space Agency (ASI), has been running since 2014 to investigate carefully the propagation effects in the Ka and Q bands and, thus, to support the design of high throughput systems and propagation impairment mitigation techniques. In the framework of this experiment, ASI deployed two large ground terminals (Cassegrain antenna with 4.2 m diameter) in Tito Scalo (South of Italy) and Spino d'Adda (North of Italy). This contribution investigates the effect of antenna strut elongation on propagation measurements, which causes an additional reduction of 1-2 dB in the received signal during sunny days.**

***Index Terms*— Atmospheric propagation, Propagation measurements, Satellite antennas, Satellite communications**

I. Introduction

Large gateways of future satellite communications (Satcom) systems will likely operate at Q-/V-band frequencies (40-50 GHz) in order to guarantee the large bandwidth required to accommodate advanced high data-rate broadcast and multimedia services. This will make Satcom systems even more competitive to terrestrial networks, with the further advantage of reaching a wider pool of users without the need of additional cabling. The price to pay for the use of carrier frequencies in the Q/V bands is a significant increase in atmospheric impairments [1]. This implies the need of a reliable system design and an extensive use of Propagation Impairments Mitigation Techniques, such as Link Power Control, site diversity, or onboard adaptive power allocation [2], together with adaptive coding and modulation [3] and data rate adaptation [4]. As a result, the accurate assessment of all atmospheric propagation impairments becomes more and more crucial when frequency increases. These include effects, like those due to gases and clouds, that are almost negligible or with limited impact at lower bands (e.g. Ku and Ka).

In this framework, the Aldo Paraboni propagation payload [5], [6], aboard the Alphasat satellite, has been conceived and supported by the Italian Space Agency (ASI) with two continuous-wave (CW) beacons operating at 19.701 and 39.402 GHz. The two main Italian ground stations, located at Tito Scalo (South of Italy) and Spino d'Adda (North of Italy), have been recording the beacon signals since 2014. The beacon measurements are supported by additional data collected by radiometers, rain gauges, and weather instruments. The main goal of the experimental campaign is to investigate, in detail, atmospheric propagation effects, which must be accurately separated from those induced by the receiving station in order to achieve the typical target accuracy of a few tenths of dB. Indeed, the preliminary analysis of the measured beacon signals shows an anomaly consisting in a signal drop (up to 2 dBs) that is not related to any atmospheric events, but is rather associated to the receiving antenna. This contribution offers a comprehensive investigation of this anomaly to identify the causes and, to a larger extent, to provide insights on a problem that might affect other receiving equipment in the frame of propagation experiments, or that can have a non-negligible impact on the performance of gateways in near future Satcom systems operating at Q/V band. A similar effect has been theoretically studied and simulated in the literature [7]-[8] for the single reflector case and in [9] for the classical Cassegrain configuration (Figure 1 with $\beta = 0°$).

The remainder of this paper is organized as follows: Section II summarizes the main characteristics of the "Aldo Paraboni" payload for the scientific experiment and the ground stations deployed in Italy; Section III describes the anomalous behavior in the measured beacon signal, while Section IV investigates the measurement anomaly induced by the antenna on the received signals and discusses the results. Finally, Section V draws some conclusions.

Manuscript received May 8, 2017.

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Digital Object Identifier 10.1109/TAP.2016.xxx

II. The Alphasat Aldo Paraboni Experiment

The Alphasat satellite was successfully launched on July 25th, 2013, and successively positioned at 25°E longitude on a geosynchronous inclined orbit (the maximum inclination of the orbital plane above the equatorial plane is 3 degrees). The experimental payload has been operative since January 2014.

As shown in Fig. 1, the payload of the Alphasat Aldo Paraboni propagation experiment includes two coherent CW beacons operating at 39.402 GHz (Q band) and 19.701 GHz (Ka band) [5]. The Q-band polarization is linear with 45° tilt angle, while the Ka-band one is linear vertical. The beacon transmitter chain is fully redundant. Fig. 2 shows the coverage area of the two beacons.

The Italian Space Agency deployed two identical ground stations in Italy, the first one located in Tito Scalo (near Potenza, South of Italy) and the second one in Spino d'Adda (near Milan, North of Italy). Both stations measure co-polar signals at 19.701 and 39.402 GHz (and the cross-polar signal at 39.402 GHz), with a sampling rate of 16 Hz. The ground stations are equipped with a monopulse auto tracking system with an accuracy higher than 0.01°. In Table I the geographical coordinates of the two sites and the main characteristics of the two links to the Alphasat satellite are shown.

TABLE I

Geographical Coordinates of Tito Scalo and Spino d'Adda Alphasat Ground Stations and Main Characteristics of the Links

Station	Tito Scalo	Spino d'Adda
Latitude (°N)	40.6	45.4
Longitude (°E)	15.7	9.5
Altitude a.m.s.l. (m)	765	84
Antenna Azimuth (°)	165.9	158.7
Link elevation (*)	42.1	35.5

The antenna consists of two dual shape reflectors in Cassegrain configuration. The main (nearly) parabolic reflector (in aluminium, with an rms surface error of 0.15 mm) has a diameter of 4.2 m and an F/D (focal length to diameter ratio) of 0.32; it was obtained by high accuracy

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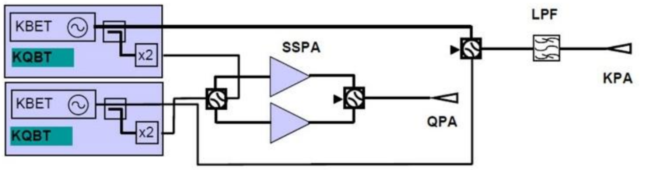

Fig. 1. Block Diagram of the Alphasat Aldo Paraboni Scientific Experiment Payload (courtesy of Thales Alenia Space – Italy), where KQBT is the Ka/Q band transmitter (The Q band beacon transmitter is derived from the Ka band beacon transmitter KBET). The beacon transmitter chain is fully redundant.

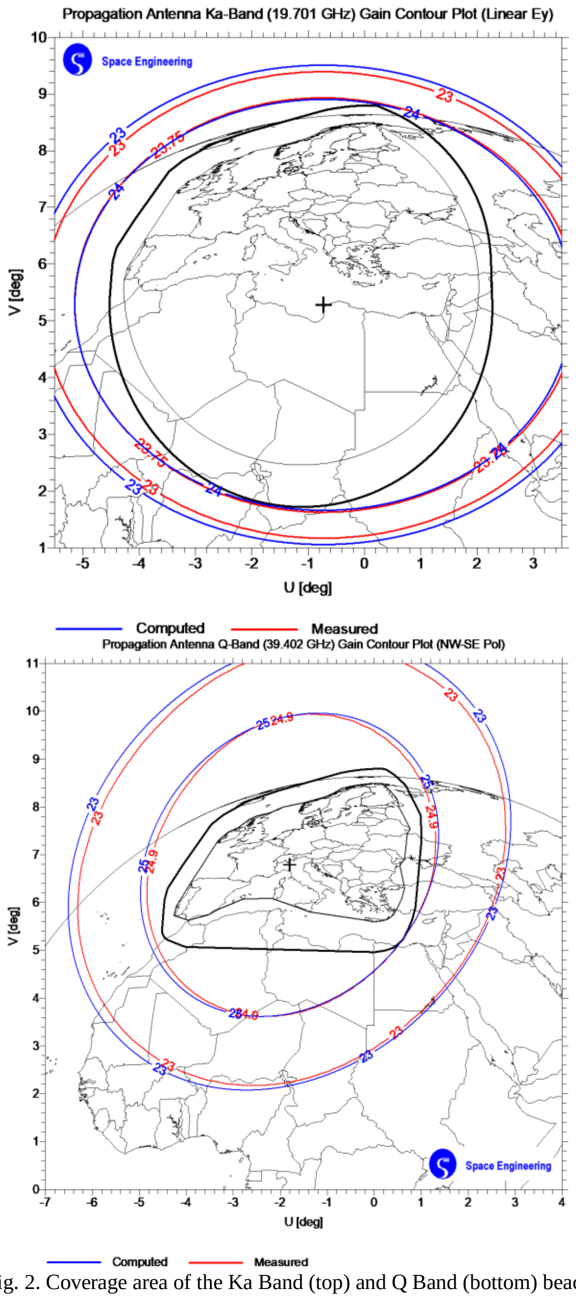

Fig. 2. Coverage area of the Ka Band (top) and Q Band (bottom) beacons.

milling from a single piece aluminium mould and its thickness is about 2 cm. The three aluminium struts (60 × 30 mm rectangular section) supporting the (nearly) hyperbolic subreflector (with a diameter of 440 mm and an rms surface accuracy of 0.1 mm), are 2.2-meters long. The main reflector and subreflectors are not perfectly parabolic and hyperbolic geometric surfaces since they have been distorted to reduce sidelobes. The feed at the centre of the main reflector receives both beacon signals. The antenna layout is illustrated in Fig. 3, while Fig. 4 depicts the antenna deployed at Spino d'Adda pointing at the Alphasat satellite. The antenna has been designed to be operative with winds up to 85 km/h, even if Spino d'Adda is in a flat, not windy region.

The whole antenna system is similar to the one used for the ground stations of the SICRAL 1 and 1b satellites, property of the Italian Defence Ministry [10]. The main difference is in the feed, which, for the Alphasat Aldo Paraboni experiment, receives the two frequencies of the propagation experiment (19.701 and 39.402 GHz) as well as the four frequencies of the communication experiment (37.9, 38.1, 47.9 and 48.1 GHz) [5]. The use of a dual-mode horn allows a good axial symmetry of the radiation pattern and limited sidelobes. The antenna gain is approximately 55 and 62 dBi at 19.701 and 39.402 GHz, respectively, which correspond to an efficiency of about 0.65 and 0.73, respectively.

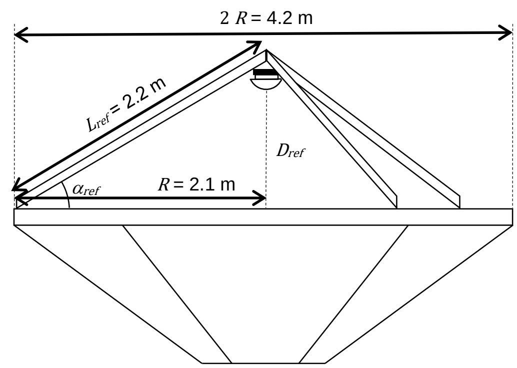

Fig. 3. Layout of the Cassegrain antenna installed at Tito Scalo and Spino d'Adda (zenithal pointing).

Fig. 4. Alphasat ground station in Spino d'Adda pointing at the Alphasat satellite.

III. Anomaly Identification in the Measured Signals

The measurement campaign in Tito Scalo and Spino d'Adda started at the end of 2014 by collecting the received signal level (dBm) at 19.701 and 39.402 GHz, to be afterwards converted into total atmospheric attenuation A with the support of microwave radiometric measurements [11]. In fact, with the aid of mass absorption models (e.g. the MPM93 model proposed by Liebe et al [12]), brightness temperature values measured by radiometers at different frequencies can provide an accurate estimate of A in rain-free conditions, which, in turn, allows

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removing from beacon data any fluctuations due to the satellite instability and/or possible drifts in the receiver temperature.

Since the beginning of the measurements, an anomalous behaviour in the signals has been observed: even in absence of atmospheric events

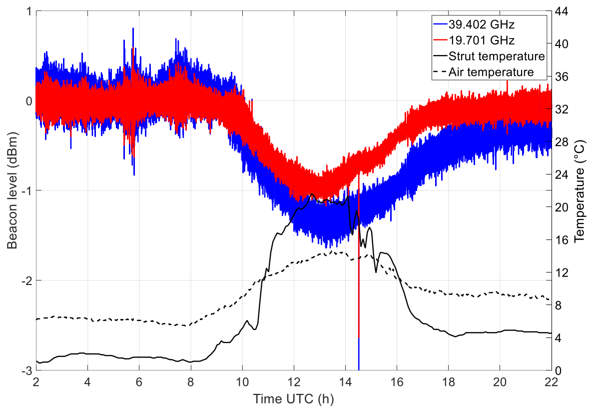

Fig. 5. Signal level (dBm in the left vertical axis) at 19.701 GHz (red curve) and 39.402 GHz (blue curve) recorded at Spino d'Adda on a sunny Winter day, on December 19th, 2014. The concurrent strut (solid black curve) and air (dashed black curve) temperatures (°C on the right vertical axis) are also reported.

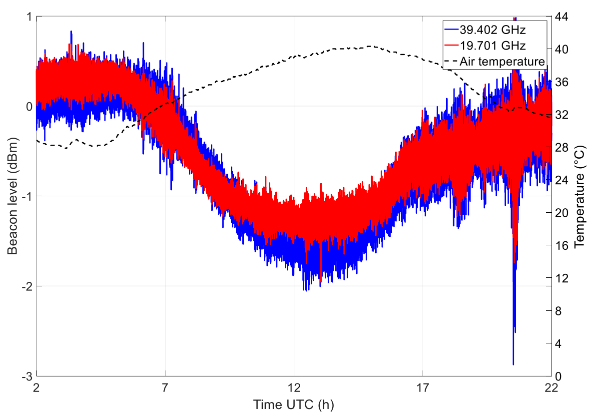

Fig. 6. Signal level (dBm in the left vertical axis) at 19.701 GHz (red curve) and 39.402 GHz (blue curve) recorded at Spino d'Adda on a sunny Summer day, on July 7th, 2015. The concurrent air temperature (dashed black curve) is also reported (°C on the right vertical axis).

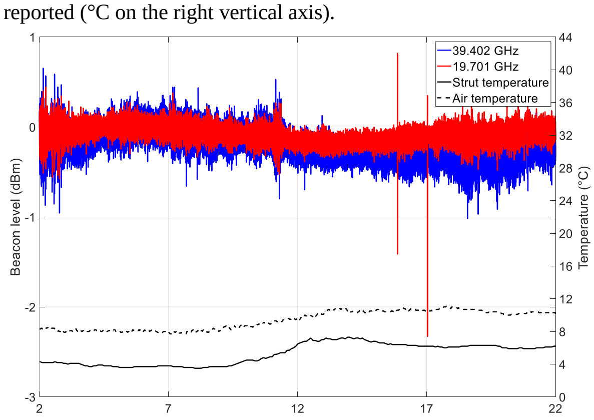

Fig. 7. Signal level (dBm in the left vertical axis) at 19.701 GHz (red curve) and 39.402 GHz (blue curve) recorded at Spino d'Adda on a cloudy Winter day, on December 20th, 2014. The concurrent strut (solid black curve) and air (dashed black curve) temperatures (°C on the right vertical axis) are also reported.

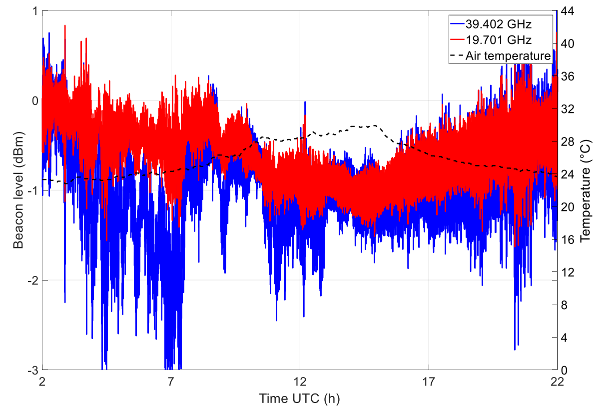

Fig. 8. Signal level (dBm in the left vertical axis) at 19.701 GHz (red curve) and 39.402 GHz (blue curve) recorded at Spino d'Adda on a cloudy Summer day, on September 16th, 2015. The concurrent air temperature (dashed black curve) is also reported (°C on the right vertical axis).

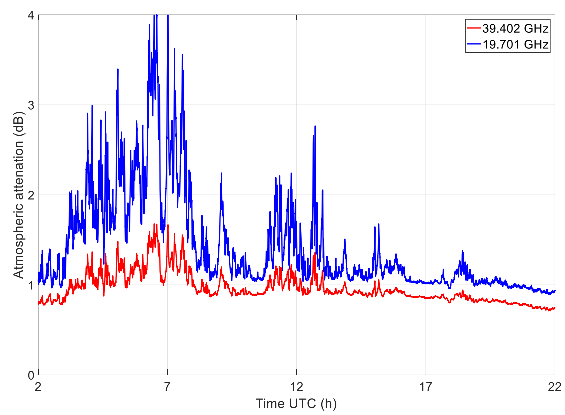

Fig. 9. Atmospheric attenuation (dB) at 19.701 GHz (red curve) and 39.402 GHz (blue curve), as derived from radiometric measurements recorded at Spino d'Adda on a cloudy Summer day, on September 16th, 2015.

(i.e. cloud or rain attenuation), in sunny days, the power received from both satellite beacons decreases during the central hours of the day (also during Winter), as clearly shown in Fig. 5 for Spino d'Adda (December 19th, 2014). The blue curve shows a signal drop of about 1.5 dB at 39.402 GHz and the red curve a drop of about 1 dB at 19.701 GHz. The air temperature is also reported (dashed black curve), ranging from about 5 to 15 °C.

A similar (but more pronounced) effect is visible in Summer, as shown in Fig. 6 (July 7th, 2015): in this case, the air temperature varies from 28 to 41 °C.

On the other hand, the anomalous behaviour is not visible during cloudy (non-rainy) days, as indicated, for example, in Fig. 7 (December 20th, 2014) and in Fig. 8 (September 16th, 2015): in fact, the daily air temperature variation is similar to that reported in Fig. 6, but is associated to quite a limited signal drop. It must be noted that the signal drop in Fig. 8 is partially due to cloud attenuation as shown in Fig. 9, where the attenuation derived from co-located radiometric measurements on the same day is depicted (the radiometric attenuation for December 20th, 2014, was nearly flat with an average value around 0.4 dB and 0.8 dB, at 19.701 GHz and 39.402 GHz, respectively). It is anyway expected that the effect is higher in Summer, due to the cloud radiation which is normally higher from bright Summer clouds with respect to the dark Winter clouds.

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The same anomaly was observed in Tito Scalo, but it is not shown here for the sake of brevity.

IV. Anomaly Analysis and Results

After excluding the chance that the anomaly was due to the effect of a gain variation in the low noise amplifier (LNA), which is thermally controlled, we focused on the possible effect induced by the elongation of the struts supporting the subreflector, in turn due to the sun radiation during a typical day. In fact, such elongation, assuming it occurs simultaneously and it is similar for all the struts, moves the subreflector away from the antenna focal point. As we observed that the signal drop is not perfectly correlated with the air temperature, as evident in Fig. 5 (the air temperature starts rising around 8 UTC, while the signal drop begins after 9 UTC), we installed, on one of the struts of the Spino d'Adda antenna, a thermometer equipped with a data logger (Escort iMiniPlus PDF [13], see Fig. 10). The thermometer sampled temperature every 5 minutes, from December 18th, 2014, to January 2nd, 2015, with an accuracy higher than ± 0.5°C and a resolution of 0.1°C.

Fig. 10. Thermometer installed on one of the three struts of the Spino d'Adda antenna.

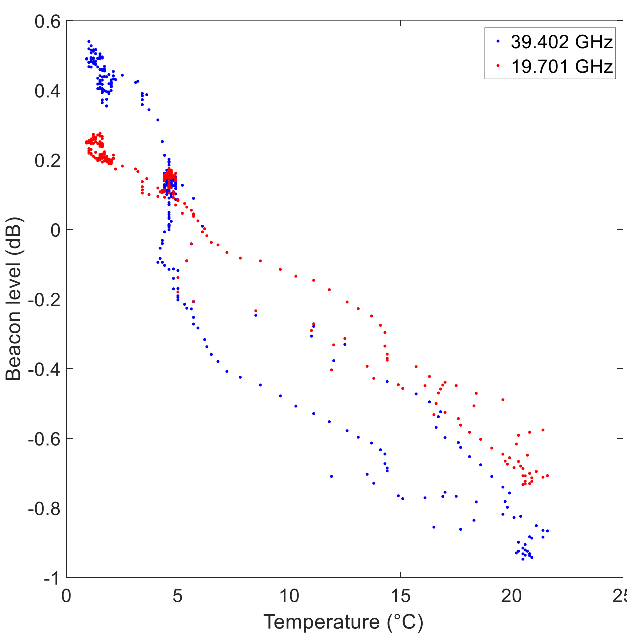

Fig. 11. Scatter-plot between the strut temperature (°C) and the beacon signals (dBm) at 19.701 GHz (red dots) and 39.402 GHz (blue dots) at Spino d'Adda in a sunny Winter day, on December 19th, 2014. The correlation coefficients are -0.986 and -0.954, respectively.

The strut temperature, as measured by the thermometer, appears to be very well correlated with the signal drop, as is evident from comparing the time series of the beacon signals and strut temperature (solid black curve) in Fig. 4, as well as from the data reported in the scatter-plot of Fig. 11 (both figures refer to December 19th, 2014). Specifically, in Fig. 11, the beacon levels have been averaged over 5 minutes for the data to be concurrent with the strut temperature. It must be noted that the relationship between the beacon level and the strut temperature is not perfectly linear and biunique; this is due to the fact that other factors are acting, such as the non-uniform radiation (and so elongation) on the three struts, which can contribute not only to an axial shift of the subreflector, but also to its rotation, and the deformation of the main reflector and subreflector. Moreover, the effect is probably amplified by the fact that the antenna has been designed to operate concomitantly at Ka and Q/V bands, and an optimization at both frequency bands is not possible.

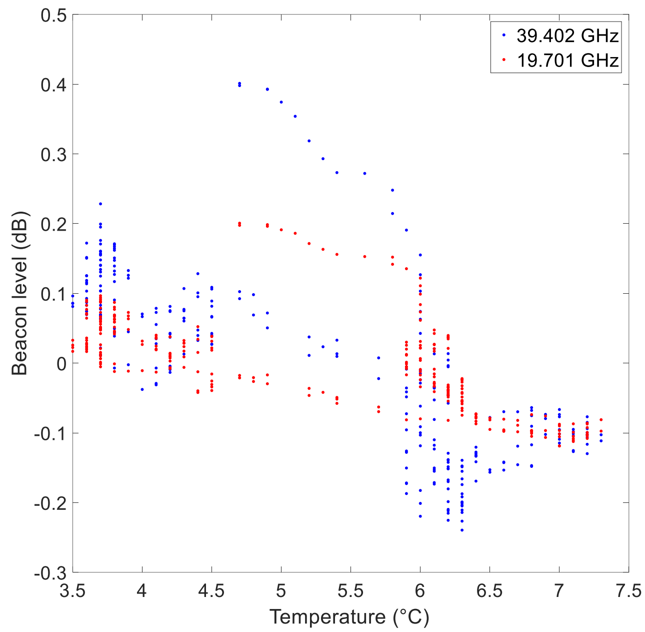

Fig. 12. Scatter-plot between the strut temperature (°C) and the beacon signals (dBm) at 19.701 GHz (red dots) and 39.402 GHz (blue dots) at Spino d'Adda in a cloudy Winter day, on December 20th, 2014. The correlation coefficients are -0.637 and -0.703, respectively.

Looking at Fig. 12, which depicts the same scatter-plot but for December 20th, 2014, even if only a weak correlation between the beacon signals and the strut temperature can be noticed, the strut temperature variation is limited throughout the whole day and, consequently, the beacon level variation.

After identifying such a tight correlation between the signal drop and the strut temperature, the study was focused on verifying theoretically whether the subreflector displacement could actually cause such a drop in the received beacon signals.

Let us assume a reference condition at 20 °C (293.15 K), for which the radius of the main reflector dish, R, is 2.1 m, the length of the strut, L_{ref}, is 2.2 m, and the reference distance between the subreflector and the dish aperture plane is D_{ref} = 0.656 m (see Fig. 3, where $\alpha_{ref} \cong 17°$). When the temperature increases, the most relevant effect is the elongation of the strut; as already mentioned, indeed other effects can be observed in principle, such as the deformation of the main reflector and subreflector and rotation of the subreflector, but they can be probably neglected given the dish geometry and they will not be considered in this study for the sake of simplicity. Consequently, the impact of strut elongation, when calculating the displacement of the subreflector, was only taken into account.

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Considering the coefficient of thermal-expansion of the aluminium, $C_{al} = 23.1 \cdot 10^{-6}$ (K^{-1}), it is possible to calculate the length of the strut at temperature T(K), L_T:

$$L_T = L_{ref}\left[C_{Al}\left(T - T_{ref}\right) + 1\right] \quad (1)$$

where T_{ref} is 293.15. Assuming R is not varying, the displacement of the subreflector can be simply calculated as:

$$\Delta D = \sqrt{L_T^2 - R^2} - D_{ref} \quad (2)$$

TABLE II

STRUT LENGTH, L_T, AND SUBREFLECTOR DISPLACEMENT, ΔD, AS A FUNCTION OF THE STRUT TEMPERATURE, T

T(°C)	L_T (mm)	ΔD (mm)
0	2199.0	-3.42
5	2199.2	-2.56
10	2199.5	-1.71
15	2199.7	-0.85
20	2200.0	0.00
25	2200.3	0.85
30	2200.5	1.70
35	2200.8	2.55
40	2201.0	3.40

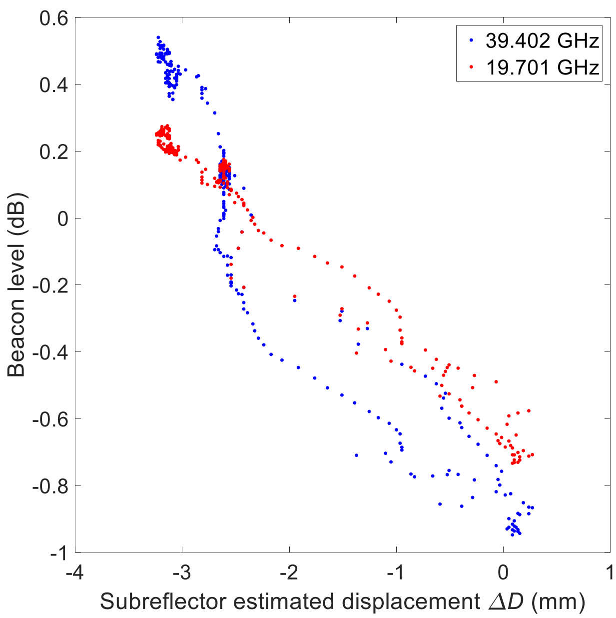

Fig. 13. Scatter-plot between the estimated subreflector displacement, ΔD (mm), with respect to D_{ref}, and the beacon levels (dBm) at 19.701 GHz (red dots) and 39.402 GHz (blue dots) at Spino d'Adda in a sunny Winter day, on December 19th, 2014.

Table II reports L_T (mm) and ΔD (mm) for various values of temperature T (reported for convenience in °C); negative values of ΔD correspond to a displacement of the subreflector towards the dish aperture plane. Being that the wavelengths are equal to 15.2 and 7.6 mm, at 19.701 and 39.402 GHz, respectively, the values of ΔD are definitely compatible with a defocusing effect. The obtained results are comparable to the theoretically derived ones for different antenna geometries in [5], [6].

Fig. 13 shows, for December 19th, 2014, the correlation between the signal drop at the two beacon frequencies and ΔD calculated using (2) and the measured strut temperature; the peak-to-peak variation is roughly 4 mm. This displacement should be compared with that reported in Fig. 14, for December 20th, 2014, which is limited to tenths of mm. In the latter case, the strut temperature variation causes a signal drop likely lower than the daily oscillation of gaseous attenuation.

The detrimental defocusing effect cannot be easily corrected by using air temperature as evident from comparing Fig. 6 and Fig. 8, where similar air temperature variations are associated to different effects on the received beacon signals, depending on sky conditions. On the contrary, the defocusing could be probably limited by using a different metal alloy to build the struts. For example, Invar is characterized by an expansion coefficient $C_{in} = 1.2 \cdot 10^{-6}$ (K^{-1}), which would limit ΔD variations to ±0.18 mm with strut temperature ranging from 0 °C to 40 °C: the associated signal drop would be even smaller than the values depicted in Fig. 14.

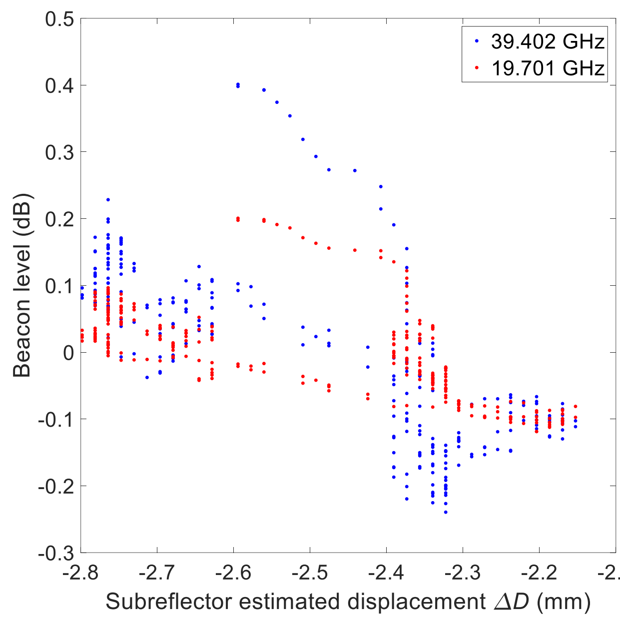

Fig. 14. Scatter-plot between the estimated subreflector displacement, ΔD (mm), with respect to D_{ref}, and the beacon levels (dBm) at 19.701 GHz (red dots) and 39.402 GHz (blue dots) at Spino d'Adda in a cloudy Winter day, on December 20th, 2014.

V. CONCLUSIONS

This paper illustrates and discusses the anomaly on the beacon signals received by the two large Italian ground stations (4.2 diameter antenna, two reflectors in Cassegrain configuration, subreflector supported by three struts 2.2-meter long) in the frame of the Alphasat Aldo Paraboni experiment. Specifically, measurements show a clear signal drop (up to 2 dB) not due to the atmosphere, but to thermal effects on the receiver antenna. While a 2-dB variation in the signal can be negligible, in clear sky conditions, in typical Satcom systems at Ka band, it has to be taken into account in propagation experiments, which aim at assessing the atmospheric attenuation with an accuracy on the order of tenths of dBs. A non-negligible impact is also expected on the performance of gateways operating at Q/V band.

Indeed, the analysis of the data clearly points out that the signal drop is compatible with feed defocusing effects, in turn induced by the elongation of the struts because of the variation in the sun radiation throughout the day. This effect could be probably reduced using other materials to build the struts, such as an Invar alloy. Moreover, the effect can be limited if the antenna is operating and optimized in Q/V band, as will be the case in the gateways of the future High Throughput Systems.

Acknowledgments

The authors would like to acknowledge the Agenzia Spaziale Italiana (A.S.I.), in particular Giuseppe Codispoti, for supporting the Alphasat Aldo Paraboni propagation experiment. The authors would like to thank Mr. Carmelo Mollura (Leonardo SpA), for providing accurate information on the antenna characteristics, Mr. Antonio Tomassone, for his help in the setup of temperature measurements of the antenna in Spino d'Adda, and Dr. James Nessel for his review of the text.

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