# SATELLITE OBSERVATIONS IN METEOROLOGY

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This article deals with satellite meteorological observations. It gives an overview of meteorological satellites, deals with their utilization possibilities and characteristics. Next part is dedicated to the variables that can be observed by satellites, to the satellite outputs and to their measurement ability. The last part of the article is devoted to the future development of satellites including nanosatellite technology and satellite data analysis in which currently much attention is paid to the volcanic ash and dust recognition.

K e y w o r d s: meteorology, meteorological satellite, nanosatellite.

## 1 INTRODUCTION

Meteorological observation satellites have many application areas. They are used for processing of different meteorological analyses, forecasts, weather warnings, for climate studies, for various operations (such as airports, construction works on land or at sea), for agricultural meteorology and hydrology and of course for weather and climate research. World Meteorological Organization (WMO) describes the requirements according to the application in global, regional and national scale. The global observation system is designed to meet these requirements and consists of ground and space subsystems. The ground subsystem includes a wide variety of stations that have a specific use, such as surface synoptic stations and climatologic. The cosmic subsystem consists of satellites that transmit information to terrestrial stations that consequently receive the transmitted data and are also used for satellite control.

## 2 METEOROLOGICAL SATELLITES

Satellites observe the Earth remotely. Satellites use the gravitational force of an object (planet) to orbit around it.

They are mainly used to scan the Earth's surface, and to provide these gathered information to the ground subsystems. Satellites have a variety of sensors placed on them that are used for meteorological data sensing and acquisition. Further sensing systems are used for movement of energy observation. The energy is reflected from the ground or objects that are placed on the surface. Satellites provide many different types of observation. There are also ground sensors, which collect information from the Earth's surface. The information gathered by the two types of sensors can be compared to each other. [1]

The quality, availability and speed of processing of satellite data in the nineties, has greatly improved, which of course increased their effectiveness. There is an ongoing improvement and development of satellite instrumentation. Currently, the established global system of meteorological satellites is used to monitor the Earth's atmosphere. Spacecrafts sense large areas, but they are not always able to provide detailed information. Generally speaking, satellites placed in higher altitudes record larger areas but in lower quality. That is the reason why the two basic types of observation (in-situ and remote) that are complementary to each other, are combined. The result is providing of high-quality information about the atmosphere. [1]

Each satellite flies over the trajectory, which is called the satellite orbit. Orbits are distinguished by their orientation, altitude as well as the rotation to the Earth's surface. These satellites use either polar or geostationary orbits. [2]

### 2.1 Geostationary satellites

Geostationary satellites are placed in a static height of about 36,000 miles above the Earth. Here they orbit around the Earth at the same speed as the Earth rotates around its axis, which is about once per every 24 hours. In practice this means that they remain in a fixed position in regard to the Earth's surface and observe the same part of the Earth's surface. From the perspective of an observer on Earth the satellite does not change its position in the sky.

Location of geostationary satellites is usually directly above the equator. Due to the satellites working height and position holding, they have large energy demands. To ensure a continuous coverage of the entire planet with the exception of the polar-regions coverage, five geostationary meteorological satellites are required to operate around the Earth. Currently there are five Japanese GMS, U.S. satellites GOES-8 and GOES-9, European METEOSAT, the Indian INSAT and Russian GOMS placed on the geostationary orbits. [2]

### 2.2 Satellites on polar orbits

Angle, height and profile of the track polar satellites used in meteorology varies according to their type. The inclination of the orbit plane to the plane of the Earth's equator is about 80 to 100 degrees. This means that satellite passes above or nearly above both poles. Its orbit is in the range of 600 to 1250 km above the Earth's surface. Such satellites are the U.S. civilian weather satellites NOAA. Other polar satellites include the Russian METEOR and the USA military DMSP satellite. METEOR satellites provide a relatively low-quality data, while data from the DMSP is unavailable. Therefore, most of the civil service dealing with meteorology uses data from NOAA satellites. [2]

## 3 QUANTITIES MEASURED BY THE METEOROLOGICAL SATELLITES

Meteorological quantities which are measured operationally at present, with varying resolution and accuracy, include the following:

- the temperature profile and the temperature at the cloud top and at the surface of the sea/land;
- the humidity profile;
- the wind at cloud level and at the ocean surface;
- liquid and total water and precipitation rate;
- net radiation and albedo;
- cloud type and height of cloud top;
- total ozone;
- the coverage and the edge of ice and snow. [3]

### 3.1 Measurement parameters using electromagnetic radiation

In this group are imaging and planning techniques involved, which use electromagnetic radiation with a wavelength from $1\times10^{0}$ to $3\times10^{-7}$ m (to a frequency from $3\times10^{8}$ to $1\times10^{5}$ Hz), which are classified as visible, infrared, ultraviolet and microwave bands. Accordingly, what follows is an element in the atmosphere with the selected range of wavelengths of radiation detected. At first operational meteorological satellites sensors were designed primarily for capturing visible infrared radiation (i.e. from 10.7 to 10.5 m), thus in short wavelengths. As technology advanced microwave remote sensing have also developed. The microwave remote sensing works with much larger wavelengths (i.e. from $10^{-3}$ to 1 m) and less frequent. The most convenient for meteorological purposes are the visible, infrared and microwave parts of the spectrum. The various radiation wavelengths are able measure the same elements but in a different way, some are more suited to specific surfaces and conditions than others. A combination of data from different sensors is required to produce an accurate and complete picture of the Earth's surface. [4]

## 4 METEOROLOGICAL SATELLITE OUTPUTS

At present, meteorological satellites gain a lot of data describing the state and evolution of the Earth's atmosphere. The data are obtained in a vertical or horizontal direction and can be used to both forecasts and analysis of past events. The collected information are processed into graphical and tabular forms for operational use. With this information, the user gets an overview of the observation results. The results displayed in meteograms and graphs are used globally for the prediction of basic meteorological variables. Satellite photos are also used in routine weather forecasting. Satellite outputs are carried to Earth in two ways:

- from the satellite memory;
- using direct transfer of images. [5]

In the first mode, data is recorded and stored in the satellite memory, from which there are transmitted to the ground station. Considering EUMETSTAT satellites collection, processing and distribution of meteorological data and satellite control is performed in the governing land control station located in the German city of Darmstadt. [5]

In the second mode, the satellite data are directly transmitted from the spacecraft deck. However, this data are limited by location, because the information can only be received in the local area where the time interval is equal to the length of the direct radio visibility of each satellite station. The size of the range of the area varies depending on satellite technology and its orbit height. [5]

Another specific aspect that should be taken into account is the difference in size between the terrestrial and satellite observations. Generally speaking, data gathered from the ground produces higher resolution than the information obtained from satellites. Digital photos have a format where the image is divided into small areas of the same size, which are called pixels. The brightness of all pixels is characterized with a numerical value or number in a digital format. Every digital value presents a different level of brightness. Information from the sensors of different wavelengths are collected and stored in different channels. Image data from satellites can be obtained in a variety of formats such as internal binary and raster images.

### 4.1 Radiometer SEVIRI channels

SEVIRI radiometer is the main equipment used by the MSG satellite (Fig. 1). This device can record the Earth from 12 different spectral channels.

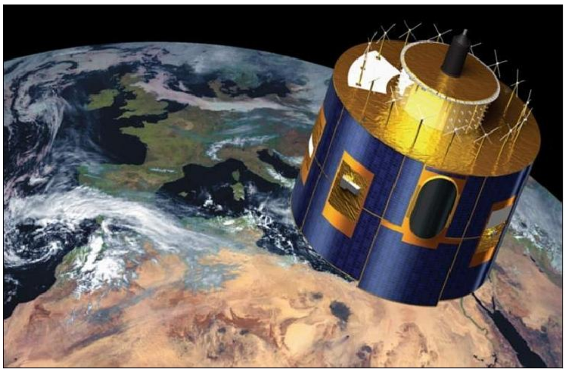

**Fig. 1 MSG satellite**

First two channels MSG satellites are visible absorption bands designed for cloud tracking and its structure monitoring. They also provide information on the Earth's surface, aerosols and provide the most natural view of the atmosphere and of the Earth's surface. These two channels, in combination with the third are also used to monitor the development of vegetation. The third channel is used for infrared analysis and helps to distinguish clouds from snow cover and the presence of ice crystals in clouds. It helps to differentiate the aerosols in the atmosphere. The fourth channel picks up short-wave infrared band and distinguishes low clouds and fog at night (without the presence of sunlight). It helps to measure the temperature of the Earth's surface and sea-level and is very useful in mapping of forest fires. [6]

Both channels five and six are sensitive to the concentration of water vapor in the upper half of the troposphere. They help to identify semi-transparent clouds. These channels also enable the identification of hot, cold, moist and dry air masses. [6]

Throughout the infrared bands of the seventh channel it is possible to distinguish cirricumulus cloud, ice crystals and water droplets. Data from the eighth channel provides us with the knowledge of the total amount of ozone in the lower stratosphere and its daily variability. The ninth and tenth channels are atmospheric window channels. They provide information about the temperature of the radiation cloud and the Earth's surface. Division of the spectrum into two channels enables an increase in their sensitivity to clouds and the surface. Their common use is to reduce the effects of the atmosphere on the final temperature of cloud tops. These channels are also used to calculate the meteorological potential for the identification of storms. [6]

Channel eleven is sensitive to the absorption of thermal radiation by carbon dioxide ($CO_2$). This is why it is used for the detection of atmospheric instability and lower tropospheric temperatures. Channel twelve picks up reflected solar radiation over a wide range from 0.6 to 0.9 μm at high spatial resolution up to 1 km². It provides the most natural representation of the atmosphere and Earth's surface in terms of the perception of the human eye. It is very good at enabling us to visually distinguish cloud structure and its optical density. Using this channel we can observe very specific detail, such as the effect of gravity waves on the surface of the tropopause and the discharge of steam from the tops of a thunderstorm in the stratosphere. [6]

SEVIRI radiometer has the ability to provide high definition information for areas within 1 km on channel 12. For the other channels (1–11) the resolution is for areas of 3 km. However, the resolution of the Central European region is reduced, because of the oblique angle. For channels 1–11 it is 6 x 4 km and the channel 12 is 3 x 2 km. The ground surface is scanned by the radiometer providing full size images at a rate of four per hour. Radiometer scans the planet from the South Pole to the North Pole. To create one entire image the satellite has to rotate at a rate of one hundred revolutions per minute. Consequently it takes 1250 revolutions to make one frame. When transferring the High Rate SEVIRI data all 12 spectral channels must be used. Channels 1–11 are used for lossless compression. Channel 12 is partly lossed compressed. Transmission Low Rate SEVIRI, when at a reduced transmission carries 5 selected spectral channels (1, 3, 4, 5, 9) and they are compressed at a loss. We can only get two sets of such data for 1 hour that is 30 min / 1 frame. [7]

All data collected in addition to that data are in 6-hour intervals (00:00, 06:00, 12:00, 18:00) and are subject of the license of EUMETSAT. For access to a package of meteorological data it is required to purchase software (EUMETCast Client Software) and the relevant license. [7]

### 4.2 Interpretation of satellite images

Compressed data from SEVIRI radiometer can be decompressed with no xrit2pic algorithm. This particular algorithm decompresses data and composes the final image. The result is always the image saved in .jpg format. The Earth is photographed in 12 spectral bands. These bands allow us to obtain information on their radiation and absorptive properties. Combining these channels, however, we get even more information about the atmosphere but also the Earth's surface. The combination of channels is called RGB composition. In RGB composition each channel displays any of the three color shades: Red Green Blue. That means if channel 3 will display the red, channel 2 will display the green and channel 1 the blue one, resulting in a multi-color RGB image called composition. The resulting coloration of a RGB composition depends on the physical characteristics of selected channels. Furthermore, it depends on the selected combination of channels and assigning each color channel. It is important to adjust the intensity of the signals from the intervals selected channels. [7]

## 5 FUTURE PERSPECTIVES

### 5.1 ESA mission

The European Space Agency (ESA) addresses developments of satellites in Europe. ESA sends into space, among other satellites and spacecraft, also those ones which are designed for Earth observation. Earth Watch includes the well-established meteorological missions with the European Organisation for the Exploitation of Meteorological Satellites. There are currently six Earth Explorer missions.

- GOCE: ESA's gravity mission (launched in 2009)
- SMOS: ESA's water mission (launched in 2009)
- CryoSat: ESA's ice mission (launched in 2010)
- Swarm: ESA's magnetic field mission (launched in 2013)
- ADM-Aeolus: ESA's wind mission (launched in 2015)
- EarthCARE: ESA's cloud and aerosol mission (launched in 2015)
- Earth Explorer 7: Following ESA's Call for Ideas for the seventh Earth Explorer in 2005 and the subsequent selection in 2009, three missions – Biomass, CoReH2O and PREMIER. [9]

ESA is also developing a new set of Sentinel missions aimed at climate monitoring. Sentinel missions have not yet three satellites in space and in the future rendering the other two satellites is planned.

- Sentinel-1 – mission operational radar imaging, mission for land and ocean services (launched in 2011),
- Sentinel-2 – surface monitoring (started in 2012),
- Sentinel-3 – ocean monitoring (started in 2012),
- Sentinel-4 – atmospheric composition from geostationary orbit monitoring (planned to 2017),
- Sentinel-5 – for atmospheric composition monitoring (scheduled for 2020). [9]

Developed and procured by ESA, MetOp is a series of three satellites dedicated to the operational meteorology until at least 2020. The programme, which forms the space segment of Eumetsat's Polar System (EPS), is Europe' contribution to a cooperative venture with the US, providing data to monitor climate and improve weather forecasting. Currently there are 2 MetOp satellites in space and there is a scheduled future plan to deliver the third satellite.

- MetOp-A – weather service (launched in 2006),
- MetOp-B – polar meteorology (started in 2012),
- MetOp-C – polar meteorological services (scheduled to 2015) [9]

Following on from Meteosat Second Generation, MTG is a cooperative venture between Eumetsat and ESA, and will ensure continuity of high-resolution meteorological data to beyond 2037. The new series will comprise of six satellites: four MTG-I imaging and two MTG-S sounding satellites. In addition to the advanced imaging capabilities offered by the Flexible Combined Imager, the satellites will offer an all-new infrared sounding capability and imaging of global lightning that will provide early warnings of severe storms. MTG-S will also carry the Sentinel-4 payload for the Global Monitoring for Environment and Security (GMES) programme. This advanced payload will analyze atmospheric chemistry and identify concentrations of trace gases like ozone and nitrogen dioxide. [10]

### 5.2 Recognition of volcanic ash

Research in the area of meteorological satellite is also focused on the data processing. Differentiation of the volcanic ash or dust from the clouds can be considered as a big challenge in this area. [8]

Extreme weather conditions such as icing, turbulence or the presence of volcanic ash can create navigational difficulties for large aircraft. If the plane encouters such conditions, it becomes very difficult to navigate. It is therefore necessary to ensure a proper assessment of weather and flight conditions. In addition to the cost of repairing aircraft volcanic ash can cause a huge financial loss if air transport is limited. These losses also depend on the concentration of particles of ash from a volcanic cloud height. However, the actual assessment of the amount and concentration of the ash cloud can be very challenging. For this purpose satellite images and numerical dispersion models are required. [8]

The continuous advances in satellite technology have produced a wide selection of different images. However, detection of volcanic ash clouds, especially their height and concentration, can be very challenging. If the ash clouds are masked by other clouds, detection is more difficult. Eruption Eyafjallajökull on the 14th April 2010 produced a huge amount of water vapor that eventually ended up as ice cloud. Therefore the ice cloud masked the ash cloud. After several hours, the ice sublimated, revealing the remaining ash cloud.

It should also be noted that satellites can only detect clouds with a concentration of ash. This means that ash may be present and unidentified owing to non-concentration of ash. Therefore, areas that are close to the visible ash clouds can also be affected by the ash and should be considered for places that are issued a warning. However, the best assessment of volcanic ash clouds involves careful monitoring of satellite images and deep knowledge of their dispersion nature. The main advantage of satellite data is their wide spatial and temporal coverage, which allows the detection of severe weather events in comparison to other sources. [8]

RGB's composition "Dust" is useful not only for the detection of Saharan sand storms, but can also help to detect volcanic ash clouds. This composition RGB "dust" clouds of volcanic ash are shown in orange. The RGB composition "ash" in the clouds appears yellowish in color. The main benefit of the composition RGB "Ash" is that it shows the three main components of volcanic (ash, sulfur dioxide and ice crystals) in different colors, allowing users to track the movement of these elements from the point of eruption. [8]

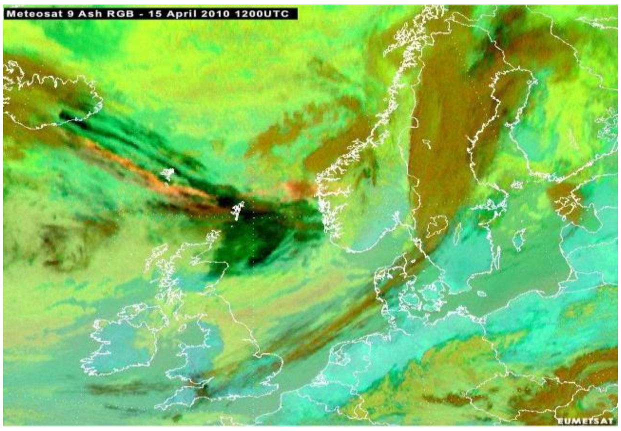


**Fig. 2 Ash composition**

### 5.3 Nanosatellites

Large satellites continue to be affordable only to big national projects or extremely wealthy organizations. As such, emerging countries and small organizations are adopting smaller spacecrafts as means to their space exploration endeavours by forcing the miniaturization age to the space industry. Adopted almost exclusively by small organization with limited budgets nanosatellites have as their main requirement the maintaining off the overall costs at minimum. The small scale counter parts of the traditional space missions represent the tool for Earth observation and near Earth space monitoring in the new age of space explorations. Almost 10 years ago the beginning of this new age became clear with the introduction of the CubeSat (Fig. 3) standard [11]. Generally, the nanosatellite term designates satellites in the mass range of the 1 – 10 kg. However, the most representative for this class is the CubeSat which restricts developers to a volume of approximately 10 x 10 x 10 $cm^3$. Previous experience with small satellites existed before the CubeSats, but their introduction marks the moment when a critical mass of developers begun working on similar designs using similar components. These types of spacecrafts are designed to support Earth observation, space environment monitoring and space qualification efforts at minimal costs.

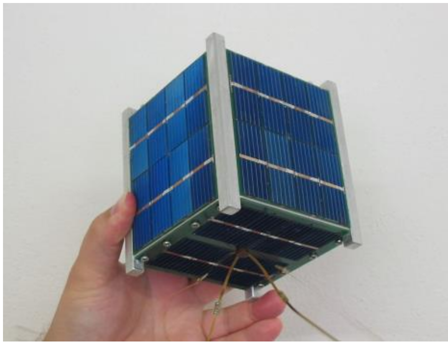

**Fig. 3 CubeSat nanosatellite [11]**

The main characteristic of the nanosatellite are given by their size, which is in the order of tens of centimeters. All the other subsystems need to be scaled down to accommodate the design requirements. There are two approaches in designing of a nano class spacecraft: either start from the payload and scale the satellite to that payload or scale the payload to the overall dimensions and try to accommodate the other subsystems. The further new method involves setting a design for the payload and revisiting it if after adding the rest of the subsystems when the overall restrictions are not met. This might require going into many iterations of the payload and subsystems design. Being in development for over a decade, different technologies have been adopted by the nanosatellite designers and advances have been made for increasing the capability of these spacecrafts. We are now at a time when the efforts are starting to show results and inmission demonstrations of these technologies are beginning. An important restriction imposed by the energy available on board is the processing power that can be feasibly accommodated on small satellites. Hence the on board computers typically found on nanosatellites launched in the past decade are microcontrollers functioning at frequencies of several MHz. The reason is not the lack of advanced processors that could be integrated, but the need to limit the functioning periods for them as they drain the batteries rapidly. The proposed solution is to use a mixed approach: low power microcontrollers for general functions and high power processor for demanding tasks like attitude determination and control systems or data processing in payload units. This method has already been applied by the integration of units functioning at hundreds of MHz on board of nanosatellites already launched or being scheduled for the launch. Most advanced applications require precise determination of the orbit and the attitude of the satellite. Others also need capabilities to change the orientation and some even the position of the satellite. This is the technology field where most nanosatellite research is focused. Miniaturized attitude determination sensors existed at the time nanosatellites started being launched and various sensors were rapidly integrated: sun sensors, magnetometers, Earth horizon sensors, star trackers.

## 5 CONCLUSION

International organizations involved in the production, discharge and operation of meteorological satellites in the future attain to provide a global coverage, in order to map out the rest of the Earth (oceans, deserts and Polar Regions) as well as the already mapped densely populated areas. Future developments in technology will increase the number of channels and increase spatial and temporal resolution of images. There is the idea that in addition to the current satellites (geostationary and polar) satellites will also appear on eccentric orbits that are inclined to the equator differently and will observe all the places on Earth irrespective of their geographic location. With the development of these satellites the amount of information in the meteorological field will increase. It is therefore possible that the current information provided today, which is now only available for specialists will become freely available in a redistributed version for the general public. So you may be able to see the current weather images directly on your PC, TV or smartphone to a specific area of your interest. [6]

Detailed information and high resolution processing together with new types of data (vertical profiles of temperature, humidity and atmospheric flow) still remain in the domain of specialized units. Through them meteorologists are able to assimilate data and create numerous weather prediction models of the atmosphere. These currently provide the short-term weather forecasts, which predict rainfall, developing of storm clouds, fog and other dangerous phenomena and that all for the large areas. In the future we will be able to see such information in unimaginable temporal and spatial resolution and in details and considering future development in term of the nanosatellite development the satellite meteorological information will be accessible not only for the meteorological community or wealthy organizations but also for the general public. [6]

BIBLIOGRAPHY

[1] VOJTKO, Rastislav – REICHWALDER, Peter. *Interpretácia leteckých a družicových snímok v geológii* [online]. 2009 [cit. 2013-01-01]. Dostupné na internete: <geopaleo.fns.uniba.sk/vojtko/archive/sm/ilds_kap03_v.0.1.pdf>.
[2] BYDŽOVSKÁ, Martina. *Systém meteorologických družic, data a využití* [online]. Praha: 2004. Dostupné na internete: <kratas.borec.cz/down/druzice.pdf>.
[3] World Meteorological Organisation. *Guide to Meteorological Instruments and Methods of Observation* [online]. WMO-No. 8, Seventh edition, 2008 [cit. 2012-10-18]. Dostupné na internete: <http://radiometrics.com/wp-content/uploads/2012/11/WMO_Guide_to_Meteorological_Instruments.pdf>.
[4] JURAŠEK M., et al. *História družicových meteorologických pozorovaní v Slovenskom hydrometeorologickom ústave* [online]. Životné prostredie, 43, c. 4 s. 208-211, 2009. [cit. 2013-01-09]. Dostupné na internete: <http://www.elis.sk/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=1642&category_id=58&option=com_virtuemart&Itemid=9>.
[5] KONDRATEV, K. YA. - BORISENKOV, E. P. – MOROZ A. A. *Interpretation of observation data from meteorological satellites* [online]. 1970. [cit. 2013-01-16]. Dostupné na internete: <https://ia601203.us.archive.org/26/items/nasa_techdoc_19710000615/19710000615.pdf>.
[6] FERANEC, Ján. *Slovensko očami satelitov*. Bratislava: VEDA 2010. 263s. ISBN: 97-88022411-05-9.
[7] BARAN, Ondrej. - VYSKOČIL, Pavel et al. *Automatický systém pro příjem a zpracování družicových meteorologických snímkú* [online]. 2010 [cit. 2013-02-17]. Dostupné na internete: <http://brmlab.cz/_media/project/noaa.pdf>.EUMETRAIN.ORG.: Volcanic ash. 2010.
[8] ESA.INT. *ESA's Living Planet Programme* [online]. 2013 [cit. 2013-03-16]. Dostupné na internete:<http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/ESA_s_Living_Planet_Programme>.
[9] EUMETSAT.: *Europe´s future geostationary meteorological satellite system* [online]. 2012 [cit. 2013-03-20]. Dostupné na internete: <http://www.eumetsat.int/groups/cps/documents/document/pdf_br_prgfs01_en.pdf>.
[10] TRUSCULESCU, Marius. – BALAN, Mugurel et al. *Nanosatellites: The Tool for Earth Observation and Near Earth Environment Monitoring* [online]. 2012. [cit. 2013-03-20]. Dostupné na internete: <www.intechopen.com/download/pdf/27165>.

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