Non Invasive Electromagnetic Quality Control System

Jérôme DREAN, Luc DUCHESNE, SATIMO, Courtaboeuf, France
Per NOREN, SATIMO, Gothenburg (Sweden)

Abstract. The quality control of materials on industrial production lines requires the use of very rapid and in most cases non invasive control systems. Different technologies are currently used in existing control systems: X-rays, Gamma, optical, infrared, ultrasound, etc, each of them dedicated to a specific application or combined together to improve the performance of the detection.
Electromagnetic waves are also a good candidate for non invasive testing due to their capability to penetrate deeply inside non metallic materials. Nevertheless, their use has yet been limited for industrial applications and their large potential is still unexploited because of the difficulty to build systems able to perform real time measurements over large cross-sections of materials.
SATIMO has developed a new type of non invasive control system based on low-intensity microwaves and allowing real time scanning of cross-sections of materials several meters large, scrolling at speeds up to 300 m/minute.
This article is divided into four main parts. The first part deals with the principles of electromagnetic wave behaviour inside materials. Then, the architecture of the new quality control system is presented, as well as its advantages. The third part shows typical results obtained with different materials. Finally, an application in an industrial plant is described.
Keywords: *Electromagnetic waves, Modulated Scattering Technique, antennas, sensors, transmission, reflection.*

Introduction

SATIMO has a long history in the domain of non-invasive testing and is working with systems based on electromagnetic waves since more than 15 years. Until now, electromagnetic waves have not been used very much in the industrial domain to characterize the density or the homogeneity of materials or to detect defects like cavities, wet spots or hot spots.

SATIMO has developed a unique patented technology allowing rapid scanning of large cross sections of materials, and with this technology designed a system adapted to industrial environments (see Figure 1). The system is composed of an emission part (above) with antennas that transmit a plane wave through a material scrolling on a conveyor. The reception part (below) is composed of an electronically scanned sensor array and a collector of antennas. This system is modular; each module measures 64 cm and several modules can be assembled together, depending on the width of the conveyor. Plastic radomes protect the system against demanding environments and water projection. The system is compliant with the IP60 norm. A mechanical support is adapted to the conveyor configuration.


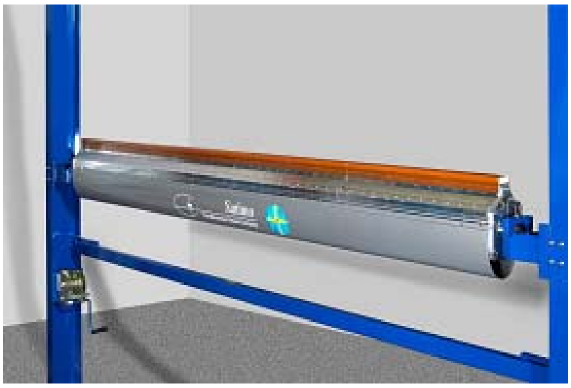

Figure 1 : SATIMO Quality Control System (left) and Sensor Array in the Reception Part (right)

Principles of the behaviour of electromagnetic fields inside materials

Materials can be characterized using electromagnetic waves (macroscopic level) thanks to their dielectric permittivity (ε) and magnetic permeability (μ). The permittivity and the permeability are related to some intrinsic properties of the materials:

- Physical : e.g. temperature, density
- Chemical : e.g. composition

When an electromagnetic wave encounters an interface between two media with different indices of refraction, some part of the wave is reflected, some part is refracted and the rest is scattered or attenuated within the medium [1].
The complex dielectric permittivity $\varepsilon = \varepsilon' - j\varepsilon''$ describes those effects since the real part of the coefficient is used to calculate the index of refraction as

$$n = \sqrt{\frac{\varepsilon'}{\mu}} \qquad (2.1)$$

and since μ is approximately unity for non conducting dielectric materials, equation 2.1 can be simplified to

$$n = \sqrt{\varepsilon'} \qquad (2.2)$$

This value is also corresponding to the dividend by which the speed of light is reduced when the wave propagates in the material.
The imaginary part of the complex dielectric permittivity (ε’’) is also known as the loss factor and describes the attenuation of the wave when it is propagating in the medium.
Figure 2 presents the general scattering configuration and principally for a medium (M)[2]. All the information related to the scattering is contained in the scattered field following the equation (2.3). The total electrical field (E_{tot}) is composed by the incident field (E_{inc}) and the scattered field (E_{sca}).

$$E_{tot} = E_{inc} + E_{sca} \qquad (2.3)$$

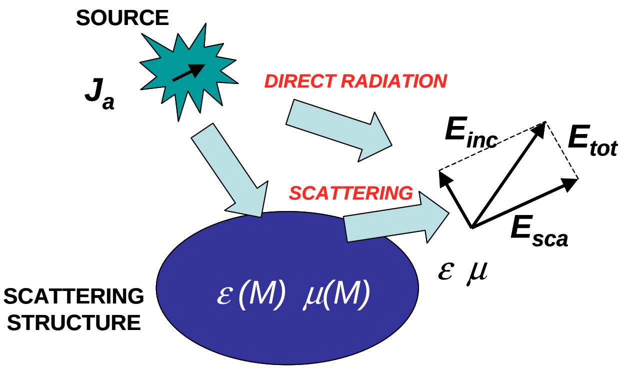

Figure 2 : General scattering configuration

The goal of the measurement is to detect some target features from partial measurements of the scattered field. The relevant features under investigation are expected to locally impact the dielectric properties or the shape (geometry, dimension, position, etc) of the materials under test. Different levels of testing complexity can be performed, like detection (e.g. pass-fail testing, sorting, etc), localization (e.g. optimal cutting, etc), identification or measurement (e.g. temperature, humidity, chemical composition, etc). Data processing techniques are used to identify the problematic like the direct monitoring, the imaging or the tomographic reconstruction, and the parametric estimation [3].
Figure 3 shows the classification of the defects. The distributed defect is considered larger than the wavelength λ defined by the equation (2.4) where λ_0 is the wavelength in free space.

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon'}} = \frac{C_0}{F_0\sqrt{\varepsilon'}} \qquad (2.4.)$$

with $\lambda_0 = \frac{c_0}{F_0}$

- C_0 : Speed of light
- F_0 : Frequency

In the case of localized defects, the small inclusions can be detected if their size is equal to or larger than λ/2. For example, knots in wood boards can be localized. The frequency F_0 is very important to improve the detection of the defects. In fact, the resolution becomes better when the frequency F_0 increases (Wavelength λ_0 decreases).

However, if the operating frequency is increased, the attenuation of the wave in the material under test also increases. A compromise has to be defined between the characteristics of the material under test, the type of the defects, and the operating frequency.

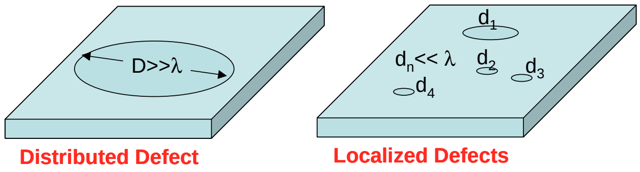

Figure 3 : Classification of the defects

Figure 4 shows the interference pattern between an incident plane wave and a scattered spherical wave created by a small inclusion. In this case, the small inclusion behaves like an equivalent dipole. If the thickness of the material is important, data processing using back-propagation techniques can be used to accurately localize the defect in the material [4].

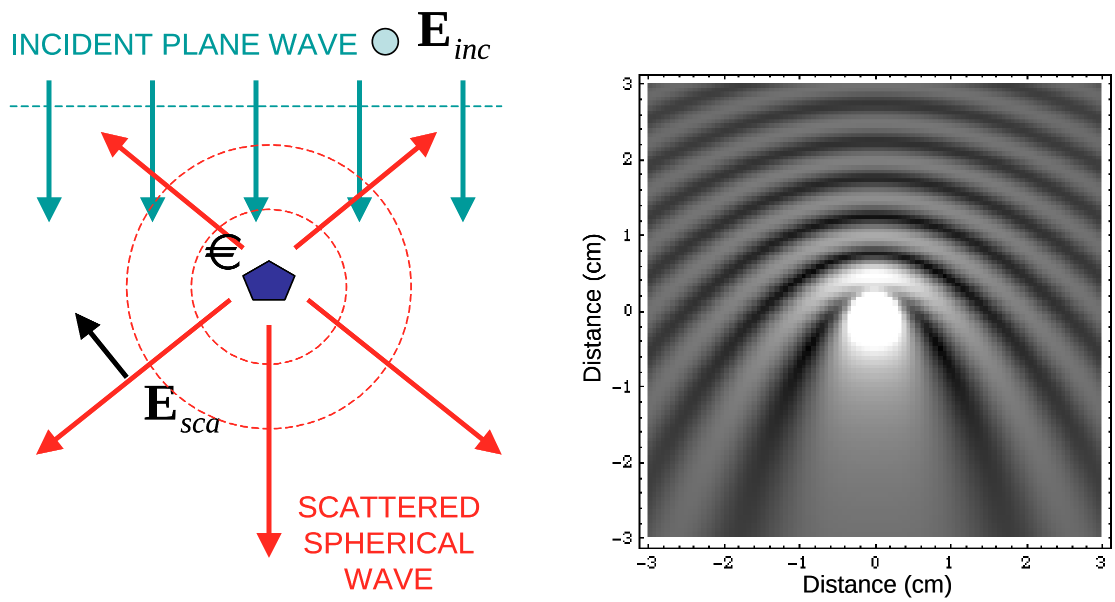

Figure 4 : Scatterer of the plane wave on a small inclusion and behaviour between plane and spherical waves

Architecture of the new quality control system

The SATIMO quality control system can be used in transmission or reflection configurations. Figure 5 presents both types of configurations. Figure 5 (left part) presents a single transmission configuration used to perform measurements of materials like wood, paper, stone or glass wool, glass, etc. The material under test is illuminated by a patch array at carrier frequency F_0. The incoming signal is transmitted through the material. The behaviour of the signal can be modified in the material under test by the presence of defects. The resulting signal is then spatially discretized by a retina of miniature sensors using the Advanced Modulated Scattering Technique (AMST). The length of the retina is equal to or larger than the width of the material under test. Finally, a patch array collects the discretized signal and the receiver measures its real and imaginary parts. Data processing is then applied to the real and imaginary parts to improve the detection of the defects.

Figure 5 (right part) presents the configuration in single reflection mode. The main principle is similar to the configuration in single transmission mode. The difference is that the patch arrays illuminator and collector are located on the same side of the material under test. This solution takes advantages of double transmission. In fact, the plane wave at the carrier frequency F_0 crosses the material twice and this reflection is improved if a metallic plate is located behind the material under test.

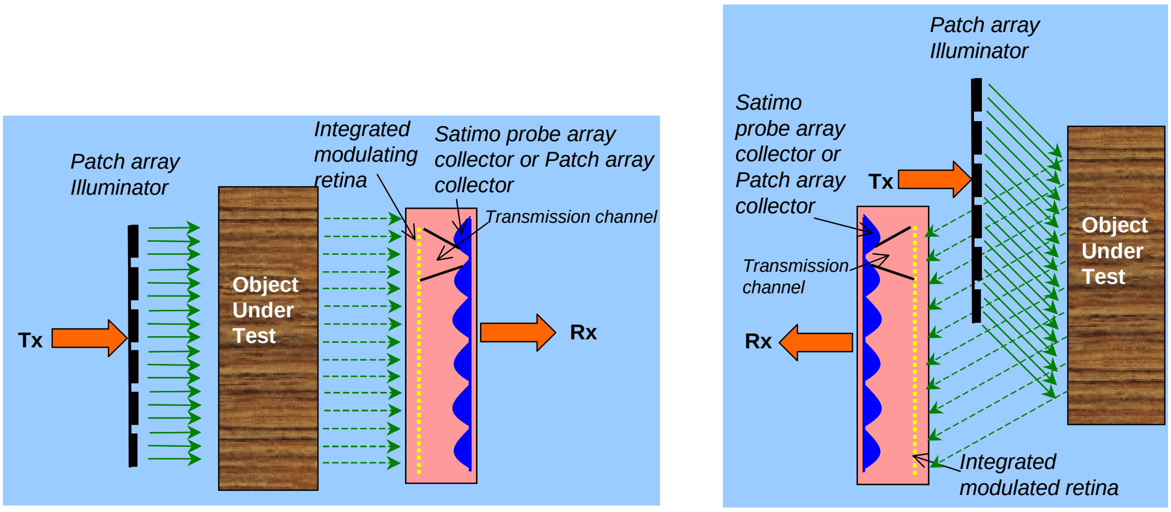

Figure 5 : Transmission and reflection configuration

Typical results obtained with different materials

Electromagnetic quality control systems can be adapted to many applications, especially for detecting defects, unwanted objects, and cavities in non-metallic materials. The same technology can also be used for measuring physical properties of materials: global moisture content, moisture distribution, density, etc. The applications are numerous, including wood, paper, plastic, glass, stone and glass wools, plaster boards, leather, and food products.

This chapter presents experimental results from scanning of stone wool and wood. One module of 64 cm has been used for the tests. The distance between the patch array illuminator and the collector has been set to 35 cm. This distance is adapted to the maximum thickness of the stone wool production conveyor, which is around 27 cm.

1. Measurement of defects in the stone wool

Figure 6 presents a wet spot (accumulation of glue), having a diameter around 2 cm, detected in the stone wool. This type of defect is located inside the stone wool and is invisible optically and to infrared sensors. Figure 6 also shows the real time visualization interface during the measurement performed to detect the defect. Two graphs present the raw data of the real and imaginary parts. The graph below presents the processed data. The wet spot is clearly visible. Additional data processing using back-propagation can be integrated to locate precisely the defect in the material.

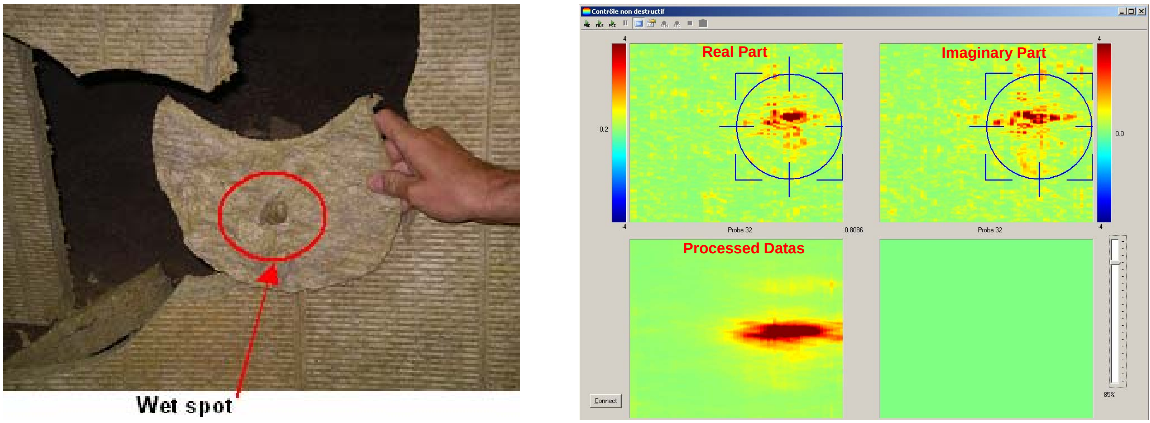

Figure 6 : Detection of a wet spot in the stone wool material and data processing applied to the detection of the wet spot

Figure 7 shows a hot spot (agglomerate of fibers in fusion) having a diameter around 2 cm detected in the stone wool material. Figure 7 also shows the graphs with the real and imaginary parts, and the processed data. The hot spot is relatively simple to detect because the stone wool is burnt around the defect and the dielectric properties of the material are also modified at this place.

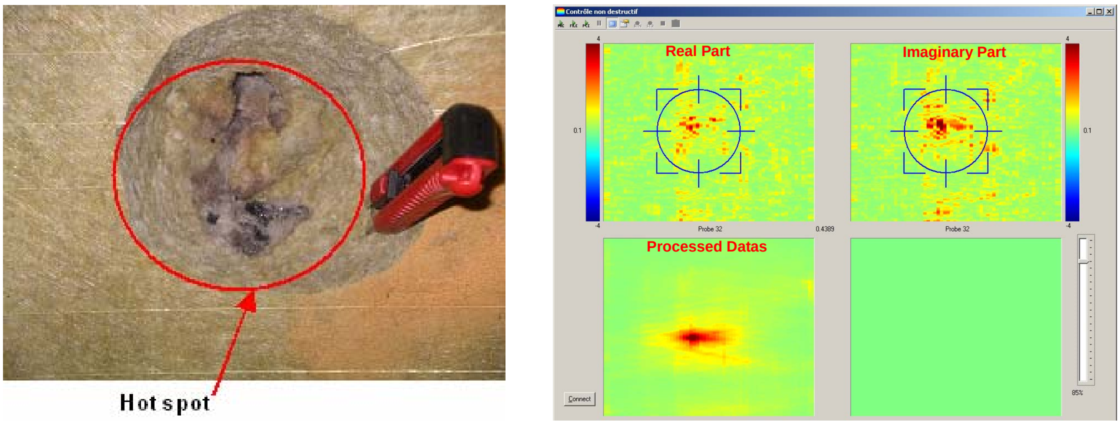

Figure 7 : Detection of a hot spot in the stone wool material and data processing applied to the detection of the hot spot

2. Measurement of the defects in wood

The second set of results presents detection of knots in a wood board. Figure 8 (left part) shows two knots detected in a board of wood. The detection is based on the dielectric contrast between the knots and the wood. Figure 8 (right part) shows the raw data of the real and imaginary parts and the processed data. Two spots with different dimensions are detected by the software.

This example was applied to knots. However, other characteristics of the wood can also be controlled like moisture and density.

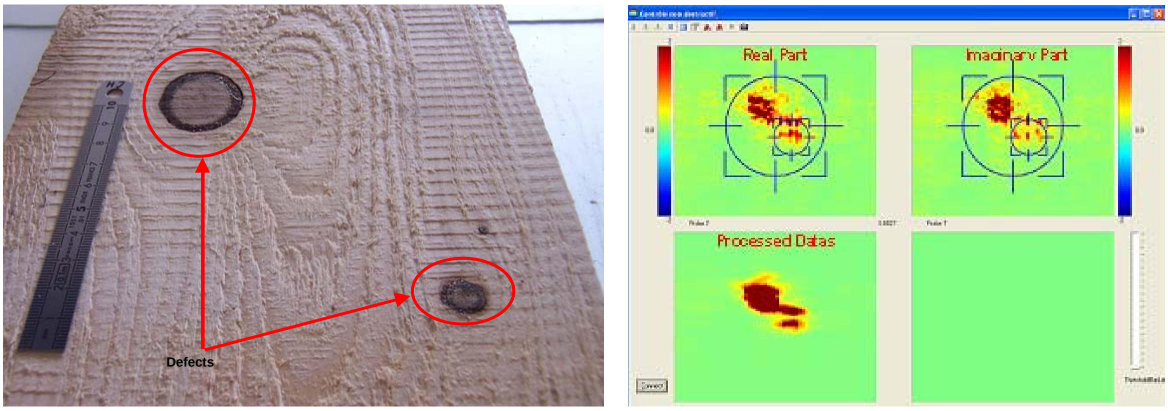

Figure 8 : Two knots detected in the wood and data processing applied to the detection of the knots

Figure 9 (left part) presents a knot of 3 cm diameter located on the edge of the wood board. The results in Figure 9 (right part) show the real and imaginary parts and the processed data. The scattering due to the edge of the board does not disturb the detection of the knot thanks to the dynamic reference applied continuously to the system during the measurements.

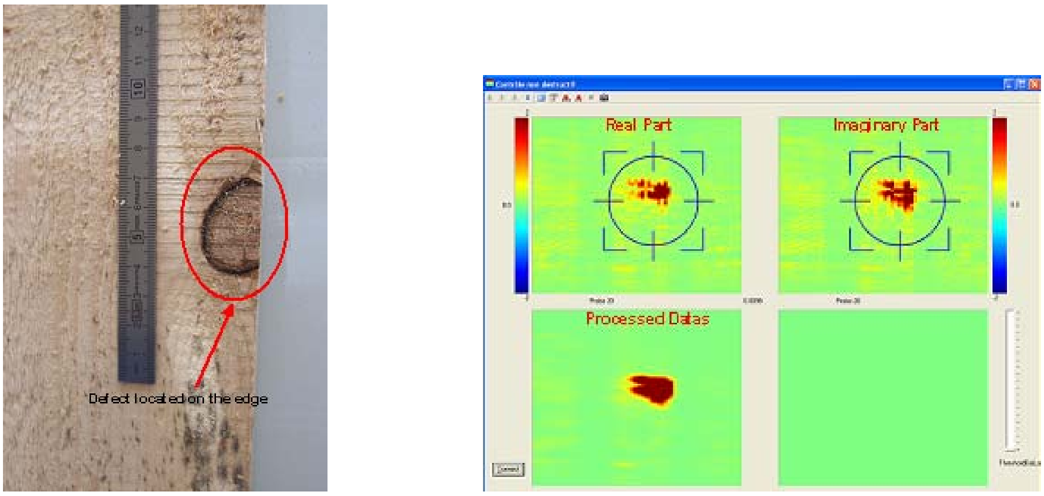

Figure 9 : Detection of a knot on the edge of the wood and data processing applied to the detection of the knot

Industrial application

The SATIMO quality control system has been installed on a production line for Saint-Gobain ISOVER in order to control the quality of the stone wool material. The goal of this project is to detect defects like hot spots and wet spots. The installed system has proved to be very successful in detecting these defects, and it also allows production engineers to run statistics on the results in order to track and improve the industrial process.

Figure 10 and Figure 11 show the system integrated on the production line. Figure 10 (left picture) presents the illuminator (above) and the collector (below). Each part is composed by four modules of 64 cm length. The distance between the two parts is about 40 cm. The collector is located 3 cm below the stone wool material shown on the Figure 11. The collector is composed by 256 miniature sensors scanned electronically with a resolution of 10mm. The illuminator and the collector are designed for X-band operation (9 GHz).

Figure 11 (right picture) shows the instrumentation cabinet that supplies and drives each part of the system. The instrumentation cabinet holds a Radio Frequency (RF) Unit, which contains the RF components, and a computer. A PC card scans the miniatures sensors with a rapidity compatible with several meters large conveyors scrolling at speeds up to 300 m/minute. A real time interface has been configured for the customer to visualize all the defects detected in the material. The defects are registered in a database, which allows statistical processing.

The SATIMO system is connected to the customer automaton. The automaton transmits the information of the line speed, the density and the thickness of the material and receives the positioning of the defect (right or left) and the command to trigger marker guns.

Figure 10 : Non invasive system installed on a stone wool production line

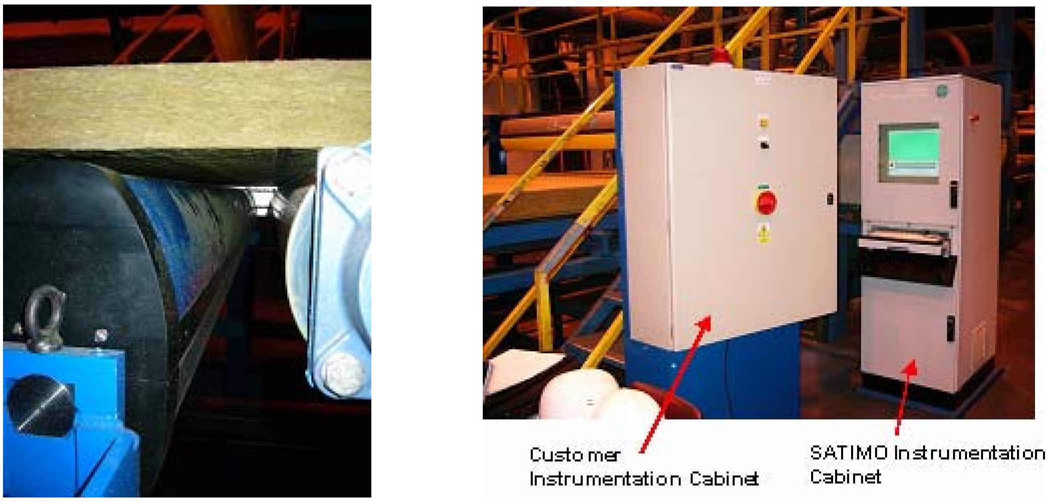

Figure 11 : Positioning of the reception part with the conveyor, and instrumentation cabinets

Conclusion

A non invasive quality control system has been developed by SATIMO. Its modularity, its ability to support several meters of production line width and line speeds up to 300m/minute allows implementation of the system for many applications. Calibration is not necessary due to a continuous reference with the material under test. The SATIMO system is not only dedicated to the detection of localized defects but it is also able to measure relative density and homogeneity. SATIMO is currently working to upgrade the X-band system to Ku-band (18GHz) and Ka-band (36GHz) to improve the resolution up to the order of 1mm.

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