Professional paper | Received: 21-04-2012 | Accepted: 04-12-2013

The Paris Meridian Arc Length and Definition of the Metre

Miljenko SOLARIĆ and Nikola SOLARIĆ

University of Zagreb, Faculty of Geodesy, Kačićeva 26, 10000 Zagreb, Croatia
miljenko.solaric@geof.hr, nikola.solaric@geof.hr

Abstract: Pierre François-André Méchain and Jean-Baptiste Joseph Delambre participated in measuring the Paris meridian arc length in order to determine the length of the metre. Jean-Baptiste Biot and François Dominique Jean Arago worked on extending the meridian at a later date.

Keywords: meridian arc length, Paris meridian, surveying, trigonometric chain, definition of length in the International System of Units, metre

1 Introduction

General economic growth in France during the 18th century resulted in the rapid development of trade, industry and navigation and the need to introduce unique units of measurement. Thus, the French Royal Academy of Sciences started a project to establish new units of measurement in 1791, as they were being demanded by all larger commerce networks in France and throughout the world. The intention was to define a new unit of length called the metre, representing one ten-millionth of the meridian arc from the North Pole to the Equator. The French wanted to define the metre using the meridian passing through Paris, but there were several other proposals. In addition, new units of measurement were to be introduced in the decimal system in order to facilitate trade. At first, the task of measuring the Paris meridian arc length was entrusted to Cassini IV, Legendre and Méchain. Subsequently, however, the Constituent Assembly of France charged François-André Méchain and Jean-Baptiste Joseph Delambre in 1795 with the task of surveying the section of the Paris meridian between Dunkirk and Barcelona (URL5). Conducting the survey proved to be much more dangerous than the young scientists had thought, as it coincided with the difficult times of the French Revolution. Therefore, we are going to describe their work and the problems they faced.

2 The Survey of the Paris Meridian Arc Length in Order to Define the Length of the Metre

Pierre François-André Méchain (1744–1804) (Fig. 1) came from a poor family. He wanted to become an architect, but he was also very interested in astronomy. His mathematical ability was noted early. Education at *L'École Nationale des Ponts et Chaussées* in Paris was expensive, so he had to leave and tutored two boys from noble families near Paris, which enabled him to purchase some good astronomical instruments and pursue his hobby. However, his father lost a court case and Méchain had to agree to sell his instruments in order to settle the family's debt. His instruments were bought by Jérõme Lalande, who was impressed with Méchain's abilities. Méchain spent next years producing maps and searching for comets. He produced some of maps for military use in Germany and Italy. Afterwards, he helped Cassini IV determine the distance between the Greenwich and Paris observatories using a trigonometric network. At first, he used old instruments, and later, a repeating circle. He soon became known as the most precise observer. In addition to comets, he recorded 29 nebulae and became a member of the Royal Academy of Sciences (URL3).

In 1791, the Committee for Weights and Measures proposed to the National Assembly that Méchain and

Stručni rad | Primljeno: 21-04-2012 | Prihvaćeno: 04-12-2013

Duljina luka Pariškog meridijana i definicija metra

Miljenko SOLARIĆ i Nikola SOLARIĆ

Sveučilište u Zagrebu, Geodetski fakultet, Kačićeva 26, 10000 Zagreb
miljenko.solaric@geof.hr, nikola.solaric@geof.hr

Sažetak: Na točnoj izmjeri duljine luka Pariškog meridijana za potrebe određivanja duljine metra sudjelovali su Pierre François-André Méchain i Jean-Baptiste Joseph Delambre. Poslije su na njegovu produženju radili Jean-Baptiste Biot i François Dominique Jean Arago.

Ključne riječi: duljina luka meridijana, Pariški meridijan, izmjera, trigonometrijski lanac, definicija duljine međunarodnoga sustava jedinica mjera, metar

1. Uvod

Opći ekonomski rast Francuske očitovao se u brzom usponu trgovine, industrije i pomorstva tijekom 18. stoljeća i tada dolazi do potrebe uvođenja jedinstvenih mjernih jedinica. Tako je Kraljevska akademija znanosti u Francuskoj 1791. godine postavila projekt uspostave novih mjernih jedinica jer su to tražile sve veće trgovačke veze u Francuskoj i u svijetu. Željelo se definirati novu jedinicu za duljinu nazvanu metar kao 10-milijunti dio duljine luka meridijana od sjevernog pola do ekvatora. Francuzi su željeli da metar bude definiran s pomoću meridijana koji prolazi kroz Pariz, no bilo je i više drugih prijedloga. Osim toga nastojalo se uvesti nove jedinice mjera u decimalnom sustavu jer je na taj način bila olakšana trgovina. Na početku su za taj zadatak izmjere duljine luka Pariškoga meridijana bili zaduženi Cassini IV., Legendre i Méchain. Međutim, poslije je Ustavotvorna skupština Francuske 1795. godine zadužila Pierrea François-Andréa Méchaina i Jean-Baptistea Josepha Delambrea da točno izmjere dio luka Pariškog meridijana od Dunkerquea do Barcelone (URL5). Pri izvođenju te izmjere pokazalo se da je to puno opasniji pothvat nego što su mislili mladi znanstvenici. Naime, to je bilo teško vrijeme kad se u Francuskoj dogodila revolucija. Zato ćemo opisati njihov rad i probleme s kojima su se susreli.

2. Izmjera duljine luka Pariškog meridijana za potrebe definiranja duljine metra

Pierre François-André Méchain (1744–1804) (sl. 1) potjecao je iz siromašne obitelji. Želio je postati arhitekt, ali imao je i posebice velik interes za astronomiju. Njegova sposobnost za matematiku bila je odmah uočena. Studiranje na École Nationale des Ponts et chaussées u Parizu bilo je skupo pa je morao prekinuti studij i podučavati dva dječaka iz plemićkih obitelji u blizini Pariza. Tako je mogao kupiti neke astronomske instrumente dobre kvalitete i nastaviti svoj hobi. Međutim, kad je njegov otac izgubio parnicu, morao je prodati svoje instrumente i isplatiti obiteljski dug. Njegove instrumente kupio je Jérõme Lalande, koji je bio impresioniran Méchainovom sposobnošću. Sljedećih nekoliko godina izrađivao je karte i tražio komete. Neke od tih karata izradio je za vojsku u Njemačkoj i Italiji. Zatim je pomagao Cassiniju IV. 1787. godine na određivanju točne udaljenosti između opservatorija u Greenwichu i Parizu s pomoću trigonometrijske mreže. Na početku je mjerio starim instrumentima, a poslije Bordinim repeticijskim krugom. Ubrzo je stekao ugled najpreciznijeg opažača. Osim kometa registrirao je i 29 maglica pa je bio izabran i u Kraljevsku akademiju znanosti (URL3).

Povjerenstvo za utege i mjere predložilo je 1791.

Figure 1. Pierre Méchain (1744-1804) (URL4)
Slika 1. Pierre Méchain (1744–1804) (URL4)

Figure 2. Jean-Baptiste Joseph Delambre (1749-1822) (URL2)
Slika 2. Jean-Baptiste Joseph Delambre (1749–1822) (URL2)

Delambre survey the trigonometric chain between Dunkirk and Barcelona, in order to determine the length of the metre. The trigonometric chain was divided into two parts. Delambre was to survey the northern section from the belfry in Dunkirk (Fig. 3) to Rodez Cathedral, a distance of 742.7 km, which had been surveyed by Cassini de Thury prior to 1740. Méchain was to survey the southern section from Rodez Cathedral (Fig. 4) to Montjuïc (Mont-Jouy) Fortress near Barcelona (Fig. 5), which had been measured less accurately as 333 km in length (URL3, URL14).

Méchain travelled to Barcelona in June 1792, where he set up triangulation points in Catalonia during the summer. He measured angles using a repeating circle in autumn, and measured the latitude by astronomical methods in Barcelona very carefully during the three months of winter. Thanks to cooperation from the Spanish, he was allowed to survey from the top of Montjuïc Fortress.

When war broke out in March 1793 between France and Spain, Méchain had to leave Montjuïc (485 m above sea-level) due to its military purpose. After being injured while testing a hydraulic pump, he returned to the upper Pyrenees. However, he was still unable to return to Montjuïc because of war, so he measured the latitude from a hotel in Barcelona. By March 1794, Méchain had connected this two points (Montjuïc – hotel) by terrestrial measurements (angle measurements) and discovered that the two latitudes did not match. This was very awkward for him, considering his conscientiousness and reputation as the most successful observer with the repeating circle. A difference of 3 seconds of arc in latitude corresponds to 100 m in meridian arc length (Murdin 2009, page 102). Unfortunately, the war meant he was unable to return to Montjuïc to check his astronomical measurements. He did not say anything about it to anyone. Méchain knew that measuring the difference between the latitudes of the first and last point on the meridian arc was very important and required great care. That was a reason for him to be worried.

The situation in France was chaotic, so Méchain followed his friend's advice and went from Spain to Genova in neutral Italy, where he was informed that the meridian project had been cancelled. It was relaunched in April 1795 and Méchain was supposed to return to Paris. However, he feared for his life as many scientists had been guillotined during the French Revolution. Therefore, he travelled to Marseille and Perpignan at the end of August to resume measurement. Weather conditions were very poor, but Méchain continued to refuse to return to Paris and meet Delambre, who had finished measuring the trigonometric network in the northern section and had not measured anything for two years, as he had been incarcerated several times during the revolution. Although Delambre sent Méchain all his measurement data, Méchain refused to reciprocate. He was afraid that his measurement error would be discovered if he returned to Paris. So he started altering his data, taking care that deviations were minimal.

Méchain believed that accuracy could be achieved with a repeating circle. He did not understand statistics based on the random error theory, which had not yet been developed. He was also unaware of systematic errors, which cannot be eliminated by repeating measurements. He felt responsible for something which was not really his fault. Refraction, which differed at the top of the hill from that at the hotel virtually at sea level in Barcelona, also influenced the results.

Like Delambre, Méchain measured carefully the baseline using four platinum bars 2 *toises* (3.9 m) in length. He set the base along a straight road near Perpignan, and it was about 6000 *toises* long (URL14). According to Bialas (1982, page 170), at the time, baselines were measured

Narodnoj skupštini da Méchain i Delambre točno izmjere trigonometrijski lanac između Dunkerquea i Barcelone za potrebe određivanja duljine metra. Trigonometrijski lanac bio je podijeljen na dva dijela. Sjeverni dio od zvonika u Dunkerqueu (sl. 3) do katedrale u Rodezu (sl. 4), dug 742,7 km, koji je već prije 1740. godine prilično točno izmjerio Cassini de Thury, trebao je precizno izmjeriti Delambre. Južni dio od katedrale u Rodezu do tvrđave Montjuïc kod Barcelone (sl. 5), koji je bio manje točno izmjeren, dug 333,0 km, trebao je izmjeriti Méchain (URL3, URL14).

Méchain je u lipnju 1792. otputovao u Barcelonu, gdje je tijekom ljeta u Kataloniji postavio neke trigonometrijske točke, u jesen je mjerio kutove Bordinim repeticijskim krugom, a zimi tijekom tri mjeseca mjerio je vrlo pažljivo astronomskim načinom geografsku širinu u Barceloni. Zahvaljujući tadašnjoj kooperativnosti Španjolaca bilo mu je dopušteno da mjeri na vrhu u dvorcu Montjuïc.

Kad je izbio rat između Francuske i Španjolske u ožujku 1793. Méchain je morao napustiti dvorac Montjuïc smješten na nadmorskoj visini od 485 m, jer je imao vojnu namjenu. Pošto je doživio povredu pri testu hidrauličke crpke, nakon dužeg oporavka vratio se izmjeri na vrhove Pireneja. Međutim, nije se mogao vratiti u dvorac Montjuïc zbog rata pa je mjerio geografsku širinu iz hotela u Barceloni. Do ožujka 1794. Méchain je terestričkim mjerenjima (mjerenjem kutova) povezao te dvije točke (Montjuïc – hotel) i otkrio da se geografska širina iz hotela u Barceloni i ona izmjerena u dvorcu Montjuïc ne slažu. To je za njega bilo jako neugodno otkriće jer je bio savjestan, a slovio je i kao najuspješniji opažač s Bordinim repeticijskim krugom. Naime, razlika od 3 kutne sekunde u geografskoj širini odgovara 100 m u duljini luka meridijana (Murdin 2009, str. 102). Nažalost u dvorac Montjuïc nije mogao otići provjeriti svoja astronomska mjerenja zbog ratnog stanja. O tome nije nikoga obavijestio. Méchain je bio svjestan da je izmjera razlike geografske širine prve i posljednje točke na luku meridijana vrlo važna i da zahtijeva najveću pozornost pri astronomskim mjerenjima. To je bio razlog za njegovu zabrinutost.

U Francuskoj je bilo nesređeno stanje, te je Méchain na prijedlog prijatelja iz Španjolske otišao u neutralnu Italiju u Genovu, gdje je čuo da se otkazuje meridijanski projekt. Projekt je ponovno započet u travnju 1795. i on se trebao vratiti u Pariz. Međutim, bojao se otići u Pariz jer je znao da su za vrijeme Francuske revolucije mnogi znanstvenici završili život na giljotini. Stoga je otputovao u Marseille, a zatim krajem kolovoza u Perpignan kako bi nastavio mjerenja. Vremenski uvjeti za mjerenje bili su loši, a Méchain je i dalje odbijao vratiti se u Pariz kako bi se sreo s Delambreom, koji je izvodio izmjeru trigonometrijske mreže na sjevernom dijelu i nije imao gotovo ništa izmjereno u razdoblju od dvije godine. Naime, zbog revolucije Delambre je nekoliko puta bio zatvaran pa nije bio u mogućnosti izvoditi mjerenja. Ipak je sve svoje podatke izmjere poslao Méchainu, koji mu je odbio poslati svoje. Bojao se da će, ako se vrati u Pariz, biti otkrivena njegova pogrešna mjerenja. Stoga je počeo mijenjati svoje podatke pazeći pritom da je odstupanje od prosjeka smanjeno.

Vjerovao je da se s pomoću Bordina repeticijskoga kruga može postići bilo koja željena točnost. No nije razumio statistiku, koja se temelji na teoriji slučajnih

Figure 3. Belfry in Dunkirk, northern point of the meridian arc (URL14)

Slika 3. Zvonik u Dunkerqueu, sjeverni kraj meridijanskog luka (URL14)

Figure 4. West front of the cathedral in Rodez (URL15)

Slika 4. Zapadni pogled na katedralu u Rodezu (URL15)

Figure 5. Tower of Montjuïc (Mont-Jouy) Fortress, southern point of the meridian arc (URL8)

Slika 5. Toranj u tvrđavi Montjuïc (Mont-Jouy), južni kraj meridijanskog luka (URL8) using bimetal platinum and brass measuring rods, proposed by Borda to substantially reduce the effect of temperature on rod length.

In the meantime, Méchain had been promised the directorship of the Paris Observatory, which was a great temptation, so he returned to Paris. Soon after he was appointed to this high position in French science, he managed to initiate a new project for extending the meridian arc to the Balearic Islands. He claimed it would increase the accuracy of meridian arc length measurement. In his request to Napoleon, he emphasised the strategic importance of the Balearic Islands and the fact that his project would improve relations between Spain and France. Napoleon approved the project, so Méchain travelled from Paris to Spain on 26 April 1803. When he arrived in Barcelona, he discovered the Spanish opposed the project and would not provide a passport for the Balearic Islands. Therefore, he surveyed the trigonometric network on the Spanish coast up to Montsia, 762 m above sea level, 160 km from Barcelona and 145 km from Valencia. However, he was still unable to see the island of Ibiza from Montsia. He contracted malaria and passed away soon after.

In the meantime, Delambre linked the geodetic trigonometric networks of Bourges, Orléans and Sologna and returned to the north to Dunkirk in order to determine the latitude by astronomical methods and compare it with the latitude at Montjuïc.

However, when Delambre worked later on Méchain's data for his own base (*Base du Systeme métrique*), he discovered that Méchain had changed his results in order to make them appear more accurate. Delambre did not want to diminish confidence in the metric system by publishing these facts. In fact, he considered Méchain's results constituted important scientific discoveries rather than errors, and sought to preserve Méchain's reputation.

Jean-Baptiste Joseph Delambre (1749–1822) (Fig. 2), was a French mathematician, astronomer and geodesist. At the age of 15 months, he contracted smallpox and almost lost his sight. Against the odds, poor eyesight did not stop him from becoming interested in astronomy, and it actually gradually improved. Delambre attended the Jesuit College in Amiens, studying English and German and continuing in the same city when the Jesuits were banned in 1764. One of his teachers encouraged him to continue studying in Paris. He was awarded a scholarship to the *Collège du Plessis* in Paris, where he studied classical languages. However, he did not get a scholarship to the University, and his parents could not afford his education, so he had to give lessons to noblemen's children. Although he was self-taught in mathematics, he quickly became renowned in that discipline. In order to avoid problems during the revolution, he changed his last name from de Lambre to Delambre, so that it would not sound aristocratic (URL1).

At first, Delambre was interested in Greek astronomy and later, also in contemporary astronomy. He read Laland's *Traité d'astronomie* in 1780, and he also attended his lectures at the *Collège de France,* where he soon impressed Laland with his knowledge of astronomy, becoming his best student. In 1786, Delambre recorded Mercury in transit across the Sun, which other astronomers were unable to do because it happened about 40 minutes later than the predicted time, and they had not taken into consideration deviations caused by other planets. At a meeting of the Royal Academy of Sciences, Laplace presented his work on planet movement deviations caused by other planets. Delambre decided to observe the movement of Uranus in order to verify Laplace's theory. The Academy awarded him the 1789 Grand Prix for calculating the exact orbit of Uranus, and he received the award again in 1792.

The Royal Academy of Sciences established the Committee for Weights and Measures in 1790, consisting of Borda, Condorcet, Laplace, Legendre and Lavoisier. After changing the direction of its work several times, it published a report on 19 March 1791, recommending that the system be based on the metre, defined as one ten-millionth part of the meridian arc from the North Pole to the Equator. At first, Cassini IV, Legendre and Méchain were charged with determining distance from Dunkirk to Barcelona in *toises* (the old unit) as accurately as possible. Subsequently, Delambre replaced Cassini IV and Legendre. Delambre was charged with surveying the northern section from Dunkirk to Rodez, and Méchain with the southern section from Rodez to Barcelona. The task was difficult enough in peacetime, but it proved even harder because of the French Revolution and wars with neighbouring countries.

In June, Delambre started looking for trigonometric points near Paris. He was arrested in September because his authorisation was from the king, who had also been arrested. Delambre was only released after obtaining new documents. However, he was arrested again because the authorities found his documents suspicious, and he was accused of spying. The National Convention issued him with new papers, so he resumed his work on measuring the trigonometric chain. He made some progress before winter and his return to Paris, then continued south of Dunkirk the following spring. In December 1793, work on measuring the Paris meridian was cancelled by a decision of the Committee for Public Security. Official functions could only be executed by people who were *trustworthy for their republican virtues and abhorrence of kings.*

pogrešaka, što do tada nije bilo razvijeno. Nije znao za takozvane sustavne pogreške koje se ne mogu ukloniti brojem ponavljanja mjerenja. Okrivljivao je samoga sebe za ono za što nije bio kriv. Osim toga sigurno je da je na rezultat utjecala i refrakcija i da se ona razlikovala na vrhu brijega i dolje u hotelu u Barceloni, koja je približno na razini mora.

Méchain je, isto kao i Delambre, pažljivo mjerio duljinu baze s pomoću četiri platinske šipke, svake duge 2 *toisea* (3,9 m). Bazu je postavio uzduž ravne ceste kod Perpignana, a bila je duga oko 6000 *toisea* (URL14). Prema Bialasu (1982, str. 170), duljine baza mjerene su s pomoću bimetalnih mjernih šipki izrađenih od platine i mjedi i na taj se način, prema Bordinu prijedlogu bitno reducirao utjecaj temperature na duljinu mjernih šipki.

U međuvremenu Méchain je dobio obećanje da će biti postavljen za ravnatelja Pariškog opservatorija, što je bilo veliko iskušenje pa se vratio u Pariz. Ubrzo je bio izabran na taj visoki položaj u francuskoj znanosti pa se uspio izboriti za novi projekt produživanja mjerenja meridijanskog luka na Balearsko otočje. Tvrdio je da bi se tako poboljšala točnost mjerenja duljine luka meridijana. U svom zahtjevu Napoleonu istaknuo je i strateški značaj Balearskih otoka te da bi njegov projekt mogao poboljšati odnose između Španjolske i Francuske. Napoleon je taj projekt odobrio pa je Méchain otišao iz Pariza u Španjolsku 26. travnja 1803. Kad je stigao u Barcelonu otkrio je da se Španjolci protive njegovu projektu pa mu nisu dali putovnicu za Balearsko otočje. Stoga je mjerio trigonometrijsku mrežu na španjolskoj obali do Montsia, koji se nalazi na nadmorskoj visini 762 m, a udaljen je od Barcelone 160 km i od Valencije 145 km. Međutim, imao je problem što od Montsia nije uspio vidjeti otok Ibizu. Obolio je od malarije i ubrzo umro (URL3).

U međuvremenu je Delambre povezao geodetske trigonometrijske mreže regije Bourgesa, Orléansa i Sologne i vratio se natrag na sjever do Dunkerquea kako bi astronomskim načinom odredio geografsku širinu i usporedio je s geografskom širinom na Montjuïcu.

Poslije, kad je Delambre radio na Méchainovim podacima za svoju bazu (*Base du Systeme métrique*), otkrio je da je Méchain promijenio svoje rezultate očitavanja kako bi bili naizgled precizniji. Delambre nije želio poljuljati povjerenje u metrički sustav i javno objaviti pronađene činjenice. Méchainove rezultate smatrao je važnim znanstvenim otkrićem, a ne pogreškama, te je htio sačuvati njegov visoki ugled.

Jean-Baptiste Joseph Delambre (1749–1822) (sl. 2) bio je francuski matematičar, astronom i geodet. U dobi od 15 mjeseci razbolio se od velikih boginja i gotovo je izgubio vid. Nevjerojatno je da se počeo interesirati za astronomiju s tako slabim vidom, međutim vid mu se postepeno poboljšavao. Pohađao je isusovački kolegij u Amiensu studirajući engleski i njemački jezik, a kad su u Francuskoj 1764. isusovci zabranjeni, nastavio je studiranje u istom gradu. Jedan od nastavnika ohrabrio ga je da nastavi školovanje u Parizu. Bio je nagrađen stipendijom za *Collège du Plessis* u Parizu, gdje je studirao klasične jezike. Poslije je izgubio stipendiju, a roditelji mu nisu mogli plaćati školovanje pa je morao davati poduke djeci plemića kako bi nastavio studij. Iako je bio samouk u matematici, u tom je području ubrzo stekao ugled. U doba revolucije, kako bi izbjegao probleme, promijenio je prezime iz de Lambre u Delambre da ne bi zvučalo aristokratski (URL1).

Na početku se Delambre zanimao za grčku astronomiju, a poslije za tadašnju suvremenu astronomiju. Tako je 1780. godine pročitao *Traité d'astronomie* J. Lalanda, a pohađao je i njegova predavanja na *Collège de France*, te ga impresionirao svojim znanjem iz astronomije i postao njegov najbolji učenik. Godine 1786. Delambre je snimio prolaz planeta Merkura ispred Sunčeva diska, što drugim astronomima nije uspjelo zbog kašnjenja Merkurova prolaza za oko 40 minuta. Do toga je došlo jer u proračunu tablica nisu bili uzeti u račun i poremećaji od drugih planeta. Tih dana Laplace je na sastanku Kraljevske akademije znanosti predstavio rad o poremećajima gibanja planeta uzrokovanih drugim planetima. Delambre je odlučio opažati gibanja planeta Urana kako bi provjerio Laplaceovu teoriju. Kraljevska akademija znanosti dodijelila mu je 1789. godine nagradu *Grand Prix* za izračun točne orbite planeta Urana, a 1792. primio je takvu nagradu po drugi put.

Kraljevska akademija znanosti osnovala je 1790. godine Povjerenstvo za utege i mjere u sastavu: Borda, Condorcet, Laplace, Legendre i Lavoisier. Ono je nakon nekoliko promjena smjera rada u izvještaju od 19. ožujka 1791. odlučilo da se sustav temelji na duljini metra definiranoj kao 10-milijunti dio meridijanskog luka od pola do ekvatora. Na početku su za mjerenje po mogućnosti što točnijeg iznosa udaljenosti od Dunkerquea do Barcelone izražene u *toiseima* (starim jedinicama) bili zaduženi: Cassini IV., Legendre i Méchain. Poslije je Delambre zamijenio Cassinija IV. i Legendrea. Delambre je bio zadužen za mjernje sjevernoga dijela od Dunkerquea do Rodeza, a Méchain za južni dio od Rodeza do Barcelone. Taj zadatak je bio težak i za mirnodopsko vrijeme, a pokazao se mnogo teži zbog Francuske revolucije i ratova sa susjedima.

U lipnju je Delambre počeo najprije tražiti trigonometrijske točke u okolici Pariza, ali je bio uhićen u rujnu jer je imao odobrenje kralja, koji je također bio uhićen. Pušten je nakon dobivanja novih dokumenata. Međutim, ponovno je bio uhićen jer su se njegovi instrumenti

Figure 6. The trigonometric chain known as the *Delambre-Méchai Meridian* used to determine the length of the metre (according to URL11, basemap from *Natural Earth* data).

Slika 6. Trigonometrijski lanac nazvan *Delambreov i Méchainov meridijan* s pomoću kojeg je određena duljina metra (prema URL11, temeljna karta iz podataka *Natural Earth*).

Table 1. Results of the Paris meridian survey according to Méchain and Delambre, 1792–1798 (Bialas, 1982, page 171) (t – toise)

Tablica 1. Rezultati izmjere Pariškog meridijana prema izmjeri Méchaina i Delambrea u razdoblju 1792–1798. (Bialas, 1982, str. 171) (t – toise)

Arc between Luk između	Diff. in lat. Razlika geo. širina	Average lat. Srednja geo. širina	Dist. of arc Duljina mer. luka	Dist. of arc for 1° Duljina luka jednog stupnja
I Dunkirk (Dunkerque) – Pantheon (Paris)	2° 11’ 20.7”	49° 56' 30''	124 945.18 t	57 076 t
II Pantheon (Paris) – Evaux	2° 40’ 07.3”	47° 30' 46''	152 291.48 t	57 066 t
III Evaux – Carcassonne	2° 57’ 48.1”	44° 41' 48''	168 849.10 t	56 979 t
IV Carcassonne – Montjuïc	1° 51’ 09.6”	42° 17' 20''	105 498.96 t	56 945 t
V Dunkirk (Dunkerque) – Montjuïc	9° 40’ 25.6”	46° 11' 58''	551 584.72 t	57 018 t

tadašnjim vlastima činili sumnjivim te su ga optužili da ih koristi za špijunažu. Tada je dobio potvrdu od Nacionalne konvencije pa je nastavio s radom na izmjeri trigonometrijskog lanca. Ostvario je mali napredak do zime i povratka u Pariz, a sljedećeg je proljeća nastavio s radom južno od Dunkerquea. U prosincu 1793. radovi na izmjeri Pariškog meridijana prekinuti su odlukom Odbora za javnu sigurnost. Službene funkcije mogle su obavljati samo osobe *koje su pouzdane, imaju republikanske vrline i gnušaju se kraljeva.*

U svibnju 1795. Delambre je nastavio s radovima koji su bili naglo prekinuti prije osamnaest mjeseci. Mjerio je trigonometrijsku mrežu između Orleansa i Bourgesa u drugoj polovici 1795. godine, između Bourgesa i Evauxa u ljetu 1796. i između Evauxa i Rodeza 1797. Između tih izmjera trigonometrijske mreže putovao je u Dunkerque u prosincu 1795. i proveo ondje nekoliko prvih mjeseci 1796. godine računajući vrlo pažljivo geografsku širinu (URL1). Također, bila je tražena i visoka točnost mjerene baze tako da bi mjerilo trigonometrijske mreže moglo biti što točnije utvrđeno. Vrlo točna mjerenja duljine baze pokraj Meluna nedaleko Pariza obavio je Delambre u travnju 1798. Baza je bila postavljena uzduž ceste duge oko 12 km, a mjerio ju je šest tjedana na isti način kao i Méchain. Pritom se služio, gdje je to bilo moguće, Cassinijevim trigonometrijskim točkama iz 1744. godine (URL14).

Mjerenja su bila ukupno vrlo dobre kvalitete, što je pokazala i usporedba između izravno izvedenog mjerenja kontrolnih baza i računanja izvedenih preko izmjerenih kutova u trokutima. Tako je nakon računanja, polazeći od glavne baze kod Meluna, preko više od 53 trokuta, dobivena razlika između izračunane i izravno izmjerene duljine iznosila samo 0,16 toisea (oko 0,31 m). Iz toga slijedi da je u izmjeri meridijanskog luka postignuta relativna točnost od 1: 37 500 (Bialas 1982, str. 171). Taj rezultat bio je osiguran tako da je za računanje sjevernog dijela trigonometrijske mreže meridijanskog luka uzeta baza kod Meluna, a južnog dijela trigonometrijske mreže baza kod Perpignana. Pritom su obje baze bile istovrijedne. Kod ponovljenog računanja prema Delambreu pojavile su se ipak male korekture kutova u trokutima od samo 0,1'' (Bialas 1982, str. 171).

Naglasimo da u to doba još nije bila poznata metoda izjednačenja rezultata mjerenja s prekobrojnim mjerenjima. Naime, Carl Friedrich Gauss (1777–1855) objavio je 1809. godine knjigu *Theoria motus corporum celestium in sectionibus conicis solem ambientium* u kojoj je naveo da je on izmislio metodu najmanjih kvadrata i da je upotrebljava od 1795. godine. Međutim, nastao je spor s Adrien-Marie Legendreom (1752–1833), koji je 1805. godine objavio novu metodu za određivanje orbita kometa i u dodatku opisao novu metodu najmanjih kvadrata, koja igra ključnu ulogu u sređivanju podataka mjerenja (URL6). Danas se uglavnom uzima da je C. F. Gauss tvorac metode izjednačenja mjerenih veličina s najmanjom sumom kvadrata popravaka.

Primjena Bordina repeticijskoga kruga u izmjeri kutova donijela je također promjenu u računanju trigonometrijske mreže. Naime, kad su se mjerili kutovi s kvadrantima s mogućnošću mjerne nesigurnosti od 15'' (kutnih sekundi) nije trebalo računati sferni eksces, te se moglo računati trokute kao da su u ravnini. Međutim, kad se počelo mjeriti kutove s pomoću Bordina repeticijskoga kruga, kojim se mjerilo s mjernom nesigurnošću od 1'', tada se više nije moglo računati trokute u ravnini, već se moralo računati sa sfernim trokutima (sferni eksces je prvi put računan u Peruanskoj ekspediciji 1735–1743) (Solarić M. i Solarić N. 2013). Tako se morao za veće trokute računati sferni eksces, tj. odstupanje zbroja kutova u sfernom trokutu od 180°. Sferni ekscesi bili su u granicama od 0'' do 2'', a samo u dva slučaja kod velikih trokuta bili su 4'' i 5'' (Vykutil 1982, str. 422).

Trigonometrijski lanac Pariškog meridijana od Dunkerquea do Barcelone, koji su izmjerili Méchain i Delambre od 1792. do 1799. godine, prikazan je na sl. 6.

In May 1795, Delambre continued the work which had been cancelled abruptly eighteen months earlier. He measured the trigonometric network between Orleans and Bourges in the second half of 1795, between Bourges and Evaux in the summer of 1796, and between Evaux and Rodez in 1797. Between surveys, he travelled to Dunkirk in December 1795 and spent the first few months of 1796 calculating the latitude very carefully (URL 1). A high degree of accuracy of the measured base was also required in order for the trigonometric network scale to be determined as accurately as possible. Delambre conducted measurements of the baseline at Melun near Paris in April 1798. The baseline of 12 km was set along a road, and Delambre measured it the same way as Méchain. Where possible, he used Cassini's old trigonometric points from 1744 (URL14).

In general, the measurements were very good, which was demonstrated by comparing direct measurements of control bases and calculations of measured angles in triangles. Thus, after calculations starting from the Melun main base over 53 triangles were completed, the difference between the calculated and directly measured lengths was only 0.16 *toise* (about 0.31 m), giving a relative accuracy of 1: 37 500 (Bialas 1982, p. 171). This result was ensured by taking the Melun base for calculating the northern section of the trigonometric network of the meridian arc, and the Perpignan base for the southern section. Both bases were equally important. Small corrections of angles in triangles amounting to only 0.1" did occur in a repeated calculation according to Delambre (Bialas 1982, page 171).

It should be noted that the method of adjusting results using repeated measurements was unknown at the time. Namely, Carl Friedrich Gauss (1777–1855) published his *Theoria motus corporum celestium in sectionibus conicis solem ambientium* in 1809, stating he had devised the least squares method and had been using it since 1795. However, there was a dispute with Adrien-Marie Legendre (1752–1833), who in 1805 published a new method for determining comet orbit, describing a new least squares method, which played a key role in adjusting measurement data (URL6). Nowadays, C. F. Gauss is usually considered the author of the least squares method.

Application of the repeating circle in measuring angles also changed the way the trigonometric network was calculated. Namely, when angles were measured with quadrants with the possibility of measuring with margin of error of 15" (arc-seconds), it was not necessary to calculate the spherical excess and triangles could be calculated like in a plane. However, when the repeating circle was employed to measure angles and its measuring uncertainty was 1", it was no longer possible to calculate triangles in a plane; spherical triangles had to be used (spherical excess was calculated for the first time in expedition to Peru 1735–1743) (Solarić, M. and Solarić N. 2013). Spherical excess, i.e. deviation of the sum of angles in a spherical triangle from 180° had to be calculated for larger triangles. Spherical excesses ranged from 0" to 2", and 4" and 5" in only two cases of large triangles (Vykutil 1982, page 422).

The trigonometric chain of the Paris meridian from Dunkirk to Barcelona measured by Méchain and Delambre between 1792 and 1799 is represented in Fig. 6. Latitudes were not measured only at the starting and ending points but also at intermediate points at the Panthéon (Paris), Evaux and Carcassonne. Measurement of the azimuths of some sides was also done. The total length of the Dunkirk – Montjuïc meridian arc (551 584.72 *toises*) is also included in Table 1.

Delambre informed the International Committee for Weights and Measures of the results of the survey in February 1799. He published details of the project in *Base du système métrique* (URL12). The first of three volumes was published in 1806, containing the history of measuring the Earth and data on the trigonometric network project. The second volume was published in 1807, containing data on the accurate determination of latitudes in Dunkirk and Barcelona. The third volume was published in 1810, discussing errors in calculating the Earth's eccentricity.

In June 1798, at the request of the National Institute, the French bishop and statesman Charles-Maurice Talleyrand (1754–1838) invited allied and neutral nations to collaborate on determining final standards of basic units for measuring length and other quantities. An international committee was formed, consisting of the Dutchman Van Swiden, the Swiss Tralles, the Spaniard Ciscar and the French Laplace, Legendre, Méchain and Delambre (Bialas 1982, page 172). The committee was to calculate the length of the meridian from the North Pole to the Equator and thus determine the length of the metre as one ten-millionth part of its length. Namely, the length of the section of the meridian arc from Dunkirk to Barcelona is only about a tenth of the meridian arc length from the North Pole to the Equator, approximately at the mean latitude 46° 12'. Therefore, the committee first had to calculate the flattening of the Earth at the pole based on:

- the results of surveying a section of the Paris meridian arc from Dunkirk to Barcelona 9° 40' 24" in size, surveyed by Delambre and Méchain (Table 1), and
- the accurately surveyed meridian arc in South America (Peru) 3° 07' 01" in size, surveyed by Bouguer, La Condamine and Godin.

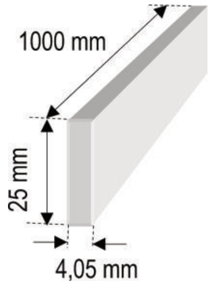

Figure 7. Diagram of the dimensions of the 1799 "final metre", called the *Archive Metre* (Brezinšćak 1971)

Slika 7. Grafički prikaz dimenzija "konačnog metra", nazvanog *Arhivski metar*, iz 1799. godine (Brezinšćak 1971)

Geografske širine nisu bile izmjerene samo u početnoj i krajnjoj točki nego i u međutočkama Pantheon (Pariz), Evaux i Carcassonne. Osim toga izvedena su i odgovarajuća mjerenja azimuta nekih strana. U tablicu 1. uvrštena je i ukupna duljina meridijanskog luka Dunkerque – Montjuïc od 551 584,72 toisea.

Delambre je u veljači 1799. izvijestio Međunarodno povjerenstvo za utege i mjere o rezultatima izmjere u projektu. Detalje o čitavom projektu naknadno je objavio u radu *Base du système métrique* (URL12). Prvi od tri volumena objavljen je 1806. godine, a sadrži povijest mjerenja Zemlje i podatke o projektu trigonometrijske mreže. Drugi volumen objavljen je 1807. godine i sadrži podatke o točnim određivanjima geografskih širina u Dunkerqueu i Barceloni. Treći volumen objavljen je 1810., a u njemu su razmatrane pogreške u računanju Zemljina ekscentriciteta.

Biskup i državnik Charles-Maurice Talleyrand (1754–1838) je na zahtjev Nacionalnog instituta u lipnju 1798. pozvao savezničke i neutralne narode da sudjeluju u utvrđivanju konačnih standarda osnovnih jedinica za mjerenje duljina i ostalih veličina. Tako je bilo izabrano šire međunarodno povjerenstvo u sastavu kojeg su bili: Nizozemac Van Swiden, Švicarac Tralles, Španjolac Ciscar te Francuzi: Laplace, Legendre, Méchain i Delambre (Bialas 1982, str. 172). Ono je imalo zadatak izračunati duljinu meridijana od pola do ekvatora i na taj način odrediti duljinu metra kao 10-milijunti dio njegove duljine. Naime, duljina dijela meridijanskog luka od Dunkerquea do Barcelone je samo oko desetine duljine luka meridijana od pola do ekvatora, drugim riječima samo njezin deseti dio i to na približno srednjoj geografskoj širini 46° 12'. Zato je povjerenstvo moralo najprije izračunati spljoštenost Zemlje na osnovi:

- rezultata izmjere dijela luka Pariškog meridijana od Dunkerquea do Barcelone, dugog 9° 40' 24", koju su obavili Delambre i Méchain (danih u tablici 1)
- posebno točno izmjerenoga meridijanskog luka u Južnoj Americi (u Peruu), dugog 3° 07' 01", koji su izmjerili Bouguer, La Condamine i Godin.

Dobili su da je spljoštenost Zemlje jednaka $f = 1{:}334$.

Iz te izračunane vrijednosti Zemljine spljoštenosti i vrijednostima izvedenih iz mjerenja na meridijanskom luku od Dunkerquea ($\varphi = 51° \ 02' \ 09{,}2''$) do Barcelone ($\varphi = 41° \ 21' \ 44{,}96''$) dobili su da duljina tog dijela meridijanskog luka iznosi 551 583,6 akademijinih toisea.

Do ukupne duljine meridijanskog luka od pola do ekvatora došlo se preko polinomskog prikaza za duljinu kvadranta elipse uzimajući u račun i kvadratne članove spljoštenosti elipsoida te su dobili da je tražena duljina luka meridijana od pola do ekvatora jednaka 5 130 740 akademijinih toisea.

Iz toga je slijedilo da je metar prema definiciji kao 10-milijunti dio luka meridijana od pola do ekvatora dug 0,513074 akademijina *toisea*, tj. da je 1 akademijin *toise* = 1,949037 metara.

To znači da je konačna vrijednost metra kraća od privremenoga[1] za samo 0,144 akademijine linije (1 *toise* = 6 stopa, 1 stopa = 144 linije).

Izrađeno je više primjeraka motki metra od platine (sl. 7), i to uz veliku pozornost s pomoću Lenoirova komparatora za definitivni standardni metar. Pritom su motke metra imale poprečni presjek 25 mm × 4,05 mm, a krajevi su bili točno udaljeni 1 metar pri temperaturi taljenja leda. Pogreška mjerenja duljine pri uspoređivanju krajnjih metarskih mjera tada je iznosila oko 1/100 milimetra. Kada je konačni rezultat bio poznat, odabrana su dva primjerka metra čije su duljine bile najbliže definiciji metra. Jedan primjerak metra i kilograma predani su na čuvanje u Arhiv Francuske Republike 22. lipnja 1799., a drugi primjerak metra i kilograma predani su na čuvanje u *Bureau des Longitudes* u Zvjezdarnicu (Brezinšćak 1971, str. 184). Primjerak koji se čuva u Nacionalnom arhivu poznat je kao *Arhivski metar (Mètre des Arhives)*.

Delambre je primljen u *Bureau des Longitudes* 1795. godine, a postao predsjednik 1800. Za tajnika Akademije znanosti postavljen je 1801. godine, što ga je činilo najmoćnijom osobom u francuskoj znanosti toga doba (URL1). Godine 1803. počeo je pobolijevati od reumatske groznice, ali je i dalje postizao uspjehe. Napoleon je 1809. tražio od Akademije znanosti da predloži nekoga za nagradu za najbolji znanstveni rad. Nagrada je otišla Delambreu za njegov rad na meridijanu. U posljednjem razdoblju karijere bio je zainteresiran za povijest matematike i astronomije pa je na tu temu napisao više knjiga.

---

[1] Narodna skupština nastojala je izbjeći stari naziv za duljinu *Pied du Roy* jer je nova vlast željela što prije zaboraviti na kralja. Zato je Lenoir izradio privremeni metar od mjedi 1795. godine, dug 443,44 akademijine linije. Ta duljina je određena iz prethodnih meridijanskih mjerenja: u Peruu, u Laplandu i duljine Dunkerque-Perpignan od Cassinija (URL16).

The calculated flattening of the Earth was $f = 1:334$.

Based on that value and values from surveys of the meridian arc from Dunkirk (φ = 51° 02' 09.2") to Barcelona (φ = 41° 21' 44.96"), the length of this section of the meridian arc was calculated as 551 583.6 *toises*.

The total meridian arc length from the North Pole to the Equator was obtained using a polynomial representation for the length of the ellipse quadrant, taking into consideration second order members of ellipsoid flattening, resulting in a meridian arc length from the North Pole to the Equator equal to 5,130,740 *toises*. Consequently, according to the definition of the metre as one ten-millionth part of the meridian arc from the North Pole to the Equator, it was the equivalent of 0.513074 *toises*, i.e. 1 *toise* = 1.949037 m. This means the final value of the metre was shorter than the provisional metre[1] by only 0.144 *lignes* (1 *toise* = 6 *pieds*, 1 *pied* = 144 *lignes*).

Several platinum metre rods (Fig. 7) were produced with special care using the Lenoir comparator for the definitive standard metre. The rods had a transverse section of 25 mm × 4.05 mm, and their ends were exactly 1 metre apart at the temperature of melting ice. The length measurement error in comparing end measures was about 1/100 of a millimetre. When the final result was obtained, the two rods closest to the definition of the metre were selected. A copy of the metre and the kilogram were transferred to the Archive of the French Republic on June 22, 1799, and another copy of each was transferred to the Bureau des Longitudes in the Observatory (Brezinšćak 1971, page 184). The copy preserved in the National Archive was known as the Archive Metre (Mètre des Arhives).

Finally, Delambre was admitted to the *Bureau des Longitudes* in 1795 and became its president in 1800. He became the secretary of the Academy of Sciences in 1801, making him the most powerful person in French science at the time (URL1). In 1803, he contracted rheumatic fever, but continued to enjoy success. In 1809, Napoleon requested the Academy of Sciences to propose a suitable recipient for an award for the best scientific work. Delambre was chosen for his work on the meridian. At the end of his career, he became interested in the history of mathematics and astronomy and wrote several books on those topics.

3 Extending the Survey of the Paris Meridian as far as the Balearic Islands

Méchain proposed extending the survey of the Paris meridian as far as the Balearic Islands. Unfortunately, he died soon afterwards, so Jean-Baptiste Biot and François Dominique Jean Arago continued the work in difficult conditions.

Jean-Baptiste Biot (1774–1862) (Fig. 8) was a French physicist, astronomer and mathematician (URL9, URL10). He was educated at the college of *Louis-le-Grand* in Paris and joined the French army in 1792. He was arrested for desertion. Biot continued studying mathematics and became a professor of mathematics in Beauvais in 1797, and a professor of mathematical physics at the *Collège de France* around 1800. He became a member of the Academy of Sciences in 1803 and an external member of the Royal Swedish Academy in 1816. Biot was a proponent of Newton's theory of gravity and he made many scientific contributions to optics, magnetism and astronomy.

When Biot and Arago were at the Paris Observatory, they discussed the termination of work on the Paris meridian caused by Méchain's death and told Pierre-Simon Laplace (1749–1827) of their plan to extend the Paris meridian southwards to the Balearic Islands. He accepted their proposal and supported it in the Committee for Weight and Measures of the Academy of Sciences. However, it turned out to be a much more hazardous adventure than the young scientists had thought.

Biot and Arago travelled together from Paris to Spain in 1806 and started extending the trigonometric network in the mountains of Spain. Conditions were very difficult, because they had to traverse rough terrain and endure bad weather conditions, along with other problems in a foreign land during wartime. Biot returned to Paris in 1808, and Arago remained, completing the work under great hardship until 1809.

François Dominique Jean Arago (1786–1853) (Fig. 9) was a French mathematician, physicist, astronomer, geodesist and politician (URL7). He was born near Perpignan. At first, he was interested in a military career, but later turned to mathematics. He enrolled in the *École Polytechnique* in Paris in 1803 and became friends with Professor Denis Poisson.

When Méchain died in Spain in September 1804, Denis Poisson suggested to the director of the Paris Observatory that Arago be appointed to Méchain's post. He used a telescope to observe the positions of stars and also started working with Biot on the refraction of light through gases. It was a very important issue in practical

---

[1] The National Assembly wanted to avoid the old measurement of length *Pied du Roy* because the new government wanted to forget the king as soon as possible. Therefore, Lenoire produced a provisional metre made of brass, equivalent to 443.44 *lignes* in 1795. The length had been determined in previous meridian surveys in Peru and Lapland and by Cassini's Dunkirk-Perpignan measurements (URL 16).

Figure 8. Jean-Baptiste Biot (1774–1862) (URL9)
Slika 8. Jean-Baptiste Biot (1774–1862) (URL9)

Figure 9. François Dominique Jean Arago (1786–1853) (URL7)
Slika 9. François Dominique Jean Arago (1786–1853) (URL7)

3. Produživanje izmjere duljine Pariškog meridijana do Balearskog otočja

Prijedlog za produživanje izmjere duljine Pariškog meridijana do Balearskog otočja dao je Méchain. Nažalost on je ubrzo umro, a radove u teškim uvjetima nastavili su Jean-Baptiste Biot i François Dominique Jean Arago.

Jean-Baptiste Biot (1774–1862) (sl. 8) bio je francuski fizičar, astronom i matematičar (URL9, URL10). Studirao je u *College Louis-le-grand* u Parizu, a 1792. pridružio se topništvu u francuskoj vojsci. Kad je napustio vojsku uhićen je kao dezerter. Nastavio je studij matematike i 1797. imenovan je za profesora matematike u Beauvaisu, a oko 1800. godine za profesora matematičke fizike na *Collège de France*. U Akademiju znanosti izabran je 1803., a za vanjskoga člana Kraljevske švedske akademije izabran je 1816. godine. Biot je bio vatreni štovatelj Newtonove teorije gravitacije i dao je mnogobrojne doprinose znanosti u optici, magnetizmu i astronomiji.

Kad su Biot i Arago radili na Pariškom opservatoriju dogovarali su se o završetku rada na Pariškom meridijanu, koji je bio prekinut Méchainovom smrću. Plan o kompletiranju Pariškoga meridijana na jug do Balearskih otoka priopćili su Pierre-Simonu Laplaceu (1749–1827). On je prihvatio njihov prijedlog i podupro ga u Povjerenstvu za utege i mjere Akademije znanosti. Međutim, poslije se pokazalo da je to puno opasniji pothvat nego što su mislili mladi znanstvenici.

Biot i Arago su zajedno otputovali iz Pariza 1806. i počeli raditi na produživanju trigonometrijske mreže u planinama Španjolske. Uvjeti rada bili su vrlo teški jer su morali fizički savladavati teren i vremenske nepogode, te se susretati s raznim poteškoćama u stranoj zemlji u ratnim vremenima. Biot se vratio u Pariz iz Španjolske 1808. godine, a Arago je ostao završiti radove uz mnogobrojne poteškoće do 1809. godine.

François Dominique Jean Arago (1786–1853) (sl. 9) bio je francuski matematičar, fizičar, astronom, geodet i političar (URL7). Rođen je u malom mjestu pokraj Perpignana. Najprije je pokazao interes za vojnu karijeru, a poslije za matematiku. U *Ėcole Polytechnique* u Parizu ušao je 1803. godine i sprijateljio se s profesorom Denisom Poissonom.

Kad je Méchain umro u Španjolskoj u rujnu 1804. Poisson je predložio ravnatelju Pariškog opservatorija da na Méchainovo mjesto uzme Aragoa. On je teleskopom opažao položaje zvijezda, a počeo je raditi s Biotom na refrakciji svjetlosti kroz plinove. To je vrlo važno pitanje u praktičnoj astronomiji, jer su vidljivi položaji zvijezda pomaknuti zbog poremećaja pri prolazu kroz atmosferu.

Nakon što je Akademijino povjerenstvo za utege i mjere prihvatilo njihov prijedlog o produživanju Pariškog meridijana, Arago i Biot postali su tim koji se pripremao osamnaest mjeseci za savladavanje potrebnih tehnika mjerenja. Rečeno im je da osim izravnog mjerenja na trigonometrijskom lancu za određivanje duljine luka jednog stupnja meridijana trebaju odrediti i duljinu sekundnog njihala na više mjesta, što bi im pomoglo u određivanju Zemljina gravitacijskog polja, tj. njezina oblika (URL 12). Iz Pariza su otputovali 1806. godine i počeli s radom u planinama Španjolske. Pridružila su im se i dva Španjolca, Chaix i Rodriguez, koji su im bili potrebni za rad u stranoj zemlji.

Radeći dalje prema jugu, Arago i Biot postavili su trigonometrijsku točku na vrh Mongo blizu Denija (sl. 10), odakle su mogli vidjeti točku La Mola na malom otočiću Formentera, udaljenom oko 100 km od vrha Mongo.

astronomy because the visible positions of stars shifted due to disturbances in the atmosphere.

After the Committee for Weights and Measures accepted Biot and Arago's proposal to extend the Paris meridian, they became a team which took 18 months to prepare for conducting the necessary measurements. In addition to direct measurements along the trigonometric chain, they also had to determine the length of second pendulum in several places, in order to facilitate a determination of the Earth's gravitational field, i.e. its shape (URL12). In 1806, they left Paris and began work in mountains of Spain. They were joined by two Spaniards, Chaix and Rodriguez, who were indispensible to the foreigners.

Working their way southwards, Arago and Biot set up a trigonometric point to Mongo peak near Denia (Fig. 10), from where they could see La Mola on the small island of Formentera, about 100 km from Mongo. In addition, they were able to spot Camp Vey on Ibiza. Galatzo (S'Esclop) on Majorca could be determined from those two points. The side of the triangle from Desierto de las Palmas to Camp Vey, which is more than 150 km long, was also completed (Murdin 2009, p. 113). Triangles with sides as long as these made it difficult to measure angles, due to the absorption of light from such distances. So the measurement of some angles was postponed until more favourable weather conditions with a clearer atmosphere prevailed. They had to wait for months in some locations. In March 1807, they both travelled to the island of Formentera, but their repeating circle broke, so they had to return to mainland Spain. Biot then returned to Paris to have the instrument repaired, while Arago stayed in Spain and used other instruments to repeat measurements along the Spanish coast. Arago was from the eastern part of the Pyrenees, so he spoke Catalan, which helped him in his work, as well as preventing him from being arrested.

Biot returned to Spain with the repaired instrument in November 1807 and joined Arago in Valencia. They travelled to the island of Formentera again, observed the positions of stars and determined the latitude of the southernmost point of the Paris meridian. In addition, they determined the length of the seconds pendulum. Two Frenchmen working in Spanish territory with a sophisticated instrument raised suspicions, especially since the French had conquered Portugal and occupied part of Spain. So in those tumultuous times, Biot returned to France and Arago continued working in Spain, disguised as a Spaniard. He went to Majorca, where he set up the Clop de Galatzó (S'Esclop) trigonometric point and managed to connect Majorca with Formentera, Ibiza, Mongo and Desierto de las Palmas in a large trigonometric network (Fig. 10). He also measured the latitudes at some points (Murdin 2009, p. 116).

As the French had ambitions regarding the Balearic Islands, the local population interpreted Arago's setting lights the top of Galatzó hill (Catalan *Mola de l'Esclop*) as a sign for the invasion of enemy forces, though he was only trying to improve the visibility of the point in the trigonometric network. He was arrested in June 1808, but he escaped from the island in a fishing boat on 28 July and arrived in Algeria on 3 August. He was granted permission to travel to Marseille, but as the ship approached the port on 16 August, Arago and the crew were taken prisoners by the Spanish and sent to Roses on the Spanish coast, from where they were transferred to Palamos. Somehow Arago managed to board a ship bound for Marseille on 28 November 1808.

Fate played with Arago once again and bad weather steered the ship to the coast of North Africa, where he was imprisoned by Muslims. Thanks to his resourcefulness, he reached Algeria on 25 December, where the French consul helped him set sail for Marseille for the third time. This time he reached his destination without any trouble on 2 July 1809.

Upon arrival in Paris with his journal detailing measurements, Arago was welcomed as a hero. He became an assistant professor at *L'École Polytechnique* and a member of the Academy of Sciences, and he also worked at the Paris Observatory, of which he became director in 1843.

According to their work on extending the Paris meridian as far as Formentera, Arago and Biot determined that one ten-millionth part of the Earth's meridian from the North Pole to the Equator was the equivalent of 443.31 *lignes* (URL14). However, according to (URL14), that result was amended in a later work to 443.39 *lignes*. According to the reference ellipsoid WGS 84 (World Geodetic System) determined using contemporary satellite techniques, the modern value of one ten-millionth part of meridian arc length equals 443.38308 *lignes*, i.e. 1.00019657 m. Therefore, in relation to the definition of the metre, the difference is 0.19657 mm.

Arago was an imperturbable republican who participated in politics, enabling the financing of new astronomic instruments for the Paris Observatory and state support for the Academy of Sciences.

It should be noted that the Archive Metre remained the standard metre in France in practice, even when it became known that it did not exactly correspond to the new definition of the metre (URL 14). The introduction of new units of measure was very slow in France and some other countries. Even today, the international SI system is not accepted everywhere. The discovery that

Također, na približno takvoj udaljenosti mogla se vidjeti i točka Campvey na otoku Ibizi. Iz te dvije točke mogla se odrediti i točka Galatzo (S'Esclop) na otoku Mallorci. Pritom je bila ostvarena i stranica Desierto de las Palmas – Campvey, duga više od 150 km (Murdin 2009, str. 113). Tako duge stranice u trokutima stvarale su poteškoće u mjerenju kutova zbog apsorpcije zraka svjetlosti koje dolaze s tako velikih udaljenosti. Zato su za ostvarenje mjerenja nekih kutova na udaljene točke morali čekati povoljnije vremenske prilike s prozračnom atmosferom. Na nekim mjestima morali su čekati mjesecima. U ožujku 1807. obojica su putovali na otok Formentera, ali se njihov Bordin repeticijski krug slomio pa su se morali vratiti na kopneni dio Španjolske. Biot se tada vratio u Pariz noseći instrument na popravak, a Arago je ostao u Španjolskoj i upotrijebio preostale instrumente za ponavljanje mjerenja uzduž španjolske obale. Arago je potjecao iz istočnog dijela Pireneja, te je tako znao katalonski jezik što mu je znatno pomoglo u radu, a u nekim ga je slučajevima i spašavalo od zatočenja u zatvor.

Biot se vratio u Španjolsku s popravljenim instrumentom u studenome 1807. i pridružio se Aragou u Valenciji. Tada su ponovno išli na otočić Formenteru, gdje su opažali položaje zvijezda i određivali geografsku širinu te najjužnije točke na Pariškom meridijanu. Osim toga određivali su i duljinu sekundnog njihala na tom mjestu. Dvojica Francuza sa sofisticiranim mjernim instrumentima koji rade na španjolskom teritoriju postali su sumnjivi, posebice stoga što su Francuzi osvojili Portugal i okupirali dio Španjolske. U tim burnim vremenima Biot je pobjegao natrag u Francusku, a Arago je nastavio raditi u Španjolskoj, prikriven kao Španjolac. Tako se uputio i u Mallorcu, gdje je postavio trigonometrijsku točku Clop de Galatzó (S'Esclop) i uspio povezati Mallorcu s Formenterom, Ibizom, Mongom i s Desierto de las Palmasom u veliku trigonometrijsku mrežu (sl. 10). Pritom je mjerio i geografske širine na nekoliko točaka (Murdin 2009, str. 116).

Kako su se Francuzi željeli proširiti i na Balearsko otočje, stanovništvo je osvjetljavanje vrha brda Galatzó (katalonski Mola de l'Esclop), koje je Aragou služilo za vidljivost te točke na veliku daljinu u trigonometrijskoj mreži, protumačilo kao aktivnost špijuna za potrebe invazije protivničke vojske. Stoga je Arago morao ići u zatvor u lipnju 1808., a 28. srpnja je pobjegao s otoka u ribarskom brodu te 3. kolovoza stigao u Alžir. Dozvolu za putovanje u Marseille iz Alžira dobio je, ali kad se brod približio Marseilleu 16. kolovoza pao je kao zarobljenik u ruke Španjolaca. Posada i Arago bili su odvedeni kao zarobljenici u Roses na Španjolskoj obali, a poslije su ih prebacili u Palamos. Međutim, Arago se ipak uspio 28. studenoga 1808. ukrcati na brod za Marseille.

Figure 10. Trigonometric network by Biot and Arago, 1806–1809, extending the Paris meridian to the Balearic Islands (Natural Earth data and according to URL 13)

Slika 10. Trigonometrijska mreža Biota i Aragoa iz 1806–1809. godine za produživanje Pariškog meridijana do Balearskih otoka (podloga Natural Earth i prema URL 13)

Opet se sudbina poigrala s Aragoom jer je nevrijeme bacilo brod na obalu Sjeverne Afrike, gdje su ga zarobili muslimani. Zahvaljujući snalažljivosti stigao je 25. prosinca u Alžir, odakle je uz pomoć francuskoga konzula otputovao po treći put u Marseille. Ovaj put je stigao u svoje odredište u Francusku bez nezgoda 2. srpnja 1809.

Po dolasku u Pariz sa svojim dnevnikom u kojem su bila zapisana i mjerenja, prihvaćen je kao heroj. Postao je docent na *École Polytechnique* i član Akademije znanosti, a radio je i na Pariškom opservatoriju, gdje je postavljen za ravnatelja 1843. godine.

Arago i Biot su svojim mjerenjima na produživanju Pariškog meridijana do otoka Formentera utvrdili da 10-milijunti dio Zemljina meridijana od pola do ekvatora ima 443,31 akademijinu liniju (*lignes*) (URL14). Međutim, prema (URL14) rečeno je da je u kasnijem radu taj rezultat povećan na 443,39 akademijinih linija. Moderna vrijednost 10-milijuntog dijela duljine luka meridijana prema referentnom elipsoidu WGS84 (World Geodetic Sistem), određenom uz pomoć najsuvremenijih satelitskih tehnika mjerenja iznosi 443,38308 akademijinih linija, tj. 1,00019657 m. Dakle, razlika metra prema definiranoj zamisli iznosi 0,19657 mm.

Arago je bio nepokolebljivi republikanac i sudjelovao je u političkom životu zemlje pa je na taj način omogućio the Archive Metre had shortcomings led to the production of premeasures for the metre and kilogram, composed of 90% platinum and 10% iridium, ensuring that no changes would be made over a long period of time (Fig 11). During its first assembly in 1889, the General Conference on Weights and Measures proclaimed one of forty existing premeasures as the international premetre (A6) and defined the unit of length called the "metre" as *an interval between two middle lines on the metre premeasure at 0 °C, preserved in the International Bureau of Weights and Measures in Sèvres. The premeasure is exactly 1 metre long if the atmospheric temperature is 0 °C and pressure is normal when it is supported in a horizontal position with two cylinders with diameters of at least 1 cm which are 571 mm apart.*

An attempt was made to define the metre as accurately as possible by applying new understandings in physics, so that its length could be reproduced anywhere on Earth as accurately as possible. Thus it was changed in 1960 and 1983:

- The so-called *wave metre* came into effect from 1960, without changing the length of the 1889 metre. It was defined as *the length equal to 1 650 763.73 of wavelength in vacuum of radiation corresponding to the transition between levels 2 p10 and 5 d3 of the crypton 86 atom.* It could be reproduced anywhere in the world with a reliability of about $\pm 10^{-8}$ m = ±0.01 μm (Brezinšćak 1971).
- Since 1983, the metre has been defined using the speed of light in a vacuum as *equal to the distance light travels in a vacuum during one 299 792 458th of a second* (Benčić 1984, URL14). The length of metre determined in such way is especially suitable for determining distances in geodesy and astronomy, and can be reproduced anywhere in the world.

4 Conclusion

The survey of the Paris meridian helped define the length of the metre, although the length could have been determined arbitrarily. It is necessary to point out that the desire was to accept this measurement unit for the whole world and for all times.

Acknowledgements

We would like to thank our reviewers for their helpful comments, which contributed to the quality of this research on the history of geodesy. The survey of the Paris meridian helped define the metre as the basic unit of length in the international system.

We would also like to thank the Ministry of Science, Education and Sport of the Republic of Croatia for partially financing this paper, which was written as part of the project *Development of Scientific Measuring Laboratory for Geodetic Instruments*, No. 007-1201785-3539.

References / Literatura

Benčić, D. (1984): O osnovnoj mjernoj jedinici u geodeziji, Geodetski list br. 1–3, str. 5–11
Bialas, V. (1982): Erdgestalt, Kosmologie und Weltanschauung, Konrad Wittwer, Stuttgart.
Brezinšćak, M. (1971): Mjerenje i računanje u tehnici i znanosti, Tehnička knjiga, Zagreb.
Murdin, P. (2009): Full Meridian of Glory, Springer Science + Business Media, USA.
Solarić, M., Solarić, N. (2013): Francuska geodetska znanstvena ekspedicija u Peru (in preparation).
Vykutil, J. (1982): Vyšší geodézie, Kartografie, Praha.

URLs / Mrežne adrese

URL 1: Jean Baptiste Joseph Delambre, http://www-history.mcs.st-and.ac.uk/Mathematicians/Delambre.html (6. 7. 2011.)
URL 2: Jean Baptiste Joseph Delambre, http://en.wikipedia.org/wiki/Jean_Baptiste_Joseph_Delambre (7. 3. 2011.)
URL 3: Pierre Méchain, http://www-history.mcs.st-and.ac.uk/Biographies/Mechain.html (6. 7. 2011.)
URL 4: Pierre Méchain, http://en.wikipedia.org/wiki/Pierre_M%C3%A9chain (7. 3. 2011.)
URL 5: The history of measurement, http://www-history.mcs.st-and.ac.uk/HistTopics/Measurement.html (7. 7. 2011.)
URL 6: Figure de la Terre et méridienne de Delambre et Méchain, http://fr.wikipedia.org/ (12. 7. 2011.)
URL 7: Francois Arago, http://fr.wikipedia.org/wiki/Fran%C3%A7ois_Arago (12. 7. 2011.)
URL 8: Montjuic Castle, http://en.wikipedia.org/wiki/Montju%C3%AFc_Castle (12. 7. 2011.)
URL 9: Jean-Baptiste Biot, http://en.wikipedia.org/wiki/Jean-Baptiste_Biot (12. 7. 2011.)
URL 10: Jean-Baptiste Biot, http://www-history.mcs.st-and.ac.uk/Biographies/Biot.html (1. 8. 2011.)
URL 11: Cartography and the Cassini and Maraldi families, http://www.catnaps.org/cassini/cart.html (28. 3. 2011)
URL 12: Dominique François Jean Arago, http://www-history.mcs.st-and.ac.uk/Biographies/Arago.html (7. 8. 2011.)
URL 13: In the Foot steps of Arago, http://lec.ugr.es/~julyan/papers/arago/indeks.html (31. 8. 2011.)
URL 14: History of metre, http://en.wikipedia.org/wiki/History_of_the_metre (31. 8. 2011.)
URL 15: Cathedral in Rodez, http://en.wikipedia.org/wiki/Rodez_Cathedral (2. 9. 2011.)
URL 16: Un historique du metre, http://www.industrie.gouv.fr/metro/aquoisert/metre.htm (20. 7. 2011.)

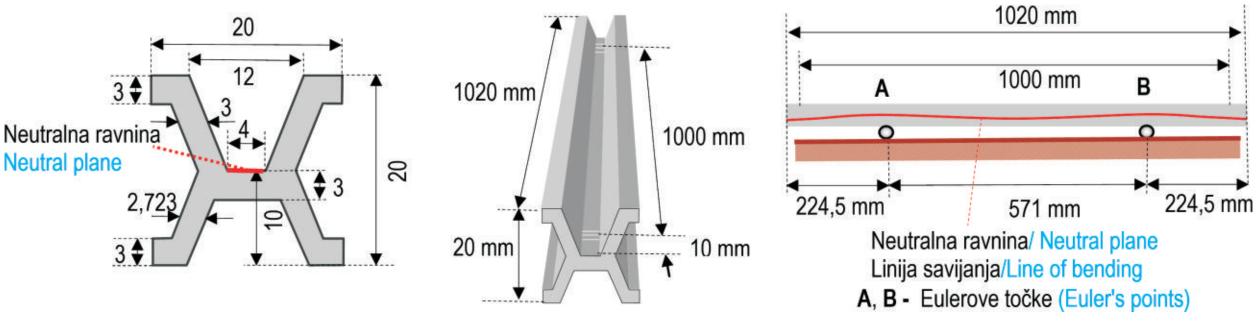

Figure 11. Diagrams showing the dimensions of the international historical metre with lines engraved in a neutral plane. All measurements are in mm.

Slika 11. Grafički prikaz dimenzija međunarodnog prametra s crticama ugraviranim u neutralnu ravninu. Mjere su izražene u milimetrima

financiranje kupnje novih astronomskih instrumenata za Pariški opservatorij, a osigurao je i financijsku potporu države Akademiji znanosti.

Treba primijetiti da je *Arhivski metar* ostao pravno praktički standard za metar u Francuskoj čak i onda kada je bilo poznato da ne odgovara točno definiciji metra (URL14). Uvođenje novih mjernih jedinica u život išlo je vrlo sporo u Francuskoj, ali i u drugim zemljama tako da i danas neke zemlje nisu prihvatile taj međunarodni sustav mjernih jedinica (*System International*, skraćeno *SI sustav*). Poslije je utvrđeno da postoje i neki nedostaci *Arhivskog metra*. Zato se studiozno pristupilo izradi *Pramjera metra i kilograma* izrađenih od 90% platine i 10% iridija, a pritom se posebno pazilo da u dugom razdoblju ne dođe do bilo kakvih promjena (sl. 11). Generalna konferencija za mjere i utege na svom prvom zasjedanju 1889. godine proglasila je jedan od četrdesetak izvanrednih primjeraka prametra međunarodnim prametrom (obilježen oznakom A6) i jedinicu duljine "metar" definirala: *Jedinica duljine je metar koji je pri temperaturi 0 °C definiran razmakom između dvije srednje crtice na pramjeri metra, pohranjenog u Međunarodnom uredu za mjere i utege u Sèvresu. Pramjera ima točno duljinu 1 metar kad je pri temperaturi 0 °C i normalnom atmosferskom tlaku poduprta u vodoravnom položaju s dva valjka promjera najmanje 1 cm, koji su međusobno udaljeni 571 mm.*

Tijekom vremena nastojala se što točnije definirati duljina metra s novijim spoznajama iz fizike tako da bi se mogla reproducirati duljina metra na bilo kojem mjestu na Zemlji i što točnije, te su one mijenjane 1960. i 1983. godine:

- Od 1960. godine bio je službeno na snazi tzv. *valni metar*, a pritom *nije mijenjana duljina metra* iz 1889. godine. On je definiran kao:
  Metar je duljina jednaka 1 650 763,73 duljine vala u zrakopraznom prostoru zračenja koje odgovara prijelazu između razina 2 p10 i 5 d3 atoma kriptona 86.
  Mogao se reproducirati bilo gdje na svijetu s pouzdanošću oko ± 10^{-8} m = ± 0,01 µm (Brezinšćak 1971).
- Od 1983. godine metar je definiran s pomoću brzine svjetlosti u zrakopraznom prostoru ovako:
  Metar je jednak duljini puta koji svjetlost prijeđe u zrakopraznom prostoru za vrijeme 299 792 458-og dijela sekunde (Benčić 1984, URL14).
  Tako definiran metar posebno je pogodan za određivanje udaljenosti u geodeziji i astronomiji, a može se reproducirati bilo gdje na svijetu.

4. Zaključak

Izmjera Pariškog meridijana pomogla je određivanju duljine metra, iako se mora priznati da se ta duljina mogla uzeti proizvoljno. Međutim, treba naglasiti da se željelo da ta mjerna jedinica bude prihvatljiva za sve narode svijeta i za sva vremena.

Zahvala

Najljepše zahvaljujemo recenzentima na korisnim primjedbama, kojima su pridonijeli boljoj kvaliteti ovog istraživanja geodetske prošlosti. Izmjera Pariškog meridijana pripomogla je definiciji metra kao osnovne jedinice za duljinu u međunarodnom sustavu jedinica.

Zahvaljujemo također Ministarstvu znanosti, obrazovanja i sporta RH, što je djelomično financiralo ovaj rad koji je izrađen u okviru projekta *Razvoj znanstvenog mjeriteljskog laboratorija za geodetske instrumente* br. 007-1201785-3539.