USING ELECTRICAL CAPACITANCE TOMOGRAPHY SYSTEM FOR DETERMINATION OF LIQUIDS IN ROCKET AND SATELLITE TANKS

Zbigniew Gut
Łukasiewicz Research Network – Institute of Aviation
Al. Krakowska 110/114, 02-256 Warsaw, Poland
zbigniew.gut@ilot.edu.pl • ORCID: 0000-0002-1463-4755

Abstract

One of important problems in aerospace engineering is to determine the amount of fluid in the tank in a microgravity environment. There are several methods for doing it, however, there are no proven methods to quickly gauge the amount of propellant in a tank in low gravity conditions. New and more accurate methods of such a measurement are being continually searched for. One of interesting solutions is using Electrical Capacitance Tomography (ECT) for this purpose. The article presents both numerical analysis and experimental test results using a spherical tank. The main purpose of the simulation was to determine the effect of the number of electrodes and noise signal level on the quality of reconstruction images. In numerical simulations, different models of dielectric permittivity distribution have been reconstructed. On the basis of numerical simulations, a 24-electrode sensor was designed and made. In experimental tests, different distribution of medium inside the spherical tank was investigated. The results show that the method can directly measure the mass of fuel in the tank, as well as it allows for a visualization of fuel distribution, independent of the tank position in space, and the liquid-propellant system will be used.

Keywords: tomography, satellite, tank.

1. INTRODUCTION

The lack of gravity in the space makes it challenging to measure the amount of liquid propellant remaining in storage tanks. The main problem is the chaotic motion of fuel volume in the tanks due to the lack of gravitational force, which hinders diagnosing the accurate amount of fuel in the tank. There are several methods for doing so and the most popular are: Pressure-Volume-Temperature Method (PVT Method) [1][2][3], Optical Mass Gauging (OMG) [4][5], Radio Frequency Mass Gauging (RFMG) [6].

The PVT application is set up for gauging the level of liquid in a propellant pressure tank via two methods. The first method is the ullage compression method (UCM). The level of liquid in the propellant tank is determined after adding a known delta volume of liquid to the tank without venting the ullage pressure. A real-time algorithm uses the known delta monomethylhydrazine (MMH) volume added, the delta temperature and the delta pressure of the tank ullage to calculate the volume of the tank ullage.

The other method is called the external helium tank method (EHTM), and uses an external helium tank that is pressurized and connected to the propellant tank, but is initially isolated from the tank.
Starting with stable pressures and temperatures in both tanks, the pressurized helium tank is opened to the propellant tank until the pressures and temperatures stabilize. The volume of the propellant tank ullage is calculated from the delta pressures and temperatures in the tanks. In these two methods, the level of the liquid is determined from the remaining volume in the propellant tank.

The OMG is based on the premise that a propellant tank will act as a pseudo-integration optical sphere with respect to light source that is introduced into its interior. A spectrum of light which is emitted into an object can reflect from the surface, absorb and penetrate through the object. It is assumed that light, which is measured at a given tank port, will be proportional to the fraction of the input light that is not absorbed. In this case, this is related to the propellant mass or volume fraction. For any particular material, the transmission or absorption spectrum is unique.

The RFMG technique measures the electromagnetic eigenmodes or natural resonant frequencies of a tank containing a dielectric fluid. The hardware components consist of an antenna probe mounted internal to the tank and an RF network analyzer that measures the reflected power. At a resonant frequency, there is a drop in the reflected power, and these inverted peaks in the reflected power spectrum are identified as the tank eigenmode frequencies using a peak-detection software algorithm. This information is passed to a pattern-matching algorithm which compares the measured eigenmode frequencies with a database of simulated eigenmode frequencies at various fill levels. The best match between the simulated and measured frequency values occurs at some fill level, which is then reported as the gauged fill level.

Each of the methods have advantages and disadvantages, as well as varying feasibility for space flight applications. Many of these methods are not suitable for low gravity environments simply because they rely on gravitational forces to maintain a uniform distribution in the substance being gauged. In addition, some techniques capable of liquid or vapor mass gauging are not adequate for solid mass gauging due to their inability to discriminate between the presence of each form. To succeed in properly measuring the amount of fuel present in a tank that is exposed to a variable gravity environment, a technique must be independent of fluctuations in gravitational forces, changes in mass distribution and changes in properties, which may be associated with changes of state or compressibility.
2. ELECTRICAL CAPACITANCE TOMOGRAPHY SYSTEM

ECT is a measurement technique that reconstructs dielectric constant distribution in an object by measuring the capacitances between the electrode pairs which are mounted around the object. A typical application is real-time monitoring of multi-component flows within pipelines. Specific applications, where ECT has been successfully exploited, include solid-gas and liquid-gas systems, such as fluidized beds, pneumatic conveying, multi-phase flow and combustion [7][8][9]. In principle, ECT is used to investigate and monitor any process where materials are non-conducting, and the other phases and components have differing values of permittivity.

A typical ECT system has three main units: a sensor, a measurement system and a computer as shown in Figure 4.

![ECT system](image)

The sensor consists of a set of electrodes symmetrically mounted outside measurement space. The sensing electronics measure the capacitances for all possible electrode combinations when the electrode sizes and location are fixed, depending only on the permittivity distribution inside the ECT sensor head. The computer system has two major functions. Firstly, it controls the measurement operations performed by the sensing electronics and secondly, it uses the measurement data to reconstruct tomographic images. Electrical Capacitance Tomography systems are normalized at the upper and lower permittivity values for image reconstruction. Traditionally, capacitance measurements $C^*$ are normalized between 0 and 1, where the value of 0 corresponds to a lower permittivity, and the value of 1 corresponds to a higher permittivity material.

At present, ECT is mainly used for the visualization of permittivity distribution in two dimensions (2D). In 2D capacitance tomography, with its planar system of electrodes, some inhomogeneities and location of objects cannot be properly distinguished in three dimensional (3D) space. However, 3D images can be achieved by interpolating series of 2D slices from different planes like in many medical applications. The authors call this approach 2.5D tomography. It is not a real 3D reconstruction as it is only a rough approximation. Evaluating the concept of capacitance tomography, we can see that it is based on obtaining a series of measurements from sensors which are placed on selected cross-section planes. Various image reconstruction techniques can then be applied to obtain the distribution of dielectric permittivity on these cross-section planes. The same idea can be used for directly obtaining the distribution of a given material parameter in 3D space.

In order to show the potential of the new approach and to prove better imaging quality in contrast to the 2.5D ECT, an experiment with simulation of the 36-electrode 3D ECT sensor model was performed. The electrodes were located in three planes each with 12 electrodes. The phantom from Figure 6 with nine droplets of oil in air was used. Three droplet groups were located specifically on the plane of each electrode layer level. Initially, the simulator worked in the mode of three ECT systems each with a 12-electrode sensor. The spatial information about the examined objects was interpolated from three cross-sectional images (obtained individually from sensors 1, 2 and 3) as presented in Figure 6. It can be...
easily seen that instead of nine droplets three rods were obtained. The interpolation process lost important information about the lack of objects between the electrode layers. Next, the 3D measurement and image reconstruction were performed. In that case all the droplets were properly distinguished.

![Image of 2D and 3D tomography comparison](image)

**Fig. 5.** Comparison 2D and 3D tomography: (a) 2D sensor, (b) 3D sensor [Gut, 2012].

<table>
<thead>
<tr>
<th>model</th>
<th>2.5 D interpolation</th>
<th>3D reconstruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>sensor 1</td>
<td><img src="image" alt="Image of 2.5 D interpolation" /></td>
<td><img src="image" alt="Image of 3D reconstruction" /></td>
</tr>
<tr>
<td>sensor 2</td>
<td><img src="image" alt="Image of 2.5 D interpolation" /></td>
<td><img src="image" alt="Image of 3D reconstruction" /></td>
</tr>
<tr>
<td>sensor 3</td>
<td><img src="image" alt="Image of 2.5 D interpolation" /></td>
<td><img src="image" alt="Image of 3D reconstruction" /></td>
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**Fig. 6.** Simulation of the 36-electrode 3D ECT sensor. 3D measurement and image reconstruction in contrast to the 2.5D interpolation [Gut, 2012].

However, in the case of 3D capacitance tomography, the basic structure of the sensors and the measurement concept are the same as in 2D tomography. 3D imaging sensor contains much more electrodes\(^1\) whose arrangement enables to cover the whole research space. In this case, it is necessary to use multi-channel measurement systems. A popular solution used in ECT is to connect on principle: one electrode\(^1\) to one measuring channel. However, in this work, a new measurement system was designed and tested.

![Image of capacitance tomography electronic unit and signal card](image)

**Fig. 7.** View of capacitance tomography electronic unit and the block diagram of signal card [Gut, 2012].

In our solution, one signal card can support up to four electrodes which lie in different planes, so the number of possible measurements slightly decreased. This results from the fact that one signal card is not able to generate an excitation signal and get measurements at the same time. In the case when all electrodes are connected to the separated signal cards, the number of possible measurements \(m\) is given by the following formula:
\[ m = \frac{n \cdot (n-1)}{2} \]  
\[ \text{Where: } n - \text{total number of electrodes in sensor.} \]

For the new solution the number of independent measurements \( m \), is given by the following formula:
\[ m = \frac{w \cdot (w-1) \cdot r^2}{2} \]
\[ \text{Where: } w - \text{number of electrodes in the row;} \]
\[ r - \text{number of rows in sensor.} \]

The new solution reduced the number of measurements, and so the costs of constructing the new system were reduced. The present system has 16 signal cards, which allows measurement from 64 electrodes. For configuration, where every electrode is connected to the separate signal card, it was necessary to assemble 64 ones.

Due to the similarities mentioned above, 3D capacitance tomography can use the same reconstruction methods as 2D classic tomography. ECT images from capacitance measurements are generated using the Linear Back-Projection (LBP) algorithm. This algorithm is simple, fast and ideal for online reconstruction, but produces relatively low-accuracy images. For improving it the iterative image computation methods are used. The most widely used iterative method to solve the problem in ECT is the Landweber technique, also called Iterative Linear Back Projection (ILBP). The full description of the algorithms can be found in many publications [10][11][12].

A very important step of the inverse process is to present reconstruction results and show them in a suitable and realistic form. 3D image presentation is always very demanding especially in view of calculation time and complex algorithms. Software written in Delphi 2006 and OpenGL (Open Graphics Library) was used for visualization. OpenGL is a standard specification defining a cross-language cross-platform API for writing applications that produce 2D and 3D computer graphics. The interface consists of over 250 different function calls that can be used to draw complex three-dimensional scenes from simple primitives.

3. NUMERICAL SIMULATION

The spherical tank is the most common satellite pressure vessel configuration. Thousands of spherical tanks have flown since the inception of the space age. Spherical geometry offers the best pressure performance, therefore, it provides the most mass-efficient pressure vessel design. The main purpose of the simulation was to determine the effect of the number of electrodes and noise signal level on the quality of reconstruction. For this reason, in the numerical simulation three type spherical sensors were used. Sensor consisting of 18, 24 and 30 electrodes which were installed in three planes, as shown in Figure 8. The geometry of electrodes was chosen so that the area of each one is similar with the radius of a sphere 210 mm in diameter.

![Fig. 8. Visualization of 3D geometry of 24 electrodes sensor [Gut, 2012].](image-url)
The main problem in 3D modelling and reconstruction is the mesh size. Meshes in 2D tomography usually have a few hundred nodes. In the case of 3D tomography the number of nodes reaches up to thousands, thus having serious impact on the reconstruction speed in online mode. The finite-element method (FEM) technique (software: Ansys® Inc.) was applied to obtain the distribution of an electric field within the sensor volume. The sensitivity map of electrode pair i-j at a spatial location \([x,y,z]\) can be calculated by vector multiplication of two electric fields, which are normal to the potential distributions. The view of mesh and exemplary potential distributions in the 3D ECT 24 electrodes sensor are shown in Figure 9.

Fig. 9. View of mesh and exemplary potential distributions in the 3D ECT 24 electrodes sensor [Gut, 2012].

Some test problems to validate the image reconstruction approaches studied in this paper have been used. In numerical simulation simple and complicated models were used. The different models are tested by the noise-free and the noise-contaminated capacitance data. The measured capacitances by ECT system are usually normalized at the high and low permittivity for image. The normalized capacitance \(C^*\) is ”0” when the sensor is full of the low permittivity material, and ”1” when it is full of the high permittivity material. Noise was generated as follows: to the calculated value of normalized capacitance an appropriate percentage of the noise level was added. Figure 10 shows a visualization of methodology determination of the noise level.

![Noise level visualization](image)

Fig. 10. Visualization of determining the noise level [Gut, 2017].

When we have a two-phase mixture flow, it is not possible to tell, a priori, how the phases are going to distribute themselves in a tank, especially in a microgravity environment. Because of the infinite possibilities of distributions of the phases, researchers have tended to use flow patterns to describe the flows. These are broad descriptions of the flow. In conditions of low gravity, several flow patterns may occur: plug, stratified, slug, annular or bubbly.

Three permittivity distributions were chosen for image reconstruction shown in Figure 11.
The first phantom was a ball with a radius of 30 mm with coordinates (0,0,50). The second phantom consisted of two balls with a radius of 30 mm and with coordinates (0,0,50) and (0,0,-50), respectively. The last model consisted of a ball with a radius of 30 mm with coordinates (0,0,45) and partially filled up sphere up to a height of 50 mm. The blue colour stands for the high permittivity materials with a value of 2.6, and the white colour represents the low permittivity materials with a value of 1.0.

The norms of the original (\(g\)) and obtained (\(g_r\)) permittivity distribution vectors to calculate the relative image error, were used according to the formula:

\[
\delta = \frac{\|g - g_r\|}{\|g\|} \cdot 100\%
\]  

(3)

The numerically determined capacitance values from the forward solver were used for reconstruction using the LBP and ILBP algorithm with 100 iterations. Figures 12 to 17 present the reconstructed images and the relative image error, assuming the variation in the noise level in the range from 0% to 10%.

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\% & LBP 18 & ILBP 18 & LBP 24 & ILBP 24 & LBP 30 & ILBP 30 \\
\hline
0 & & & & & & \\
1 & & & & & & \\
3 & & & & & & \\
5 & & & & & & \\
10 & & & & & & \\
\hline
\end{array}
\]
Fig. 13. The relative image error vs. noise level for different reconstruction methods and sensor – model 1 [Gut, 2017].

<table>
<thead>
<tr>
<th>Noise level [%]</th>
<th>LBP 18</th>
<th>ILBP 18</th>
<th>LBP 24</th>
<th>ILBP 24</th>
<th>LBP 30</th>
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<tr>
<td>1</td>
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<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
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<td>3</td>
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<td><img src="image15.png" alt="Image" /></td>
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<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
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<tr>
<td>5</td>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
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<td>10</td>
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<td><img src="image29.png" alt="Image" /></td>
<td><img src="image30.png" alt="Image" /></td>
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Fig. 14. Reconstructed images for different noise level – model 2 [Gut, 2017].

Fig. 15. The relative image error vs. noise level for different reconstruction methods and sensor – model 2 [Gut, 2017].
As one would expect, with the increase of the noise level of measurements data the quality of reconstructed images decreases. Increasing the number of electrodes slightly improves the quality of reconstructed images. These conclusions mainly concern the first two models. In the case of the last model, the situation is slightly different. In this case, changes in relative image error in the whole range of noise level changes are minimal, however, as shown in Figures above, the quality of the reconstructed images gets worse. It can be concluded that used the method used to determine image error does not provide reliable results. To confirm this thesis further, additionally simulations of two cases and with using two sensors were carried out. The first simulation consisted of a systematic increase of the liquid level in the sensor, as can be seen in Figure 18. In the second case, the movement of the sphere with a radius of 30mm along the axis z and x was simulated (Figure 20). The error values were determined for each value of the level and position of the sphere, using the same method.
As shown in Figure 19, the results from the first simulation, the course of relative image error changes have a predictable character, i.e. with increasing of filling the sensor, the values of these errors are decreasing. In the second case, as depicted in Figure 21, the character of the relative image error changes are different and depending on which axis the sphere moves along and depending on the position of the sphere. The largest errors appear when the sphere is in the centre and close to the wall of the measurement space. Especially, this note applies when using the LBP algorithm.

4. SPHERICAL SENSOR

The sensor is one of the most important elements of the Electrical Capacitance Tomography. In principle, ECT is a non-invasive method, so the principle of the construction of the sensor is based on placing a set of electrodes around the measurement area, so that the flow or distribution medium inside the tank has not been disturbed. In this work, a new 24-electrode capacitance sensor has been developed. The electrodes were mounted on a non-conducting plastic sphere with 217.0 mm in diameter, which were arranged in three planes where each plane consisted of 8 electrodes. The total volume of the sphere is $V_{sphere}=5.3$ dm$^3$. The sensor includes radial and axial guard electrodes which are used to reduce the external coupling between the electrodes and to achieve improved quality of measurements.
The gap between electrodes and driven guard was 1.5mm. The thickness of driven guard was 3mm, and distance between the electrodes and the screen was 5mm. Two holes were made in the lower and upper spheres, which allowed for easy filling and emptying the sphere. The view of spherical capacitance sensor and characteristic dimensions are shown in Figure 22.

5. RESEARCH

The most common propulsion systems are liquid, which is a combination of a chemical fuel with an oxidizer. A popular solution is to use monomethylhydrazine (MMH) as the fuel, and nitrogen tetroxide (NTO/MON-3) as the oxidizer. For safety in our research quartz sand was used to fill the sensor.

Three methods were used to determine the sphere content. The first method uses the calculated values of normalized dielectric permittivity, obtained using the LBP algorithm \( V_{LBP} \). The second method uses a normalized value of dielectric permittivity obtained using the algorithm ILBP \( V_{ILBP} \). The last method is based on normalized values capacitance between electrodes \( V_{C_s} \).

\[
V_{LBP} = \sum_{i} \frac{k_{i(LBP)}}{n_w} \cdot V_{sphere} \tag{4}
\]

\[
V_{ILBP} = \sum_{i} \frac{k_{i(ILBP)}}{n_w} \cdot V_{sphere} \tag{5}
\]

\[
V_{C_s} = \sum_{i} \frac{C_{i(k)}}{m} \cdot V_{sphere} \tag{6}
\]

\( k_{i(LBP)} \) – the normalized pixel permittivities obtained using the algorithm LBP
\( k_{i(ILBP)} \) – the normalized pixel permittivities obtained using the algorithm ILBP
\( C_{i(k)} \) – the normalized capacitances for k electrode-pair
\( n_w \) – the number of nodes representing the sensor
\( m \) – the number of unique electrode pair combinations
\( V_{sphere} \) – total volume of a sphere

Research was divided into two stages. The first stage was carried out to determine how much fluid was added when the tank stayed at rest. After a precisely defined dose of sand entered the tank, a measurement system based on recorded data again determined the contents of the tank. LBP algorithm and IBLP algorithm with 100 iterations were used in reconstruction. Obtained reconstructed images and variation of tank contents for different contents of the tank are shown in Figure 23 and 24.
In addition to the reconstructed images, in order to evaluate performance of each method, relative error was determined using the norms of the original ($V_{FILL}$) and obtained $V_{LBP}$, $V_{ILBP}$, $V_{C^*}$ volume:

$$e_{LBP,ILBP,C^*} = \frac{\|V_{FILL} - V_{LBP,ILBP,C^*}\|}{V_{FILL}} \cdot 100\%$$  \hspace{1cm} (7)

Calculated relative error for different measurement method and tank contents are shown in Figure 25.

![Figure 23: Reconstructed images for different contents of the tank [Gut, 2012].](image1)

![Figure 24: Variation of tank contents for different methods [Gut, 2012].](image2)

![Figure 25: The relative error for different measurement method and tank contents [Gut, 2012].](image3)
The next phase of the study was to determine the level in the tank for different sensor positions. In this way, a different position of the tank was simulated depending on the position of the satellite in space. Due to the fact that the shape of the electrodes is irregular, changing the position of the tank will enable to estimate the impact of distribution of the material inside the tank to the accuracy of the reconstruction and fuel content. The reconstruction was made for four tank contents: 1, 2, 3, 4 dm³, and for a few tank positions. In the analysis of the results the previous equation was used. Obtained reconstructed images and variation of tank contents for different contents of the tank are shown in Figures 26 - 29.

Fig. 26. Reconstructed images for 1 dm³ tank contents [Gut, 2012].

Fig. 27. Reconstructed images for 2 dm³ tank contents [Gut, 2012].
Additionally, in the case of the reconstructed images, the average value of relative error from five tank contents was determined in order to evaluate performance of each method, as shown in Figure 30.
6. CONCLUSIONS

Satellites fuel systems working in a space environment encounter difficulties directly connected with anti-gravitational conditions during their operations on the orbit. The main problem is the chaotic motion of fuel volume in the tanks due to the lack of gravitational force. This chaotic motion causes problems for fuel system in diagnosing the accurate amount of fuel remaining in the tank.

In this work, numerical and experimental results show that the ECT system is an interesting solution that may be used in monitoring systems of fuel tanks of satellites. In the first stage of the research, the results from the numerical analysis show that 24 electrodes sensor is sufficient to achieve the appropriate image quality. But we must remember that the spatial resolution of a tomography imaging system depends on the number of independent measurements and the fineness of sensitivity focus for each one. Therefore, more electrodes of a smaller size would result in a better imaging reconstruction. However, the measurement sensitivity of a capacitance is proportional to the electrode profile. As the electrode size is reduced, the signal-to-noise ratio (SNR) of the system decreases. In order to improve the SNR of the measurement, the size of the electrode can be increased, and is limited only by installation restrictions and cost consideration. As a consequence, the electrode size must be increased and the total number of electrodes decreases. The selection of the electrodes number and dimensions is a matter of balancing between the spatial imaging resolution and SNR.

During the analysis of numerical data, another problem was noticed. The method used to determine image error does not provide reliable results. This parameter is only a compressed form of all the information embedded in the image and only reflects part of the image details. Equation (3) has its own limitations in indicating the image error.

The research showed that using the method to determine how much fluid has been added when the tank stayed at rest has a good compliance with theoretical values. Experimental tests showed that the relative error is less than 10% when the content of the sphere was determined with the help of normalized values of dielectric permittivity obtained using the ILBP algorithm. We can notice that measurement data collected allowed not only to reconstruct the changes taking place inside the tank, but also allowed to determine the contents of the tank.

In future work, an improved ECT system will be developed to improve the resolution, and to present the images of the contents tank in real time. The proposed technique will be tested in low gravity environments by using a microgravity lift. It is believed that the ECT system holds significant promise for the future of detecting distribution and determining the amount of fluid in tanks rockets and satellites.
REFERENCES


WYKORZYSTANIE SYSTEMU POJEMNOŚCIOWEJ TOMOGRAFII KOMPUTEROWEJ DO OKREŚLANIA POZIOMU PŁYNÓW W ZBIORNIKACH RAKIET I SATELITÓW

Abstrakt
Istotnym problemem w inżynierii kosmicznej jest sposób określania ilości paliwa w zbiorniku w środowisku mikrogravitacji. Istnieje kilka metod określania poziomu cieczy w zbiorniku, jednakże nie ma sprawdzonych metod szybkiego pomiaru ilości paliwa w zbiorniku, gdy znajduje się on w stanie niskiej grawitacji. Trwają poszukiwania nowych i dokładniejszych metod pomiaru. Jednym z ciekawszych rozwiązań jest zastosowanie Pojemnościowej Tomografii Komputerowej do określania poziomu paliwa lub utleniacza w zbiornikach rakiet i satelitów. Otrzymane wyniki, które przeprowadzono z wykorzystaniem metod numerycznych oraz w warunkach grawitacji pokazują, że metoda może bezpośrednio mierzyć masę paliwa w zbiorniku, a także umożliwić wizualizację rozkładu paliwa, niezależnie od położenia zbiornika w przestrzeni i zastosowanego układu zasilania.

Słowa kluczowe: tomografia, satelity, zbiorniki.