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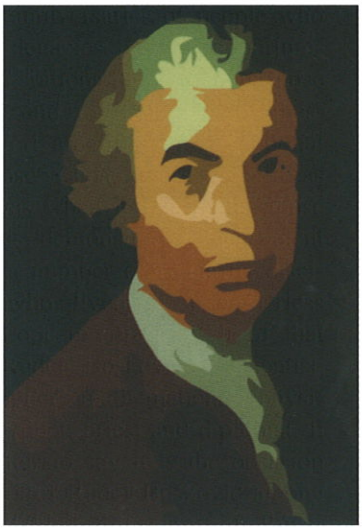
300th Anniversary of Ruđer Bošković's Birth, or 300 Years of Ruđer Bošković among Us



Birth or death anniversaries of people who left significant legacies provide opportunities for new generations to learn about those people. Forces and repercussions of messages in their work are different. Exceptional people are those whose work is still as present as it was when it was made, those whose activities demonstrated such talent and attempted a number of scientific disciplines, those who lived in a borderless Europe, as European citizens. All of that characterized Ruđer Bošković – scientist, natural philosopher, mathematician, physicist, technician, poet, priest and diplomat. It is therefore better to say it is the occasion of the 300 years of Ruđer Bošković among us than the 300th anniversary of Ruđer Bošković's birth.

What does Ruđer Bošković communicate to us through his life and work? First of all, excellence and talent always have to be developed and stimulated. Excellence generates advancements, new knowledge and new quality of life. Excellence is a value system and organization of social life. For Croatia, excellence means creating additional value in all segments of society.

Another dimension comes out of Bošković's working area, which is Europe. Being sovereign in the entire Europe, in the contemporary language of European Union is a message pointing Croatia in the right direction. It is also related to excellence because excellence is recognized in quality.

The third dimension is dedication to one's own mission and work, which is essential for producing great work and changing society.

Finally, the fourth dimension is spirituality, which resulted in such an eruption of talent and new knowledge. This can not be separated from Bošković, because he represents an entirety, as well as a message to present generations.

Ruđer Bošković can be considered for Croatian society as a "lighthouse" illuminating wide ranges of human creation for greater good.

Goran Granić

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e-mail: HATZ@hatz.hr, web: www.hatz.hr
Editor-in-Chief/Glavni urednik: Stanko Tonković
Editor/Urednik: Miljenko Lapaine
Secretary/Tajnica: Melanija Strika
Translator/Prevoditelj: Valentin Lapaine
Phone/Fax: + 385 1 4922 559 Fax: + 385 1 4922 569
Technical Editor/Tehnički urednik: Vladimir Pavlić, GRAPA, Zagreb, Croatia
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Chronology of Important Events in Organization of the 300th Anniversary of Ruđer Bošković's Birth

A letter by the Ministry of Science, Education and Sport (MZOŠ) from April 7, 2008 entrusted the Croatian Academy of Engineering (HATZ) with the organization of the Celebration of the 300th Anniversary of Ruđer Bošković's Birth. HATZ Presidency decided to accept this honour and duty. The first program proposal was produced by Prof. Dr. Z. Kniewald in September of 2008. CAETS and Euro-CASE were asked to sponsor celebration, which they accepted at the end of 2008.

In May of 2008, Prof. Dr. Z. Kniewald and Prof. Dr. S. Tonković visited the French Académie des Technologies in Paris where they takled to Dr. François Guinot, the President of the Academy. They also visited the Embassy of the Republic of Croatia in Paris, where they talked to Ambassador M. Galić and Embassy Secretary about the organization of the celebration in Croatia and France.

At the beginning of February 2012, a meeting was held in MZOŠ about the celebration program, its realization and financing. It was determined that urgent action was necessary. A meeting in MZOŠ held in the middle of June 2010 had 17 interested people discussing. The meeting resulted in a program proposal encompassing numerous ideas and possible activities related to the occasion of Bošković's anniversary in Croatia and abroad. Several other meetings were held before the final program was produced by Dr. G. Granić and sent to MZOŠ.

Let us emphasize that the Government of the Republic of Croatia proposed that 2011 be the Year of Ruđer Bošković in the Republic of Croatia. The proposal was confirmed by the Croatian Parliament, which decided that the President of the Republic of Croatia, the Government of the Republic of Croatia and the Croatian Parliament itself be sponsors of all events celebrating the Year of Ruđer Bošković, and MZOŠ and HATZ were charged with the execution of the celebration program.

Stanko Tonković

Central Celebration of the 300th Anniversary of Ruđer Bošković's Birth

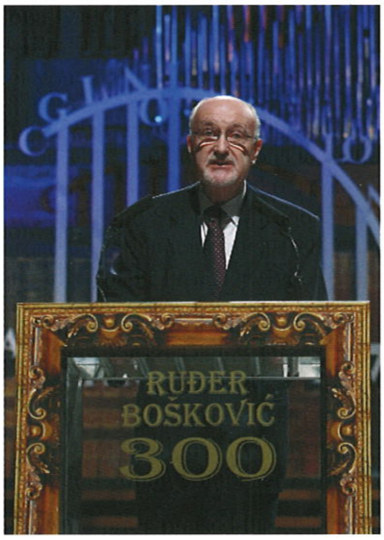
The Croatian Academy of Engineering and the Ministry of Science, Education and Sport organized the central celebration of the 300th anniversary of Ruđer Bošković's birth, which was held in the Vatroslav Lisinski Concert Hall on May 17, 2011.

The musical-scenic event evoked the time of the great scientist and philosopher. The large audience were able to hear welcome speeches and admirations to Ruđer Bošković by President of HATZ Prof. Dr. Stanko Tonković, Minister of Science, Education and Sport Dr. Radovan Fuchs, President of the Croatian Parliament Luka Bebić and President of the Republic of Croatia Prof. Dr. Ivo Josipović.

Distinguished experts on Ruđer Bošković Dr. Ivan Koprek, academician Žarko Dadić, Dr. Stipe Kutleša and Dr. Ivica Martinović talked about various aspects of Bošković's activities. The musical part of the program featured special compositions by Boris Papandopulo, Domagoj Košćak and young composer Zvonimir Dusper.

The audience and the press praised the celebration and Krešimir Dolenčić (director), Aljoša Paro (set designer), Willem Miličević (video and photo production) and executive producer Dr. Goran Granić, Secretary General of HATZ.

Speech by Prof. Dr. Stanko Tonković, President of HATZ



President of the Croatian Academy of Engineering Prof. Dr. Stanko Tonković speaks at the celebration

I am exceptionally pleased and honoured to greet you on behalf of the Croatian Academy of Engineering, one of the organizers of this celebration on the occasion of the 300th anniversary of Ruđer Josip Bošković's (Rogerio Josepho Boscovich) birth.

Ruđer Bošković was a man ahead of his time. He is one of the greatest names in Croatian and global scientific history. He is often considered a scientist, but I would perhaps consider him the most versatile person I have ever read or heard about. It is amazing what he managed to achieve in 76 years of his life. He was a Jesuit, scientist, philosopher, theologian, diplomat, skilled negotiator, writer, poet and a high ranking official in French Navy. Considering time he lived in, it is almost unimaginable how correct and revolutionary were his ideas about the physical structure of nature (atoms, atomic cores and molecules, in his most famous book A Theory of Natural Philosophy – Philosophiae Naturalis Theoria, 1758), which subsequently motivated and guided numerous scientists in evolving the modern particle physics. Bošković also wrote a number of papers related to mathematics, astronomy, optics, geodesy and cartography, hydrotechnics and famous stractural engineering expertises (dome of the St. Peter basilica in Rome, National Library in Vienna and the Cathedral in Milan). Ruđer Bošković was primarily a scientist and philosopher, but his ingenuity is also evident in solving practical problems of constructing astronomic, optical and geodetic instruments. His papers and ideas changed the scientific image of the world and his contribution to science and his technological and technical solutions make him one of the greatest global scientists and thinkers.

I would like to thank the audience again for making this celebration as great as it is!

Speech by Dr. Radovan Fuchs, Minister of Science, Education and Sport

Minister of science, education and sport Dr. Radovan Fuchs speaks at the celebration

It is an exceptional pleasure and delightful duty to address you on behalf of the President of the Government of the Republic of Croatia Mrs. Jadranka Kosor and myself on the occasion of the celebration of the 300th anniversary of Ruđer Bošković's birth. He was a Croatian scientist who earned this right after a long time, just like any other true visionary. If we asked Europeans of average education about Ruđer Bošković, I am sure their answers would be quite poor. Thus Bošković can be compared to Descartes, Galilei, Newton, Leibniz and other great new age individuals. Nevertheless, a complete opposite is the fact that Bošković's scientific dimension is sovereign in numerous fields and left a legacy to Croatian and European science and his cricital spirit, credibility and comprehensiveness managed to find its rightful place on the global scientific map.

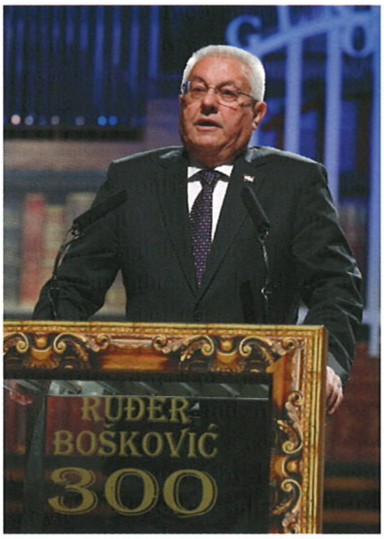
Ruđer Bošković, whose scientific work was made during five decades, offered a significantly different comprehension of space and time in comparison to numerous other distinguished contemporaries. When the Enlightenment was emphasizing the sensualistic, materialistic and atheistic worldview, Bošković rejected it and offered a significantly different understanding, which paved the way for the development of the human universe, defeating everything representing a negation of truth and justice. He built his own monument, with more than 75 capital books related to mathematics, mechanics, astronomy, optics, philosophy and literature, although he considered human work frail and ephemeral.

Each anniversary is also an occasion to send a message about the value system of a society, i.e. to show its attitude toward the past. In other words, the present and the past illuminate each other, studying history is really studying the present.

The bond between knowledge and social development is especially evident in our time. A successful future is related to a society characterized by knowledge culture, not neglecting knowledge economy. This trend of knowledge dependence, advancement, expansion and acceptance is accelerating and is becoming the central point. Science, as a field in which new knowledge is created, is the central engine of development, an activity which enables fulfilment of social needs, especially those in the field of work and general life quality. Knowledge and accompanying technological solutions are central resources for social welfare. Welfare growth is actually based on scientists who create and apply new knowledge and convey it to future generations. Despite considerable personal achievements, the existing level of competency, creativity, effectiveness and competitiveness of scientific work in the Republic of Croatia does not match needs of rapid social development. Without urgent and comprehensive changes, the present level of production, application and dissemination of new knowledge does not enable welfare realization. In this sense, a legal, organizational and financial reform of the science system and its research and educational part is a prerequisite of maintaining the Republic of Croatia in the civilization space of Europe and the developed world. We see the future of Croatia among developed countries of Europe and the world, and there is no country guaranteeing its citizens welfare, democracy and human rights while not paying greatest attention to the development of science and education.

All of this is conveyed to us by Ruđer Bošković via his life and work. His excellence, dedication and European foundation of messages are a call to our generation, and his permanent actuality and ingenuity are our motivation.

Speech by Luka Bebić, President of the Croatian Parliament


President of the Croatian Parliament Luka Bebić speaks at the celebration

Much has been said and written about Ruđer Bošković, his life and work. Nevertheless, he does not stop delighting, even three centuries after his birth. As difficult as it may seem to say something new about him, Ruđer Bošković still represents a real inspiration to scientists and the public.

Ruđer Bošković was undeniably an extraordinary person, a genius the likes of which is rarely born even in much larger and advanced countries. Perhaps our greatest draw to him was his versatiliy: he was a scientist, researcher and inventor, philosopher, diplomat and writer, a world citizen, patriot and a great humanist.

I will not delve into analyzing and evaluating his great scientific achievements, that is going to be addressed subsequently by his colleagues. However, I think this is a good opportunity for us to ask ourselves: what does Ruđer Bošković mean for present day Croatia?

Ruđer Bošković is one of Croatian greats who we are especially proud of and who makes Croatia famous in the world. He was an idealist devoted to science and global welfare who loved researching the universe and discovering its secrets. His discoveries advanced the entire humanity. It required exceptional talent, much work and persistence, creativity and some adventurous spirit.

We can freely say that Ruđer Bošković embodies the realization of a dream about the success of a man from a small country. Observed from the perspective of his life and exceptional results, Croatia is represented as a country of wise, persistent and versatile people. As a kind of "original product" from this area, Ruđer Bošković makes us recognizable and interesting in the contemporary globalized world.

Not intending to diminish the unmistakable successes of the relatively young Croatian diplomacy, I believe we are all going to agree that Croatian scientists and athletes have always been the best ambassadors of their country in the world, which was especially important when Croatia did not exist as an internationally recognized country.

Croatia is nowadays a member of all important international organizations and is soon going to become a part of the great European society. This begs the question of whether we want to seize offered opportunities, whether we want to be a factor, an active participant, an engine not only in international politics, but also in economy, science and culture, or are we merely going to be passive obersvers and consumers of other people's ideas and products?

A country cannot develop in a satisfactory way or advance if its economy is based exclusively on trade, tourism and construction. Leading, most advanced countries in the world are recognized by their products, especially those related to informatic and communication technologies, energetics, ecology, automotive industry, medicine, pharmaceutics, space exploration… Key roles in product development are played by scientific-research work and innovation, which enable market expansion and country's economic growth. It is the added value which is gained by leading countries of the world from scientific work results, both from national and international scientists, who were hosted and offered undisturbed working possibilities.

Numerous Croatian scientists work on research and scientific projects in mentioned fields in Croatia and abroad. In ideal circumstances, Croatia would be able to offer its scientists adequate research conditions so that they are not forced to go to other countries, as was the case of Ruđer Bošković. International acknowledgments to Croatian scientists bring fame to their homeland which they love and don't forget, even when they do research abroad. However, let us be honest, most often everything stops at just fame.

It is a priority for science in Croatia to be in center of all deciding social factors. Country and economic subject consensus considering the importance of investing in science is the only way which is going to enable our country to break through among the most advanced countries, which contribute to the advancement of the entire humanity. It is a comprehensive procedure which requires a lot of time, effort and first of all faith, but benefits for society as a whole are multiple, priceless and permanent.

Thus, I would like to commend all instances of investing in science and research from the country and private companies. Of course, more such investments would be desirable, and I firmly believe that we are gradually going to be able to realize this dream. Croatia has proved it is a country of talented, diligent, persistent and courageous people numerous times during its history. It is home of multiple Ruđer Boškovićs waiting to be discovered. Thus, let us enable them to develop their talents as much as possible, making them satisfied working for greater good! Therefore, let the 300th anniversary of Ruđer Bošković's birth motivate all of us for growth, aspiring to top results for creation of a competitive economy and society as a whole! Thus, I would like to congratulate this significant anniversary and wish all the scientists a lot of success in their work!

Speech by Prof. Dr. Ivo Josipović, President of the Republic of Croatia

I am glad to be able to greet you at the celebration of the 300th anniversary of Ruđer Bošković's birth. He was a great man, scientist and humanist, who left a legacy to the entire humanity. He was one of the leading thinkers of his time and one of the originators of modern science. He left a significant mark in European intellectual circles. His ideas still inspire scientists.

Ruđer Bošković can be considered a Renaissance man – a devoted Jesuit, theologian, philosopher, mathematician, physicist, engineer, astronomer, archeologist, poet and diplomat. He lectured at famous European universities and was a member of several of European academies of science, in London, Paris, Berlin and Saint Petersburg. His versatility is evident from his research themes and visionary enterprises: construction of bridges, roads, water lines, arrangement of the Tiber River, swamp draining, restoring the dome of the St. Peter in Rome, measuring the meridian arc between Rome and Rimini, establishment of the Milan observatory, inventing binoculars filled with water, an optical micrometer, dreamt of breaking through the Suez Canal and mocked those who criticized him for it.

According to existing records of Ruđer Bošković, he was imaginative and witty, *tuto fuocco* (fire itself), the most turbulent brain in the world and particularly stubborn. He loved Greek and Roman culture, especially antique mythology, not considering it unworthy of a Christian and believer and he also loved music. There is justice in the fact that our great master Papandopulo dedicated a composition to great Ruđer.

As all great people, Ruđer Bošković was also ahead of his time, but bound by its limitations. His personal drama was between affiliation and obedience to Jesuits and the Church and his philosophical and scientific belief and scientific imagination. Honestly devoted to Jesuits, he persistently sought a compromise between Church's teachings about the Earth's rest and contemporary scientific results, especially Newton's physics.

Although Bošković left Dubrovnik as a boy, he was tied to his homeland. He considered service to homeland a duty and an honour. In 1756, he wrote to his brother "The most important thing a good man has to do is to serve his homeland". Bošković acted in the same way: he was a diplomat for the Republic of Dubrovnik in times of peace, as well as in perils of war, when he sent help from afar and provided practical advice to improve life in the Republic.

If we consider messages Bošković left us, we can see they can be applied to the present. We still have to learn from him in scientific, practical and humanistic sense: he knew science and education are foundations for advancement of each society and was a living example of how actions were more important than words when it comes to patriotism.

Ladies and gentlemen, do we understand this message? Are we investing enough in science and education as engines of our society? Are we able – as indicated by President of the Parliament – to recognize those Ruđers who perhaps work at the Ruđer Bošković Institute, at institutes and universities in Zagreb, Rijeka, Dubrovnik, Split, Osijek? Are we willing to offer them what is necessary?

I believe this is the moment we should think about this subject, to think about whether the figures in the budget for science and education are enough. Do we pay enough attention and do we respect those who spend their entire lives working diligently using books, a microscope or a computer?

Personally, I do not think we are doing enough. This is our mutual responsibility and today, when we remember Ruđer Bošković, we have to promise ourselves we can do better, that we understand science and education are engines of contemporary society. Societies which do not recognize this are going to remain behind regardless of their former membership in the European Union.

This is why I am emphasizing the immeasurable value of legacy Ruđer Bošković left his country, Europe and the world. He was a visionary and a dreamer – he wanted to make the world a better place and improve the context of his three fundamental affiliations: science, Church and homeland.

President of the Republic of Croatia Prof. Dr. Ivo Josipović speaks at the celebration

Bošković and Technical Sciences

1. Introduction

Numerous pages have been written about distinguished and world famous Croatian scientist Ruđer Josip Bošković and his work. He was a scientist with a broad range of work: a philosopher, mathematician, physicist, astronomer, geodesist, instrument constructor, hydrotechnician, structural engineer, archeologist, as well as a writer and a diplomat. In preparation for the celebration of the 300th anniversary of his birth, we recalled in this Engineering Power (2008, Vol. 7, No. 1) his life and work with special emphasis on his contribution to technics. After the celebration, we surely learned something new about our famous forebear. This especially concerns technical sciences, a field of Bošković's activities, so this is a good opportunity to leave a record to help our successors in researching the life and work of the great invididual.

In the preparation of the following text, I had significant help from manuscripts listed in the list of references and which were produced in 2011 in preparation of the *Bošković Lexicon* edited by A. Bogutovac and published by the Miroslav Krleža Lexicographic Institute and the *Ruđer Bošković and Geosciences* monograph edited by myself and published by the Faculty of Geodesy of the University of Zagreb and Matrix Croatica.

2. Ruđer Bošković – Refiner and Inventor of Instruments and Proposer of New Measurement Methods and Instrument Checking

As Bošković strived to thoroughly examine each assumption, he analyzed and developed measurement methods and instrument rectification, and constructed and improved measuring devices he used in research and expert work in astronomy, geodesy or optics.

Most former astronomic and geodetic observations (measurements) were done using several instruments: binoculars with micrometer (for determining relative positions of celestial bodies), pendulum clock (for measuring time), quadrant (for measuring angles), sector (for determining zenithal star distances) and geodetic measuring rod (for measuring length).

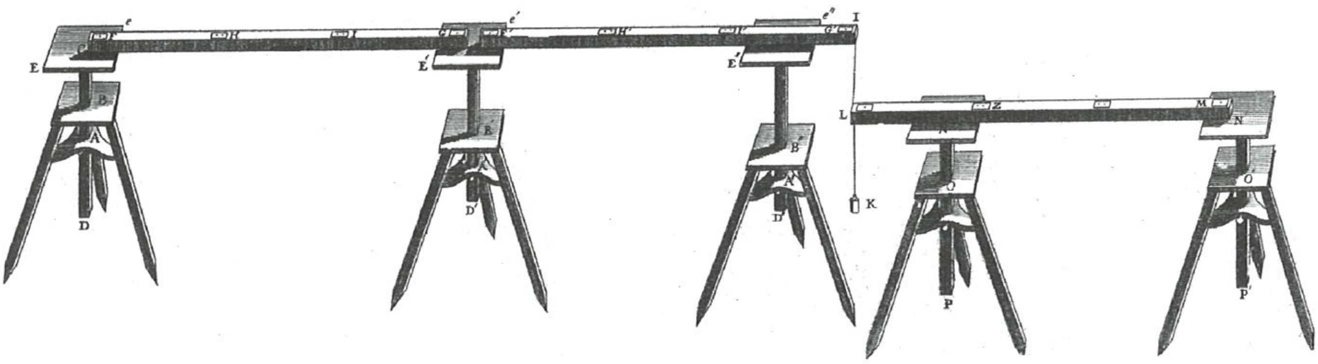
Astronomic observations of Sunspots and determining Sun rotation, passage of Mercury in front of the solar disc, comets, Sun and Moon eclipses, Jupiter's satellites and geodetic surveys with intention of measuring two meridian degrees (Rome–Rimini) motivated Bošković to systematically research and develop new instruments and measuring methods. His duties are also motivating: construction and equipping of a new observatory in Brera or obligations of optical research director in the French Navy. During this period (1736–1782), Bošković's original constructions resulted in several new instruments, such as circular micrometer, geodetic tripod, vitrometer and binoculars filled with water. Bošković also proposed numerous original changes and improvements to the geodetic measuring rod, quadrant, sector, pendulum clock and optical micrometer.

After Bošković finished studying philosophy in 1732, he instensively studied Newton's natural philosophy and started publishing scientific and expert treatises about astronomy and observed astronomic phenomena and events (Sunspots, passage of the Moon in front of the Sun, Sun and Moon eclipses, etc.). Bošković started dealing with instruments in 1739, during his study of theology and stimulated by practical issues of following comets.

2.1. Circular Micrometer

Rather than determine positions of comets in relation to positions of known fixed star using binoculars with a micrometer, Bošković proposed a simpler method without using a special micrometer. Measuring the time of a celestial body (e.g. a comet) and a star of known coordinates (α, δ) entering and exiting the visible field of binoculars, one is able to calculate the difference between the time of entering (exiting) between a star and a comet, and thus its right ascension (α). The procedure can also be used to determine the difference between declinations (δ), as well as the field of vision diameter (Marković 1968). Bošković described his method and the construction of a circular micrometer in the treatise *De novo telescopii usu ad objecta coelestia determinanda* (*On the New Use of Binoculars for Determining Celestial Object*) from August 1968.

The treatise is the oldest publication about the circular micrometer, making Bošković the most probable inventor of the circular micrometer. In 1742, Bošković published three treatises (dissertations), two of which were related to instruments and observation methods. In *De observationibus astronomicis et quo pertingat earundem certitudo* (*On Astronomic Observations and the Extent of Their Reliability*), Bošković discussed existing astronomic instruments, principles on which they were constructed, evaluation (rectification), instrumental reliability and application in astronomic surveys. Namely, Bošković discussed the advantages of using a micrometer and lists the sources of error in such surveys. He also mentioned the quadrant and warned about surveying zenithal star distances because hypotheses of the direction of gravity and the spread of light were not proven. Bošković analysed hypotheses in practical astronomy, which are bases of astronomic observation methods, in the dissertation *Disquisitio in universam astronomiam* (*Reasearch of the Entire Astronomy*). The Moon eclipse of April 1744 inspired Bošković's treatise *Nova methodus adhibendi phasium observationes in eclipsibus lunaribus …* (*New Method for Application of Moon Eclipse Phase Observation …*) in which he presented his method of determining the beginning, end or any other phase of the eclipse and determining the shadow diameter and apparent speed of



Measuring rod on Bošković's tripods

the Moon's center with four micrometer surveys of the dark side of the Moon.

Although Bošković developed the theory in 1739 and proposed original methods of measuring with the circular micrometer, it was not until the period of manual instrument construction between 1750 and 1785 that he achieved significant success in construction and testing geodetic, astronomic and optical instruments.

2.2. Geodetic Tripods and Measuring Rod

Determination of the Earth's shape was an important problem in the scientific world of the time. The problem motivated Bošković for theoretical disussions and surveying to test hypotheses. He participated in the measurment of the meridian arc length between Rome and Rimini from 1750 to 1752. During the survey, Bošković and his assistant Maire insisted on the greatest possible accuracy of geodetic measuring of angles and lengths, as well as of astronomic determinations of zenithal star distances. Thus, prior to surveying, Bošković had to improve the existing or construct a new tool for measuring length. Due to field asperity, it was impossible to accurately measure lengths of less than several kilometers, let alone those of 100 kilometers. Bošković had an idea to elevate measuring rods by placing them in horizontal position in the direction of base on special tripods. The tripods were constructed in such a way to enable simple change in height of the plate on which measuring rods are placed.

According to Bošković's blueprints, three measuring rods were produced in 1751 from old masts, each rod 27 palm lengths long (5.994 m) with divisions at every 9 palm lengths (1.98 m). Rod ends and divisions were marked with brass plates with holes. Bošković compared measuring rod lengths in base measuring with a special iron scale nine spans long, taking into consideration its stretching. First, based on the known coefficient of iron stretching and measured temperature, he calculated iron stretching and determined the length of the iron scale and the measuring rods. Bošković did not allow the measuring rods to touch. Gaps between measuring rods (between border brass plates) were measured using a compass and the value was read on a diagonal scale. Rod connections, which were not at the same level due to asperity, were placed in vertical direction using a plumb-bob. Tripod and measuring rod horizontality were controlled using levels. Previous and subsequent surveys were done using "contact" measuring rods, whose ends determined its length. Surveys using such rods decreased base survey accuracy, regardless of how precisely the rods were placed next to each other.

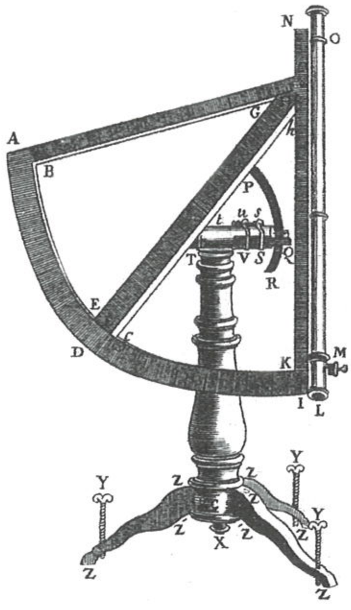
Even though tripods were constructed according to Bošković's original idea, they were unjustly named Gaussian, because Gauss proposed their introduction into geodetic practice.

2.3. Circular Quadrant and Zenithal Sector

Since the application of triangulation changed length measuring accuracy to angle measuring accuracy, Bošković needed to significantly improve existing or construct new angle measuring instruments. At the time, quadrants and sectors were used to measure angles and Bošković was familiar with their construction. However, he improved those instruments by adding new instrumental solutions and testing their accuracy.

a) Circular quadrant

Quadrants were used at the time to measure angles (horizontal directions) in triangulation. Bošković's quadrant



Bošković's quadrant

was similar to plain ones, but its precision was increased and a micrometer added (Bošković's original solution) to increase angle reading accuracy.

b) Zenithal sector

Bošković determined star positions (zenithal distances) using a comprehensively reconstructed sector in which added several of his original instrumental solutions enabling high accuracy (at the time). In selection of stars, he considered their zenithal distances, primarily due to instrument capabilities, as well as to reduce the effect of astronomic refraction.

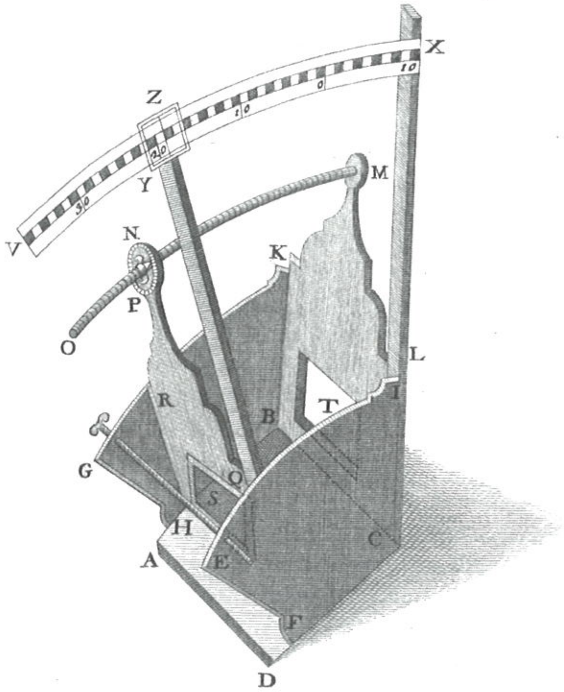
In the fourth report book published in Rome in 1755 in five books titled *De litteraria expeditione per pontificiam ditionem ad dimetiendos duos meridiani gradus et corrigendam mappam geographicam* (*On the Scientific Expedition Through the Papal States in Order to Survey Two Meridian Degrees and Correct the Map*), Bošković analyzed all issues related to practical astronomy and described instruments and tools he used in geodetic and astronomic survey of the Rome–Rimini meridian. All the instruments were constructed according to Bošković's ideas and blueprints, significantly enchanced with original parts and solutions. At the same time, Bošković proposed new methods of instrument rectification, comprehensively and critically analysed potential errors and proposed methods to reduce or eliminate them.

After exhaustive and long surveys and calculating and writing reports about survey results, Bošković published his capital work in 1758 titled *Philosophiae naturalis theoria redacta ad unicam legem virium in natura existentium* (*A Theory of Natural Philosophy Reduced to a Single Law of Forces Existing in Nature*) and continued researching, as well as travelling around Europe. Based on his research of optics, in 1755 he published the treatise *De lentibus et telescopiis dioptricis* (*On Lenses and Dioptric Binoculars*) and produced several sundials.

2.4. Bošković's Vitrometer

Upon his return to Rome in 1763, after numerous travels around France, England and Greece, Bošković was unexpectedly invited from Milan to lecture at the University of Pavia in 1763. Bošković established an observatory in Brera, which was initiated by the rector of the Jesuit board. Bošković produced all blueprints, made a program of scientific research and astronomic observations and envisioned astronomic equipment of the observatory, but he also brought his valuable instruments in order to make the observatory one of the best in Europe.

When Bošković came to Pavia and especially after the observatory was built, he wanted to organize scientific and research work there, so he intensitvely researched lenses and improvements to optical devices. In 1763, he published the first two treatises of *Dissertationes quinque ad dioptricam pertinentes* (*Five Treatises On Dioptrics*) in which he described research of errors resulting from thickness and round shape of lens, as well as from different refractions of light.



Bošković's vitrometer

In order to determine refraction index and dispersion of light in lenses, Bošković constructed a new device and named it the vitrometer.

The first version of the vitrometer from 1763 contains two glass prisms, one of which is fixed and the other is filled with water and can be adjusted. Adjusting the second prism reduced refraction of light. The second, highly improved version of the vitrometer from 1773 lacks the prism filled with water, but contains Abate's glass prism with variable angle. The prism consisted of two lenses (biconcave and biconvex) with equal curvatures. Lenses cling to each other by curved surfaces, and plane bases determine the angle of inclination. Although Bošković conducted multiple experiments with the vitrometer and warned about Newton's two incorrect assumptions, he primarily required the vitrometer for testing and improving achromatic binoculars.

2.5. Binoculars with Water

In 1766 and 1773, Bošković proposed an experiment to test the nature of light, i.e. determine whether the speed of light is greater in a material with greater density. The light aberration would also be observed. Bošković and Newton advocated the corpuscular nature of light, by which speed of light should be greater in a material with greater density (e.g. water), while aberration would be smaller. He conceived a new type of binoculars for this experiment – binoculars with water.

Bošković never managed to realize the experiment due to financial reasons. However, in the section *Theoria, & constructio novi telescopii propositi* of the second volume of *Opera pertinentia ad opticam, et astronomiam* he published and explained the theory and use of the new binoculars. The experiment is still considered to be *one of Bošković's brightest ideas*.

2.6. Pendulum Clock

In 1769, Bošković elaborated a new type of improved pendulum clock and offered it to the Royal Academy of Science in Paris. He intended to improve the clock due to changed in temperature and raising/lowering the center of oscillation without stopping the clock. The evaluation committee's basic objection was that Bošković was not familiar with the latest developments in clockmaking, stating which of Bošković's solutions were not new and according to existing theoretical and practical development of clockmaking. In the same year, Bošković replied to the committee in *Descrizione d' un nuovo pendolo a correzione* (*Description of the New Pendulum Clock With Correction*) and represented the pendulum clock's construction and its integral parts. The text was published as a chapter in a paper by Italian physicist G. Toaldo.

2.7. Optical Micrometer (Prisms with Adjustable Angle, Bošković's Prisms)

Bošković's longtime research and quality improvement of astronomic instruments and lenses, reduction of their errors and measurement errors continued after he became the director of optical research in the French Navy. When he was still in Brera, he constructed a new instrument called vitrometer for testing and improving achromatic binoculars. He continued that research in Paris, because the French Navy used achromatic binoculars on their ships. Bošković also did theoretic research and constructed a new optical micrometer.

Motivated by invention of physicist A. Rochon, who in 1777 constructed a micrometer for measuring small angular distances between the Sun and planets as well as distances between stars, Bošković proposed that a prism made out of pure quartz in Rochon's construction be replaced with a plain glass prism on the condition that the prism was smaller than the binoculars' objective. In such a micrometer, the image of one object is produced directly and the image of another object is produced by rays which passed through the prism. Bošković improved that micrometer by using two prisms with circular bases, subsequently named *Bošković's prisms*, which rotate around a mutual axis setting it into the binoculars between the objective and the focal point. The principle was also applied by Bosshardt (1920) to reduce oblique lengths to the horizon by using a pair of equal prisms which rotate in opposite directions.

2.8. Bošković's Gravimeter

Bošković conceived and described a prototype gravimeter in which the effect of gravity is transferred to a weight via an elastic spring and a wheel on a pointer. He was ahead of his time because the first contemporary gravimeters were produced in the first half of the 20th century (L. LaCoste i A. Romberg, 1936).

3. Mathematical and Statistical Analysis of Astronomic and Geodetic Surveys

Varićak (1910) described Bošković as a mathematician: "If in philosophy he is a spirit, which rises high above apparent phenomenon observed with our senses, he is not a friend to speculation in mathematics. He does not invent abstract problems nor build mathematical fortresses on a thin branch made of clouds, but he mostly works on issues he came upon naturally in astronomic and geodetic work or thinking about physical problems. Thus due to astronomic special tasks, he researched spherical trigonometry; which is surely the reason why he dealt so much with the theory of conic sections. Geodesy brought him to the first attempt of adjustment calculus ever done. He already thought about the effect of mountains on the pendulum a long time ago – which has to be taken into consideration in surveying in geodesy and astronomy – he gladly accepter Montigny's proposal to study the issue of the body of maximal attraction and was the first to solve it. He studied the properties of the sine curve synthetically because he required it to determine the appearance and disappearance of the Saturn's ring; he warned about difficulties of direction in discsussion of straight spread of light, etc.

It can be thoroughly proven that Bošković never dealt with mathematics just for the sake of it; he used it as a powerful tool for testing in other fields, thus he wanted to perfect it. This is not in contrast with him discussing discrete geometry or mentioning the issue of the possible existence of the infinitely large; those are merely reflections of his philosophical ideas."

3.1. Spherical Geometry

Bošković's first scientific contribution to mathematics was the discussion *Trigonometriae sphaericae constructio* (*Construction of Spherical Trigonometry*, 1737). In six prospositions, he offered a solution to basic problems of spherical trigonometry by using a graphical construction, i.e. a representation of relations between values using a plane drawing.

Bošković studied spherical trigonometry to facilitate its application in astronomy and geodesy. He published the treatise again with minor changes in the third volume of *Opera pertinentia ad opticam et astronomiam* (*Works Related to Optics and Astronomy*, 1785). He pointed out that procedures listed in it are useful when high accuracy is not very important, i.e. for checking data obtained by calculation.

In *Trigonometria sphaerica* (*Spherical Trigonometry*, 1745), Bošković systematically analysed spherical geometry in 23 pages. In the introduction, he noted three lemmas from elementary geometry and defined the sphere, great circles (according to Bošković, greatest), diameter, poles, spherical angle, spherical triangle and its properties. In the first part, he analysed the rectangular spherical triangle, in the second the oblique-angled spherical triangle, and finally provided a general list of 13 canons (*canones*) and 3 rules (*regulas*) encompassing all possible cases of spherical triangles. In contrast to his 1737 work in which he analysed graphical constructions, here he derived relations about triangle elements. Bošković did not write formulae using symbols, which is nowadays a common practice, but he described them in words.

In the same year, the work was included in the textbook by A. Tacquet titled *Elementa Euclidea Geometriae planae ac solidae, et selecta ex Archimede Theoremata ejusdemque Trigonometria plana* (*Euclidean Bases of Plane Geometry and Solids and Selected Theorems from Archimedes and his Plane Trigonometry*, 1745).

In the first volume of *Elementorum universae matheseos* (*Elements of Entire Mathematics,* 1754), Bošković wrote the chapter *Trigonometry*, in which he provided bases of plane and spherical trigonometry in 77 pages and 13 figures. The second volume encompassed algebra. The third volume is the most original, containing the theory of conics and geometric focus transformations. In that volume, Bošković analysed issues of continuity and infinity in the geometric context.

3.2. Bošković's Differential Forumulae of Spherical Trigonometry

Relations between elements of spherical or plane triangle are important in researching measurement errors in astronomy and geodesy. Bošković studied differential changes of elements of (spherical) triangle within the scope of studying astronomic instruments which he conceived and conducted as the director of the Brera observatory. Around 1770, he derived four formulae in which a differential change of one of the six elements of any triangle (three sides and three angles) is related to differential changes to any three of five remaining elements.

Bošković derived formulae which he called main or general differential formulae of spherical trigonometry. He sent a paper about them to the *Académie des sciences* in Paris to be published in 1772, but he unfortunately withdrew it even though it was accepted and published it in the fourth volume of his *Opera pertinentia ad opticam, et astronomiam* pod naslovom *De formulis differentialibus trigonometriae / De formules differentielles de trigonometrie* (*Works Related to Optics and Astronomy* titled *Formulae of Differential Trigonometry*, 1785), where he wrote: *"...when we have a small change in one of six elements, at least three of remaining five elements are also going to change slightly – the change can affect the remaining four or even all five elements. I refer to differentials of sides or angles as small changes. There is interdependence among the differentials which can be used to determine ones in relation to others. The relation is expressed with equations or analogies. Here I am going to provide formulae which contain these general equations and the way they can be used in certain cases with several examples of their application to astronomic problems."*

Bošković derived main differential formulae of spherical trigonometry in two ways: by elementary geometrical observations and differentiating selected relations for spherical triangle. He successfully applied those formulae to selected astronomic problems in that and other chapters of *Opera pertinentia ad opticam, et astronomiam*.

Bošković's main merit is in selecting four basic formulae out of a number of formulae associating triangle element differentials (he counted 500).

Bošković answered the question of why he chose those four fomulae in the introductory part of the treatise *On the General Idea of the Subject of This Opuscula* (*Idée générale de l'objet de cet Opuscule*), in which he explained four possible cases: 1. three sides and an angle; 2. two sides and two angles, one of which is between those sides; 3. two sides and two angles opposite of them and 4. three angles and one side.

3.3. The Bošković-Laplace Method

The method of evaluating measurement errors and mathematically eliminating their effect is based on Bošković's proposition according to which data obtained by measuring meridian arc lengths should be adjusted in the following way: a) meridian degree differences should be proportional to sinus versus differences (versin $x = 1 - \cos x$) of double latitudes, b) sum of positive corrections should be equal to the sum of negative corrections (according to absolute value), c) sum of absolute values of all corrections should be as small as possible.

Bošković's predecessors, e.g. Greek astronomers Hipparchus of Nicaea and Ptolemy, astronomers T. Brahe, J. Kepler and G. Galilei, English mathematician R. Cotes sought ways to reduce the effect of measurement errors applied certain average values or the arithmetic mean as the basis for most reliable values. The method by German astronomer T. Mayer, Bošković's contemporary was also not objective because classifying data into groups depends on the classification criterion. Bošković was the first to propose a method based on objective criteria.

In his first attempt to determine the Earth's shape, Bošković compared his arc lengths measurements of one meridian degree between Rome and Rimini and four other measurements he considered accurate enough. Those were measurements done in Quito (South America), Cape of Good Hope (Republic of South Africa), Paris (France) and Laponia (Finland). Bošković wanted to determine an ellipsoid which would be compatible with all five meridian degrees. He first tried combining two meridian arc lengths at a time corresponding to one degree of latitude. Since that procedure did not yield satisfactory results, he conceived a better one.

In the abstract of *On the Scientific Expedition Through the Papal States in Order to Survey Two Meridian Degrees and Correct the Map* (1757) in the fourth volume *De Bononiensi scientiarum et artium Instituto atque Academia commentarii,* Bošković described for the first time in detail his procedure of eliminating the effect of measurement errors. He explained it comprehensively in article 395 in supplements to Latin verses *Newer Philosophies of Benedikt Stay* (1760).

Let us emphasize that the Bošković-Laplace method is not limited to estimating measurement errors and eliminating their effect on the meridian degree arc length measurement results, but it can be applied to any related problem in which data follow a linear relationship. It can be said that the Bošković-Laplace method corrects the line position to a set of plane points (*Bošković's line*) in a way that the sum of all residuals is zero and the sum of absolute values of residuals is as small as possible.

Bošković's and Maire's work is supplemented and translated from Latin to French under the title *Voyage astronomique et geographique dans l'État de l'Église* (1770). It contains the most comprehensive presentation of Bošković's method of eliminating measurement error in the *Note* at the end of the fifth chapter, where there is also a calculation example which included the latest measurements.

Bošković interpreted the application of his method geometrically, with little calculation and without an analytic approach, which would describe the procedure using analytic mathematic expressions. French mathematician P. S. de Laplace became interested in Bošković's work. Laplace studied the problem of determing the geometrical shape of the Earth on several occasions, including Bošković's method of eliminating measurement error effect which he accepted and elaborated. In his work *On Several Points of the World System* (*Sur quelques points du système du monde,* 1789), Laplace applied Bošković's method and provided its first analytic representation and derivation. Therefore, the method first conceived by Bošković is nowadays referred to as the Bošković-Laplace method.

4. Bošković and Geodesy, Geology and Geophysics

4.1. Determination of the Meridian Arc Length and Definition of the Meter

When Bošković lived, people knew Earth was not a ball, but it was unknown whether it is flattend or elongated at poles, making that problem a very important scientific subject. Some of Bošković's first works were those about determining the Earth's shape.

Bošković assumed Earth was more irregular than a rotational ellipsoid, i.e. that meridians have not the same length and that parallels are not circles, and the assumption was supported by measuring arc lengths of different meridians in approximately same latitudes. In order to conduct such measurement, Bošković first had to find a sponsor. Pope Benedict XIV required a new accurate map of the Papal State, and since similar measurements are made for map production and arc lenght measurement, the Pope became a sponsor of the demanding endeavour. It was neccessary to devise a geodetic trigonometric network, carry out geodetic and astronomic measurements and finally, do calculations and produce a map.

Bošković did not have practical experiences with geodetic measurements. However, he was informed of his predecessors' and contemporaries' work, he noted errors or limitations in their methods and attempted to eliminate them. In order to avoid restrictions in measuring the length of trigonometric network base, he invented geodetic tripods (1751). The secretary of *Académie des sciences* J.-J. Dortous de Mairan sent him an iron measuring rod of academicians from Paris which was one toise long (around 1.95 m) with marked smaller units: feet, inch and parts of inch. A directly measured length of Roman base only differed in one step from the length of a Roman base calculated from the trigonometric base starting with the length of the Rimini bases, which demonstrated all geodetic measurements were very precise.

In order to determine the length of meridian arc between Rome and Rimini, Boškvić employed a trigonometric chain, which consisted of 11 triangles at distance of almost 240 km. The shortest triangle side was 22.79 km long and the longest 68.27 km. The trigonometric chain was placed in a way that the first point passed the top of the dome of the St. Peter basilica in Rome. Angles in triangles were measured using a quadrant with a radius of 3 Paris feet (about 90 cm), after which they were reduced to the horizon. The micrometer which Bošković added to the quadrant in order to increase its accuracy was produced in the *Collegium Romanum* workshop. All trigonometric network calculations were derived from the Rimini base, which was at a low altitude, which meant its length did not have to be reduced to the sea level. The length of the Roman base was used to control measurement and calculation accuracy. Bošković and Ch. Maire conducted astronomic and geodetic measurements along the Rome–Rimini meridian for two years. They analysed results for almost three more years. Precise astronomic measurements yielded the celestial arc between Rome and Rimini average of 2°09'47,0", e.g. after small correction the length of one degree of the Rome-Rimini meridian arc equals 56 979 toise.

Results of this great survey initiated by Bošković are described in detail in the comprehensive scientific report in 5 books titled *On the Scientific Expedition Through the Papal States in Order to Survey Two Meridian Degrees and Correct the Map* (1755). The main results were published three more times: 1757 in a brief report for the Bologna Academy journal which was translated from Latin to Croatian and published in Zagreb in 1961, then in 1760 in a supplement to the poem *Newer Philosophy of Benedikt Stay* by B. Stay and in 1770 in the French translation of *Voyage astronomique et geografique dans l'État de l'Église*. Therefore, nowadays there exists more comprehensive and detailed documentation about the Rome–Rimini meridian arc measurement than about any other meridian arc measurement.

In those works, Bošković and Maire proved that the length of one degree of the Rome-Rimini arc measured at the average latititude of 43° varied as much as 69 toise from the length of the Paris meridian as determined by C.-F. Cassini de Thury and N. L. de Lacaille at the average latitude of 43°31'. In theory, the difference due to difference in latitudes could be only 8 toise. Bošković also analysed measurement errors and concluded they could not have been so great to make the difference 69 toise. Results confirmed Bošković's assumption that the Earth's shape is more complex than the one of the rotational ellipsoid. Bošković was the first scientist who stated and proved the hypothesis.

Bošković insisted that meridian arc measurements be performed in other countries as well. His solicitation at the court of Empress Maria Theresa enabled Austrian astronomer J. Liesganig to measure the length of the meridian arc in Hungary. Measurements of two arc lengths were carried out: from Varaždin to Brno and from Czurok (Čuruga, Vojvodina) to Kistelek (Hungary) from 1760 to 1768. Bošković also stimulated the measurement of the meridian arc in Piemont (1759). When Bošković stayed in England, he presented to the *Royal Society* how science could benefit from such measurements in America. Subsequently, English astronomer Charles Mason (1728–1786) and English researcher and astronomer Jeremiah Dixon (1733–1779) measured meridian arc lengths in addition to measurements in North America for needs of demarcation and establishing the so called *Mason–Dixon Line*.

Forty years after Bošković's measurement of the meridian arc (1793), following a proposal of the committee of the *Académie des sciences*, the French National Committee decided to use the ten millionth part of the Earth's meridian quadrant in order to introduce unique and accurate measures of length. The length, "*natural and permanent and constant for all nations*" was named the meter. French scientists did not take into consideration measurement and their effect on the end results or Bošković's proof that not all meridians are equally long.

4.2. Earth's Shape

When we say *Earth's shape*, it is not entirely clear what it refers to. Geosciences accepted the definition of the Earth's shape or geoid according to which it is a surface of constant potential of the Earth's gravity which approximates the average sea level as well as possible. It is perpendicular to the direction of gravity in each point. Due to irregularities in composition of Earth's matter and its various densities, the surface is smooth, but irregular and undulating. Considering geodesists and astronomers use a plumb-bob for setting measuring instruments in the horizontal position, they have to know the Earth's shape as well as possible.

Bošković related the Earth's internal structure to the Earth's shape in *On Old Proofs for the Spherical Shape of the Earth* (1739), *Discussion about the Earth's Shape* (1739) and *On the Disparity Between Gravities at Various Places on the Earth* (1741). In *On the Scientific Expedition Through the Papal States in Order to Survey Two Meridian Degrees and Correct the Map* (1755), Bošković wrote about the geoid, although he did not call it that way, which was introduced in science a century later: "*...the term Earth's shape, which apparently has a constant and determined meaning, actually has a very unstable and unclear meaning. The area which borders seas, lakes, hills, plains and valleys is really, at least for me, very irregular, even unstable, because it changes with every movement of waves and the Earth's parts. However, those who examine the Earth's shape do not discuss this. Instead they take the other form, which is somewhat regular and very close to the mentioned one, which would be obtained if mountains and hills were leveled to the ground and valleys filled. Nevertheless, this conception of the Earth's shape is also very unclear and unstable. As there are countless types of regular curves which can pass through a given number of given points, so there are countless types of regular surfaces which can envelop the Earth so as to touch either all or given mountains and hills in given points. If a surface has to pass through the middle of a mountain or a hill, it should be regular and should exclude as much material from the outside as air beneath it, until the real, for me irregular Earth's surface, which we see, is obtained, as well as countless and different surfaces, which satisfy the problem. They can even not represent an observable unevenness, and that word also does not contain a very determined term. (...) What happens if the Earth's shape is so irregular – which can be freely assumed based on what we said – that even meridians themselves are disparate and that parallels do not correspond to circles?*"

Explaining the purpose of measuring the meridian arc in the Papal States in 1750, Bošković wrote: "*It has been long since I have assumed irregularity which could be related to the Earth's shape by an uneven composition of its parts. If such disparity is huge and if it is found even in parts very distant from the Earth's surface, irregularity is also going to be huge. If the disparity is small and near the surface, such as mountains and hills, it is going to cause small irregularity, but it is also going to disarrange the procedure which takes degrees to determine the shape*".

In measuring the meridian arc length, Bošković observed that the effect of attractive forces of mountain masses on the deviation of the plumb-bob of astronomic and geodetic instruments is significantly less than expected, leading him to the conclusion that mountains were hollow. Similar discrepancies between expected and measured deviations of the plumb-bob were observed in the expedition of triangulating the Andes in 1735, and published by French geophysicist P. Bouguer in 1749.

Bošković was the first to use the term compensation in discussion of the Earth's structure in *On the Scientific Expedition...*: "*I believe hills were mostly elevated by heating expansion of matter in the deep (...). The void originating in such a way within mountains compensates accumulated matter above them*".

The idea of mass compensation was also used by Bošković in the treatise *On Astronomic Observations and the Extent of Their Reliability* (1742), observing high and low tides under the assumption of the average density of the Earth; he believed the weight of solid parts of the Earth is compensated by subterranean caves and empty spaces. This is similar to L. da Vinci, who considered the rigidity of the crust insufficient to withstand the immense pressure of mountain ranges, so he insisted on a different explanation.

In *Works Related to Optics and Astronomy* (1785), Bošković explained that the Earth's internal parts are denser than the external ones, using the term "crust", foreshadowing the terms isostatic surface and discontinuity: "*...from small action done by huge mountains by deviating the pendulum of astronomic instruments which had however been found to exist, but it is small, it appears that it can be derived that the Earth's density in greater depth* *below the surface is much greater than near the surface; although it could originate from mountains having huge cavities. Most or even all of them originate from Earth's layers forcefully raised by internal flames, but in this case their mass does not generally attract but attracted before it was raised; which accrues, just the attracting force of water mass which was absorbed in the remaining voids and filled them to a certain level, making it the sole cause of this small deviation".*

In addition to being the first person to introduce the term compensation, Bošković was also the first to warn about the effect of mass distribution in the Earth's surface: "*...it is more likely that plumb-bob deviations are caused by wide continent and sea surfaces than individual mountains and should therefore by of a systematical meaning".*

Bošković realized the importance of the gravimetric survey a year before the originators of the first isostasy theories (hydrostatic balance of parts of the Earth's crust and mantle). He conducted the survey by determining the length of the seconds pendulum. He emphasized the need for systematical measurements in as many points as possible on land and at sea. Bošković also conceived a prototype gravimeter (instrument for measuring gravity, i.e. its differences) which would transfer the effect of gravity onto the weight of that apparatus over an elastic spring and a wheel on a pointer to indicate changes in weight. Such an instrument could also be positioned on a ship, which would enable gravity to be measured in several places during navigation.

Regardless of Bošković, the 1854 discussion by British mathematician J. H. Pratt about the discrepancy of calculated and observed deviation of the plumb-bob in measuring the so-called Indian meridian motivated English mathematician G. B. Airy in 1855 to publish the theory of isostasy – the theory "*about supporting great mountain masses in a hydrostatic balance above lower denser masses of Earth's magma, separating the Earth's crust from these masses and binding it from the bottom side with the so-called isostatic surface"*. According to Airy's theory of topographic mass compensation, mountains float on liquid lava of greater density, i.e. the higher a mountain is, the deeper it sinks. Airy's idea was not accepted at first, and it was continued to be studied by Pratt in his works; according to Pratt, mountains rose from the underworld similar to a fermenting dough.

The existence of the isostatic surface was confirmed at the beginning of the 20th century by analyzing earthquake odochrones (a graph representing the relation of the time an observed earthquake wave travelled to the epicentre distance) by Croatian seismologist A. Mohorovičić and the discovery of the boundary between the Earth's crust and mantle (Mohorovičićev discontinuity or Moho). Nowadays it is confirmed that most of the Earth is isostatically compensated.

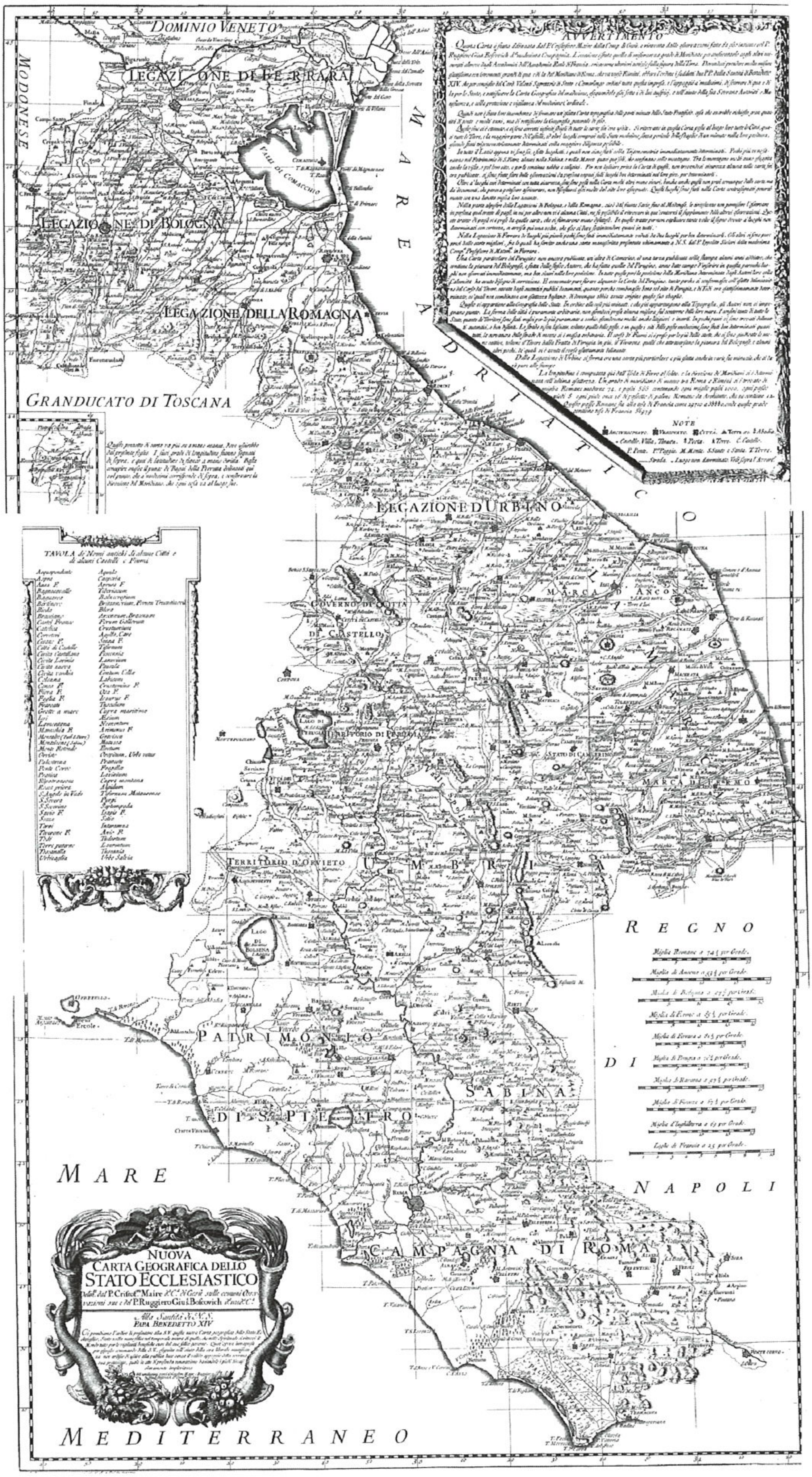
5. Bošković and Cartography

Bošković's co-author work on the first exact map of the Papal States is among the harbingers of Croatian cartography. Portuguese king Joao V was the first to motivate Bošković to conduct geodetic surveys by calling him to participate in the production of the border area of Brazil. Since Bošković was interested in the current problem of determining the Earth's shape, he accepted it on the condition that the king paid for measuring one meridian degree near the equator. Cardinal S. V. Gonzaga, state secretary of the Holy See and Bošković's friend did not like the idea of Bošković going on such a distant and unsafe travel and he managed to get an order and funds of Pope Benedict XIV to make Bošković measure the length of two degrees between the Rome-Rimini meridian instead and correct the existing map of the Papal States.

With his assistant, English Jesuit, astronomer and cartographer Ch. Maire, Bošković spent two academic years (1750–52) doing field work. Results were published in the scientific report *On the Scientific Expedition Through the Papal States in Order to Survey Two Meridian Degrees and Correct the Map* (1755), which was divided into five books. Bošković wrote the first, fourth and fifths book, while Maire wrote the second and the third one. In the first book, Bošković stated the purpose (determination of the Earth's shape), difficulties (climbing towers, belfries and mountain peaks) and research results. The third book, *Representation of what was Derived In Order to Correct the Map of the Papal States* (*Enarratio eorum, quae ad corrigendam tabulam geographicam Ditionis Pontificiae peracta sunt*) in 25 chapters is about works which preceded the production of the new map. It ends with a list of 84 cities in which latitudes and longitudes were determined trigonometrically. The work is supplemented with three sheets of the *New Map of the Papal States* (*Nuova carta geografica dello Stato Ecclesiastico*), which was not bound in the book due to its large format. The map was produced by Ch. Maire, and the text on it (*Avvertimento*) was written by Bošković.

In addition to the representation of the Papal States, which encompassed the area of contemporary central Italy, the map contains four cartouches. The one in the lower left corner contains the map title with names of authors and a dedication in Italian, the one in the upper right corner contains the text *Notes* (*Avvertimento*) in Italian and a legend, with graphic scales on the right. The decorated cartouche next to the frame on the left side, with the *List of Names of Some Old Cities, Castles and Rivers* (*Tavola de' Nomi antichi di alcune e di alcune Cittŕ di alcuni Castelli e Fiumi*), contains names in Italian and Latin.

In contrast to the Latin edition of the geodetic report, the French translation of the map of the Papal States (*Carte de l'État de l'Église*) is reduced to a third (scale of about 1:1 122 000) and bound in book and preserved in several copies. The *Note* (*Avertissement*) states it was produced according to Bošković's and Maire's *New Map of the Papal States* (*Nuova carta geografica dello Stato Ecclesiastico*). It contains only three graphic scales in which units of length are expressed in Italian and French miles and an unnamed mile, and the map does not contain a legend, making it more difficult to use.



A copy of the New Map of the Papal States (Nuova carta geografica dello Stato Ecclesiastico, 1755), Zbirka Novak

6. Bošković's Hydrotechnic Works

Bošković's most famous hydrotechnic works are: works with the flow of Tiber (in which he analyzes damage above Ponte Felice and under Ponte di Rustica), reports on damage and repair in Porto di Magnavacca, reports of Scritture on causes and damage to devices in Fiumicino due to flooding Tiber in 1750 and 1751, hydrotechnic issues of the Po River, researching the state of floods of Caina and Nistore streams for Perugia (1771), and researching the state of flood of Tidone river (1771) for Piacenza. For Duke of Modena, Bošković wrote an opinion about new work done on the Panaro river. In his expert opinion on the mouth of Adiga (1773), he proposed to the Venetian Republic a method of defensive measures against erosion. In 1757, he published Roman "Scritture" about waters in a discussion with the Church of St. Agnes. Also significant are his works and measures for repairing harbours, most importantly those of Rimini (1764) and Savona (1771), while works in the Jakin (Ancona) harbour under the coast of Capo di Monte were published in 1774. A specially unexplored area of Bošković's work in hydrotechnics with his reports of legal and expert nature were produced for the Republic of Lucca in a dispute with Toscana in 1756 and later.

Most of those works were published, except: estimation of damage to confluents of Fiumicino in 1750 and 1751, opinions of swamps next to Lago di Sesto created by the Arno River pouring in the border area of the Republic of Lucca and the Duchy of Toscane in 1756 or the report on fountains in Perugia in 1772 which were preserved as a manuscript.

With cardinal Simone Buonaccorsi, he reconnaissanced and researched the swampy area of the Pontine marshes from January 19 to March 25, 1764 when he spent three months in the field on a horse and in boats. He subsequently wrote a report on the great work, however he had to continue with the work in 1774 when he stayed in Paris, where he composed rules for a consortium established for draining those marshes.

Nowadays, 17 hydrotechnic works are known in which Bošković actively participated. In chronological order, they are:

- Estimation of damage on pegged fences of Fiumicino, fairway of Tiber (1751)
- Report on the visit to the Magnavacca harbour (1752)
- Project Ozzeri, originating from disputes about floods in the border area of Lucca and Toscana (1756)
- Report on waters in a discussion with the Church of St. Agnes (1757)
- Par of Bošković's letter to M. Clairaut about the problem of the flow and low tide theory (1761)
- On the effect of three dams on the flood of the Po River (1763)
- Plan for draining the Pontine marshes, with an opinion of the project previously created by Manfredi and Bertaglia (1764)
- Estimation of damage in the Rimini harbour with suggestions for repair (1764)

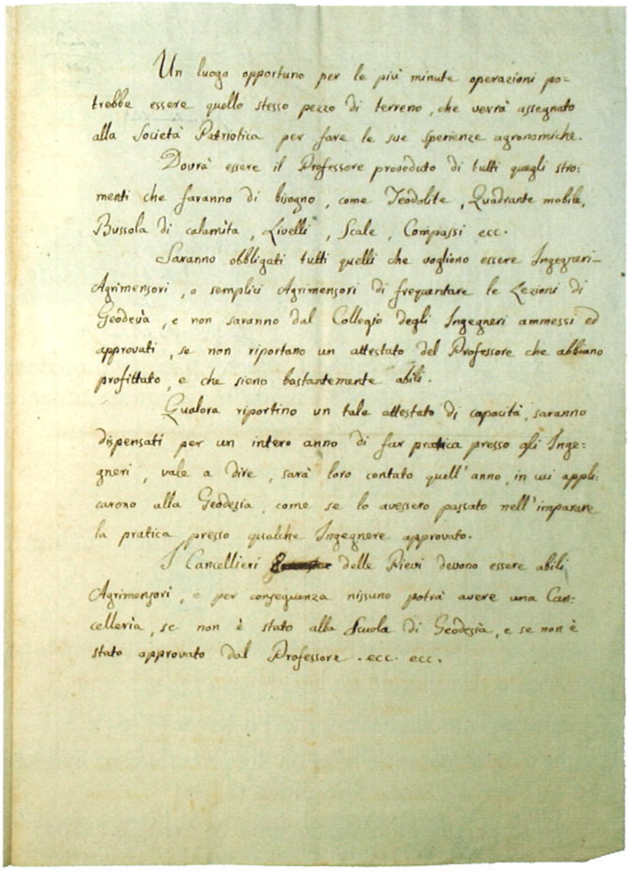
Commemorative postal stamp

- Opinion on mounds along the Po River (1764)
- Letter with a scientific base on the principles of hydraulics in Lecchi's work Idrostatica (1765)
- Flood investigation in the vicinity of Perugia (1766)
- Report of damage to the Savoni harbour, about causes and repair (1771)
- Opinion on the Tidone River in Piacenza (1771)
- Proposal of renewing the fountains in Perugia (1772)
- Opinion on the Adige River and the confluence into the Sea with a comparison of opinions by Antonio Lorgna and Šimun Stratik on arranging its basin (1773)
- Composition of a Committee for draining the Pontine marshes (1774)
- Objections to the Ximenes project of new flood-relief channel Nuovo Ozzeri in Lucca (1781).

7. Ruđer Bošković's Structural Engineering Expertises

Cracks in the dome of the Church of St. Peter in Rome motivated Bošković in 1742 to deal with construction problems. Wanting to protect the building, the Pope entrusted mathematicians Bošković, Jacquier and Le Seuer to study causes and propose a solution. Based on their research, they published *Opinions of Three Mathematicians on Damage to the dome of St. Peter* (*Parere di tre matematici sopra i danni, che si sono trovati nella cupola di S. Pietro*). The publication does not mention the authors' names, but Bošković mentioned he wrote the work alone at the end of the Venetian edition of his *Theory* in 1763.

It is unusual how a mathematicians' opinion was asked on a technical problem because construction issues used to be discussed on the basis of experience, and work on buildings was done by architects-practicians without theoretical consideration. However, mathematicians' opinion was



Un luogo opportuno per le più minute operazioni potrebbe essere quello stesso pezzo di terreno, che verrà assegnato alla Società Patriotica per fare le sue sperienze agronomiche.

Dovrà essere il Professore proveduto di tutti quegli stromenti che saranno di bisogno, come Teodolite, Quadrante mobile, Bussola di calamita, Livelli, Scale, Compassi ecc.

Saranno obbligati tutti quelli che vogliono essere Ingegneri-Agrimensori, o semplici Agrimensori di frequentare le Lezioni di Geodesia, e non saranno dal Collegio degli Ingegneri ammessi ed approvati, se non riportano un attestato del Professore che abbiano profittato, e che sieno bastantemente abili.

Qualora riportino un tale attestato di capacità, saranno dispensati per un intero anno di far pratica presso gli Ingegneri, vale a dire, sarà loro contato quell'anno, in cui applicarono alla Geodesia, come se lo avessero passato nell'imparare la pratica presso qualche Ingegnere approvato.

I Cancellieri [illegible] delle Pievi devono essere abili Agrimensori, e per conseguenza nissuno potrà avere una Cancelleria, se non è stato alla Scuola di Geodesia, e se non è stato approvato dal Professore. ecc. ecc.

Ruđer Bošković's manuscript

completely different from the architects' and was based on a mathematical method. Such solving of construction problems was completely revolutionary and unknown in existing construction. Knowing it would cause a reaction and opposition from architects, the preface noted that experiences obtained on a small number of small buildings are not enough and that more general principles applied by mechanics have to be applied.

Solving the problem mathematically, Bošković used a graphic scheme for deducing about the cracks' advancement. Based on the scheme, it was concluded that the dome's weight produces a lateral force which pushes its base toward the outside. In order to prevent this, it was proposed to install new rings in the dome. Although some authors criticized the work of Bošković and his associates, in 1743 and 1744 architects installed five additional iron rings on the dome, exactly as Bošković conceived based on a mathematical theory.

Bošković subsequently solved construction problems on several other occasions. He researched the bearing capacity of pillars in the Church of St. Géneviève in Paris, the Milan cathedral dome and damage to the National Library in Vienna.

8. Bošković's Proposal of Establishing a Geodetic School

Bošković's numerous works in the field of mathematics, astronomy, optics and physics are related to geodesy and significantly contributed to its development, and his geodetic research contributed to the development of cartography, geophysics and mathematics. Bošković did not have formal geodetic education, but he considered it necessary so he proposed the establishment and the education program of a geodetic school in Milan around 1770. A transcript of his manuscript *Project of a Geodetic School* (*Progetto per una Scuola di Geodesia*) was published in 1931 under the title *Bošković's Base for a Geodetic School in Milan,* nowadays preserved at the State Archive in Milan (Drawer no. 115, Manuscript Collections). Considering how little is known about education of geodesists in Bošković's time, the manuscript is extremely valuable, as well as Bošković's entire contribution to geodesy which is still not known enough to the general public.

References

- Granić, G. (ed., 2011): 300-ta godišnjica rođenja Ruđera Boškovića, Program središnje svečane proslave (300th Anniversary of Ruđer Bošković Birth, Program of the Central Festive Celebration, in Croatian), Ministarstvo znanosti, obrazovanja i športa, Akademija tehničkih znanosti Hrvatske, Zagreb.
- Lapaine, M. (2008): Ruđer Josip Bošković – Toward the 300th Anniversary of his Birth. Engineering Power, 2008, Vol. 7, No.1, 1-2. / Ruđer Josip Bošković – u susret 300. godišnjici rođenja, Tehničke znanosti, 2008, Vol. 15, No. 1, 1-2.
- Lapaine, M. (2011): Bošković-Laplaceova metoda, Sferna trigonometrija, Boškovićeve diferencijalne formule sferne trigonometrije, Geodezija, Kartografija, Meridijanski luk, Zemljin oblik (Bošković-Laplace method, Spherical trigonometry, Bošković's deifferential formulae of spherical trigonometry, Geodesy, Cartogrpahy, Meridian arc, Earth's shape, in Croatian). To be published in Lexicon of Ruđer Bošković, edited by A. Bogutovac.
- Lapaine, M., Kljajić, I. (2011): O Ruđeru Boškoviću i njegovu prijedlogu za osnivanje geodetske škole (About Ruđer Bošković and his proposal of establishing a geodetic school, in Croatian). To be published in Geodetski list.
- Malvić, T. (2011): Ruđer Bošković i izučavanje Zemljine građe (Ruđer Bošković and study of the Earth's structure, in Croatian). To be published in Ruđer Bošković and Geosciences, monograph edited by M. Lapaine.
- Špoljarić, D., Solarić, N. (2011): Bošković, usavršitelj i izumitelj geodetskih, astronomskih i optičkih instrumenata (Bošković, refiner and inventor of geodetic, atronomical and optical instruments, in Croatian). To be published in Ruđer Bošković and Geosciences, monograph edited by M. Lapaine.
- Župan, R., Poslončec-Petrić, V., Frangeš, S. (2011): Ruđer Josip Bošković i kartografija (Ruđer Josip Bošković and cartography, in Croatian). To be published in Ruđer Bošković and Geosciences, monograph edited by M. Lapaine.

Miljenko Lapaine