Review

Beginnings of Satellite Navigation

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Abstract: *The first satellite navigation system called the Navy Navigation Satellite System (NNSS) or TRANSIT was planned in the USA in 1958. It consisted of 5-6 artificial Earth satellites, was set in motion for the USA military in 1964, and in 1967 for civilian purposes. The frequency shift of received radio waves emitted from the satellite and caused by the Doppler effect was measured. The TRANSIT satellite speed of approaching or moving away was derived from that; the TRANSIT satellites emmited also their own coordinates. Then the ship's position was determined by an intersection of three hyperboloids, which were determined from differences of distances in three time intervals. Maintenance of this navigation system was stopped in 1996, but it is still being used in the USA Navy for exploring the ionosphere.*

Furthermore, results of Doppler measurements in international projects at the Hvar Observatory from 1982 and 1983. This was the first time in Croatia and the former country that the coordinates of the Hvar Observatory were determined in the unique world coordinate system WGS'72.

The paper ends with a brief representation of the Tsiklon Doppler navigation system produced in the former Soviet Union, and there is a list of some of numerous produced and designed satellite navigation systems.

Key words: *navigation, satellites, radio wave, broadcast ephemeris, precise ephemeris, Doppler shift of frequencies, determination position of ship, Navy Navigational Satellite System (NNSS).*

1. Introduction

One was able to apply celestial navigation of ships at sea and oceans only after knowledge from positional astronomy was gathered. Furthermore, there was a need for an instrument which could measure the altitude of celestial bodies and calculate the geographic latitude of the ship by means of astronomical tables. This instrument was given the name astrolabe (Fig. 1), and the Arabs brought it to Europe, so Christopher Columbus employed astrolabe at his transoceanic journeys in discovering America.

The first sextant was constructed by Abu-Mahmud al-Khujandi from Iran in 994 (URL 1). However, it was rediscovered by English John Hadley and American Thomas Godfrey in 1730 (URL 2). Thus the sextant (Fig. 2) replaced the astrolabe and became the main instrument for mariners' navigation. It continued until the first application of electronic navigation.

However, early mariners had a problem of determining the geographic longitude. In fact, they required accurate clocks (chronometers) in order to determine the longitude. Therefore, before accurate clocks were invented, mariners tended to cross the Atlantic by keeping their ship on a parallel, i.e. the same geographic latitude. This was the case until 1735. Than John Harrison successfully constructed a portable chronometer and proposed it for a promised reward in 1735 (De Bono 2005, page 325) (Fig. 3). During the following 30 years, he improved

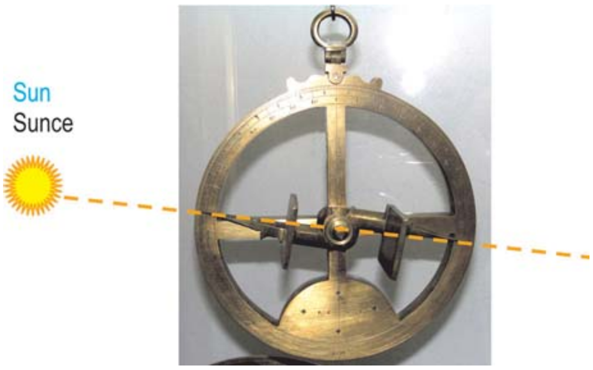

Fig. 1. The astrolabe was used for astronomical measurements in the Middle Ages and at the beginning of the New Age

Slika 1. Astrolab se rabio u srednjem vijeku i početkom novoga vijeka za astronomska mjerenja

Pregledni znanstveni rad

Prvi začeci satelitskih navigacija

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Sažetak: *Prvi satelitski navigacijski sustav nazvan Navy Navigation Satellite System (NNSS), koji je još nazivan i TRANSIT, planiran je u SAD-u 1958. godine. Sastojao se od 5 do 6 umjetnih Zemljinih satelita, a pušten je u rad za vojsku u SAD-u 1964. godine, dok je za civilnu uporabu dopušteno njegovo korištenje 1967. godine. Mjerio se pomak frekvencije primanih radiovalova odaslanih sa satelita, koji je izazvan Dopplerovim efektom. Iz toga je određena brzina približavanja ili udaljavanja satelita TRANSIT, koji su odašiljali i svoje koordinate položaja. Zatim se položaj broda određivao presjekom triju hiperboloida, koji su određeni iz razlika udaljenosti u tri vremenska intervala. Održavanje toga navigacijskog sustava prekinuto je 31. prosinca 1996., ali se još danas koristi u američkoj mornarici za istraživanje ionosfere.*

Potom su prikazani rezultati doplerovskih mjerenja u međunarodnim projektima na Opservatoriju Hvar iz 1982. i 1983. godine. Tada su prvi put u Hrvatskoj i bivšoj državi određene koordinate položaja Opservatorija Hvar u jedinstvenom svjetskom koordinatnom sustavu WGS'72.

Na kraju je vrlo kratko prikazan doplerovski navigacijski sustav Ciklon, izrađen u bivšem SSSR-u, a i pobrojani su neki od mnogobrojnih izvedenih i projektiranih satelitskih navigacijskih sustava.

Ključne riječi: *navigacija, sateliti, radiovalovi, odaslane efemeride, precizne efemeride, doplerovski pomak frekvencije, određivanje položaja broda, pomorski navigacijski satelitski sustav (NNSS)*

1. Uvod

Astronomska navigacija brodova na širokome moru i oceanima mogla se primijeniti tek nakon što je skupljeno znanje iz pozicijske astronomije. Osim toga trebalo je konstruirati i instrument kojim se može izmjeriti visina nebeskih tijela i uz pomoć astronomskih tablica izračunati geografska širina broda. Taj instrument nazvan je astrolab (sl. 1), a Arapi su ga prenijeli u Europu, pa je tako i Kristofor Kolumbo koristio astrolab na svojim prekooceanskim putovanjima pri otkriću Amerike.

Prvi sekstant konstruirao je Abu-Mahmud al-Khujandi iz Irana 994. godine (URL 1). Poslije su ga ponovno otkrili 1730. godine Englez John Hadley i Amerikanac Thomas Godfrey (URL 2). Tada je sekstant (sl. 2) zamijenio astrolab i postao glavni instrument za navigaciju pomoraca sve do prvih primjena elektronske navigacije.

Međutim, starim pomorcima dugo je bio problem odrediti geografsku dužinu. Naime, za određivanje geografske dužine bili su im potrebni i točni satovi (kronometri). Zbog toga su pomorci prije pronalaska točnih satova nastojali za prelazak preko Atlantika svoj brod voditi po paraleli, tj. držeći brod na istoj geografskoj širini. Tako je bilo sve do 1735. godine. Tada je John Harrison uspješno konstruirao prijenosni kronometar i predložio ga za raspisanu nagradu (De Bono, 2005, str. 325) (sl. 3). On ga je u idućih 30 godina poboljšao i smanjio mu dimenzije i masu s 33 kg. Njegova četvrta verzija izrađena 1761. godine bila je lijepa i malih dimenzija. Poslije je Francuz P. Le Roy 1769. godine usavršio kronometar za potrebe navigacije (URL 10). Tako su pomorci s pomoću sekstanata i kronometara mogli odrediti koordinate položaja broda, tj. geografsku širinu i geografsku dužinu pozicije broda, što im je bilo važno.

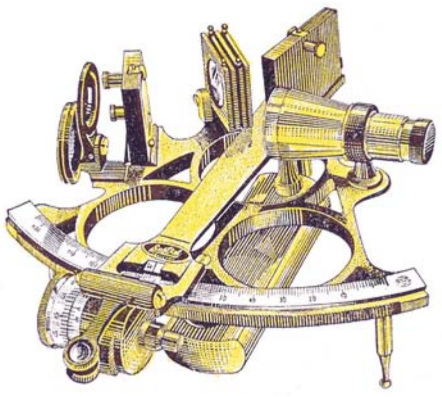


Fig. 2. Sextants are used for measuring vertical and horizontal angles

Slika 2. Sekstantima se mjere vertikalni i horizontalni kutovi

Fig. 3. H1 - the first model of Harrison's chronometer from 1735 had 33 kg (left) and H4 - the fourth version of Harrison's chronometer from 1761 (right). A duplicate of that model was produced by Larcum Kendall, and used by J. Cook on his second journey from 1772 to 1775 (URL 10)

Slika 3. H1 - prvi model Harrisonova kronometra iz 1735. godine imao je masu od 33 kg (lijevo) i H4 - četvrta verzija Harrisonova kronometra iz 1761. godine (desno). Duplikat tog modela izradio je Larcum Kendall, a koristio ga je J. Cook na svojem drugom putovanju od 1772. do 1775. (URL 10)

it and reduced its dimensions and mass from 33 kg. His fourth version constructed in 1761 was nice and small. French P. Le Roy refined the chronometer for navigation needs in 1769 (URL 10). Thus mariners, by means of the sextant and the chronometer, were able to determined the ship's coordinates, i.e. the latitude and the longitude of the ship's position, which was important to them.

On the other hand, celestial navigation had a major flaw: it could not be applied during cloudy and foggy weather, i.e. when it was essential for mariners. This is why efforts were made to discover electronic navigation methods. During the second half of World War I, the goniometer antenna was produced, which was used to determine the enemy position according to the position of their radio stations. This principle was also used in navigation from 1921, when the first radio far was installed, which can be considered the beginning of electronic navigation (Benković et al. 1986).

The first systems of hyperbolic navigation were developed during World War II, for example, the system Loran from 1942 and afterwards the phase system Decca. These two systems could only be used on some larger areas of the Earth. The global hyperbolic system Omega was developed several years later, and several more years had to pass before it got a complete configuration. It could be used for navigation anywhere on the Earth.

However, efforts were made to discover new methods which would enable accurate position determination of all types of ships. Thus, the Earth's first artificial satellites were used to determine position on oceans and seas.

2. The Doppler Effect

Christian Doppler published his most significant paper *Über das farbige Licht der Doppelsterne in Prague* in 1842. He observed double stars. The paper explains that frequency changes if the source of the wave (sound, light, etc.) moves closer or away in relation to the observer. This is the well-known effect:

> *When a train is approaching an immobile observer, the pitch of the locomotive's signal is higher, while the pitch of that same signal when the train is moving away is lower than the frequency of the actually broadcast signal of the locomotive pipe.*

An explanation as to why this frequency change of broadcast waves received by the "still observer" if the wave transmitter is approaching or moving away from the still observer is represented in Fig. 4, where only one wave is drawn for the sake of simplicity.

This phenomenon was called the Doppler effect, and the shifted frequency f_{prim} of received waves can be approximated with the following equation:

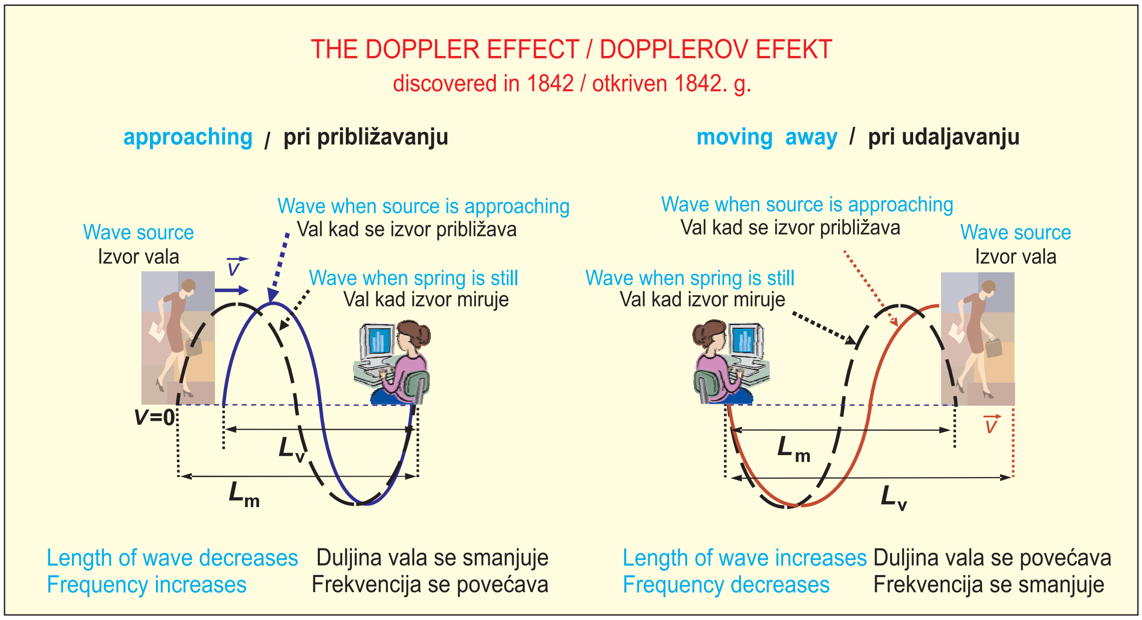
$$f_{\mathrm{prim}} \cong f_{\mathrm{odas}} \left(1 + \frac{\dot{r}}{c} \right) \tag{1}$$

where:

f_{odas} – frequency of waves broadcast from the point S,

$\dot{r}$ – *radial component of relative speed of wave sources*, i.e. the point S in relation to the point O (the "still" observer) and

c – speed of expanding waves (Fig. 5).



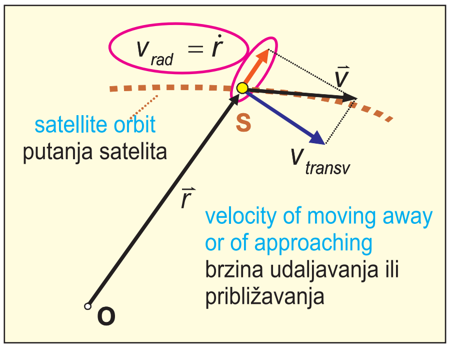


Fig. 4. (above) Frequency change when the source wave is approaching or moving away from the "still" observer

Slika 4. (gore) Promjena frekvencije kod približavanja, odnosno udaljavanja izvora vala od "mirnog" opažača

Fig. 5. (left) Representation of components of vectors of relative speed v, where v_{rad} - radial speed component and v_{transv} - transversal speed component

Slika 5. (lijevo) Prikaz komponenti vektora relativne brzine v, gdje je v_{rad} - radijalna komponenta brzine i v_{transv} - transverzalna komponenta brzine

Treba naglasiti da je astronomska navigacija imala veliki nedostatak, jer se nije mogla primijeniti za oblačna i maglovita vremena, tj. u trenucima kada je bila pomorcima najpotrebnija. Zato su se nastojale pronaći metode elektronske navigacije. U drugoj polovici I. svjetskog rata izrađena je goniometarska antena, koja je korištena za otkrivanje položaja neprijatelja prema položaju njegovih radiopostaja. Taj je princip korišten i u navigaciji od 1921. godine, kada je postavljen prvi radiofar, što se može smatrati početkom elektronske navigacije (Benković i dr., 1986).

Tijekom II. svjetskog rata razvijaju se i prvi sustavi hiperboličke navigacije. Tako je već od 1942. godine radio sustav *Loran*, a nešto poslije i fazni sustav *Decca*. Ta dva sustava mogla su se upotrebljavati samo na određenim većim područjima na Zemlji. Nešto poslije razvijen je globalni hiperbolički sustav *Omega*, koji je tek nakon nekoliko godina dobio potpunu konfiguraciju. Mogao se koristiti za navigaciju na čitavoj Zemlji.

Međutim, nastojale su se pronaći i neke nove metode koje će omogućiti što točnije određivanje položaja svih vrsta brodova. Tako su se nakon izbacivanja prvih umjetnih Zemljinih satelita oni nastojali uporabiti za određivanje položaja na oceanima i morima.

2. Dopplerov efekt

Christian Doppler objavio je svoj najznačajniji rad *Über das farbige Licht der Doppelsterne* u Pragu 1842. godine. Učinio je to na osnovi promatranja dvojnih zvijezda. U njem je objašnjeno da do promjene frekvencije dolazi ako se izvor vala (zvuka, svjetla i dr.) relativno približava ili udaljuje od promatrača. To je svima poznati efekt:

> *kada se vlak približava nepomičnom opažaču, visina tona zvučnog signala lokomotive je viša, dok je pri udaljavanju vlaka visina tona istoga zvučnog signala niža od frekvencije stvarno odaslanog zvučnog signala piska lokomotive.*

Pojašnjenje zbog čega dolazi do promjene frekvencije odaslanih valova koje prima ''mirni opažač'' ako se odašiljač vala približava ili udaljuje od mirnog opažača, prikazano je na sl. 4., gdje je zbog jednostavnosti nacrtan samo jedan val.

Ta je pojava nazvana Dopplerovim ili doplerovskim efektom, a pomaknuta frekvencija f_{prim} primljenih valova može se približno izraziti jednadžbom:

$$f_{prim} \cong f_{odas}\left(1+\frac{\dot{r}}{c}\right) \tag{1}$$

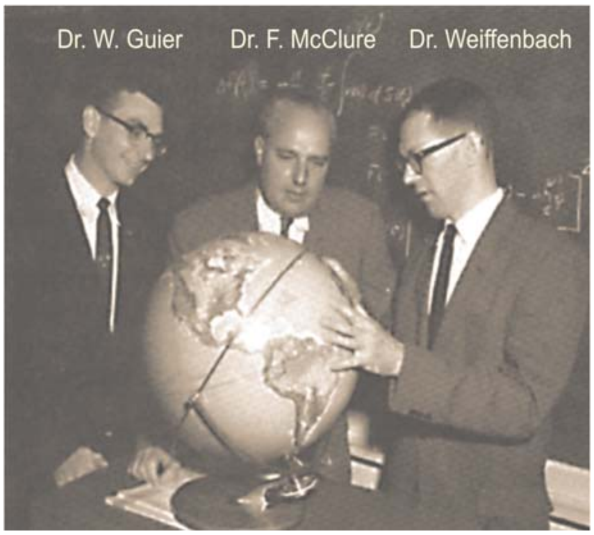


Fig. 6. Scientists from The Applied Physics Laboratory of John Hopkins University (USA) formed a station network for determining the position of Earth's artificial satellites with the Doppler effect (Yionoulis 1998)

Slika 6. Znanstvenici iz "The Applied Physics Laboratory of John Hopkins University" (SAD) oformili su mrežu stanica za određivanje položaja umjetnih Zemljinih satelita s pomoću Dopplerova efekta (Yionoulis, 1998)

The sign of the radial component of relative speed is positive if the transmitter S is moving away, and negative if it is approaching. The Doppler effect is used to determine only the radial component of speed, i.e. the speed of wave source approaching of moving away.

3. Application of the Doppler Effect for Determining Satellite Position

Determining the position of Earth's artificial satellites with optical measurements by highly sensitive photographic cameras had a significant limitation, although it was the most accurate measuring method during the 1960s. The limitation was that cameras could be used to determine the position of Earth's artificial satellites in just a small number of points of its positions. In fact, Earth's artificial satellites could not be observed by optical methods (cameras) during the daylight, cloudy and foggy weather, but also not during a bright night when the satellite was in Earth's shadow. Therefore, cameras could register positions of artificial satellites only in a relatively short time period:

☐ at dusk and at the beginning of night

☐ before and at dawn

i.e. before the satellite entered the Earth's shadow or came out of it, and only if the sky was bright.

This is why effort was made to use the Doppler effect to determine the position of artificial satellites as soon as the first artificial satellite Sputnik 1 was launched. By analyzing the Doppler frequency shift of broadcast signals from Sputnik 1, William H. Guier and George C. Weiffenbach (Fig. 6) from The Applied Physics Laboratory of John Hopkins University, USA concluded that a satellite's orbit can be determined from a single transit of the satellite (Yionoulis 1998).

Thus the "TRANET" point network with known coordinates was established at which radio waves broadcast from artificial satellites were received by special receivers. Then, satellite positions in the coordinate system of known measurement points were calculated from these received radio wave frequencies, i.e. the Doppler shift of received waves' frequencies. This method of determining artificial satellites' position resulted in much lesser accuracy than observing with specially sensitive photographic cameras. However, the Doppler method could be used during daylight, cloudy weather, fog and when the satellite was in the Earth's shadow, so that was somewhat of an advantage. Thus much more observation data about satellite positions were collected by means of Doppler measurements on Earth stations than by optical methods. Moreover, measurement data were immediately ready for further electronic processing, in contrast to the optical method where satellite positions on photographic plates had to be digitized, which took a lot of time. Only then could one electronically process optical measurement data.

4. Application of the Doppler Effect to Satellite Navigation

Shortly after launching first satellites (1958), Frank McClure and Richard Kershner (Fig. 7) from "The Applied Physics Laboratory of John Hopkins University" (USA) proposed the usage of Earth's artificial satellites for maritime navigation.

They conceived that by using a reverse procedure for determining the position of Earth's artificial satellites with Doppler's effect of radio waves, one could determine ship positions from:

1) known satellite positions
2) Doppler shifts of received frequencies of radio waves broadcast from satellites and
3) received signals (messages) from satellites about their positions.

The plan was to launch 5 to 6 TRANSIT type satellites (Fig. 8) (later also NOVA) around the Earth into approximately circular polar orbits with altitude of about h = 1000 km with a rotation period of 107 minutes (Fig. 9). This satellite system was called the Navy Navigation Satellite System (abbreviated NNSS), and was later also often called TRANSIT. Each TRANSIT satellite, due to Earth's rotation around its axis, intersects the equator after every circular trip around the Earth in a place 26° west from the place it passed the equator during the last

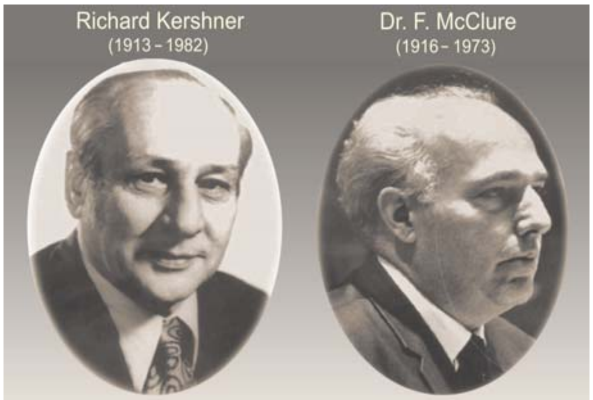


Fig. 7. Proposers and creators of the idea of the first satellite navigation Doppler system - the NNSS system, also called TRANSIT (Pisacane 1998)

Slika 7. Predlagači i idejni tvorci prvoga satelitskoga navigacijskog Dopplerova sustava - NNSS-a, nazivanog još i TRANSIT (Pisacane, 1998)

gdje su:

f_{odas} – frekvencija odaslanih valova iz točke S,

$\dot{r}$ – radijalna komponenta relativne brzine izvora valova, tj. točke S u odnosu na točku O (gdje ''miruje'' opažač) i

c – brzina širenja valova (sl. 5).

Predznak radijalne komponente relativne brzine je pozitivan ako se odašiljač S udaljuje, a negativan ako se približava. S pomoću Dopplerova efekta određuje se samo radijalna komponenta brzine, tj. brzina udaljavanja ili približavanja izvora vala.

3. Primjena Dopplerova efekta za određivanje položaja satelita

Određivanje položaja umjetnih Zemljinih satelita s pomoću optičkih mjerenja visokoosjetljivim fotografskim kamerama, i pored toga što je taj način mjerenja šezdesetih godina XX. stoljeća bio najtočniji, imalo je veliki nedostatak. Taj se nedostatak sastojao u tome da se kamerama mogao odrediti položaj umjetnih Zemljinih satelita samo u malom broju točaka njegovih položaja. Naime, umjetni Zemljini sateliti nisu se mogli opažati optičkim metodama (kamerama) za vrijeme danjeg svjetla, oblačnog i maglovitog vremena, ali ni po vedroj noći kada je satelit bio u Zemljinoj sjeni. Dakle, kamerama su se mogli registrirati položaji umjetnih satelita samo u relativno kratkom vremenskom razdoblju:

❑ u sumrak i početkom noći,

❑ pred zoru i u zoru,

tj. dok satelit nije ušao u Zemljinu sjenu ili izašao iz nje, i to samo ako je nebo bilo vedro.

To je razlog zbog čega se odmah nakon izbacivanja prvog umjetnog satelita Sputnjika 1 nastojao iskoristiti Dopplerov efekt za određivanje položaja umjetnih satelita. U SAD-u su William H. Guier i George C. Weiffenbach (sl. 6) iz The Applied Physics Laboratory of John Hopkins University (APL) analizom Dopplerova pomaka frekvencije odaslanih signala sa Sputnjika 1 došli do zaključka da se orbita satelita može odrediti iz samo jednog prolaza satelita (Yionoulis, 1998).

Tako je uspostavljena mrežu točaka TRANET s poznatim koordinatama položaja na kojima su posebnim prijamnicima primani radiovalovi odaslani s umjetnih satelita. Zatim su iz tih primljenih frekvencija radiovalova, tj. iz Dopplerova pomaka frekvencija primljenih valova izračunali položaje satelita u sustavu koordinata poznatih mjernih točaka. Tim načinom određivanja položaja umjetnih satelita postizana je znatno manja točnost od opažanja posebnim osjetljivim fotografskim kamerama. Međutim, s pomoću doplerovske metode moglo se mjeriti i po danjem svjetlu, oblačnom vremenu, magli i kada je satelit bio u Zemljinoj sjeni, pa joj je to bila izvjesna prednost. Tako se s pomoću doplerovskih mjerenja na stanicama na Zemlji skupljalo znatno veći broj podataka opažanja o položajima satelita nego optičkim načinom. Osim toga mjerni podaci bili su odmah spremni za daljnju elektroničku obradu, a pri optičkom načinu snimljene položaje satelita na fotografskim pločama trebalo je digitalizirati, što je oduzimalo mnogo vremena. Tek tada se moglo pristupiti elektroničkoj obradi optičkih podataka mjerenja.

4. Primjena Dopplerova efekta za satelitsku navigaciju

Nedugo nakon izbacivanja prvih satelita (1958. godine) Frank McClure i Richard Kershner (sl. 7) iz The Applied Physics Laboratory of John Hopkins University (SAD) predložili su da se umjetni Zemljini sateliti koriste za navigaciju na moru.

Oni su zamislili da se obrnutim postupkom za određivanje položaja umjetnih Zemljinih satelita s pomoću Dopplerova efekta radiovalova mogu odrediti položaji brodova iz:

1) poznatih položaja satelita
2) doplerovskih pomaka primljenih frekvencija radiovalova odaslanih sa satelita i
3) primljenih signala (poruka) sa satelita o njihovim položajima.

Tako je bilo zamišljeno da se u orbitu oko Zemlje lansira 5 do 6 satelita tipa TRANSIT (sl. 8) (a poslije i NOVA) u približno kružne polarne orbite na visinu oko $H = 1000$ km s periodom ophoda oko Zemlje od 107 minuta (sl. 9). Taj satelitski sustav dobio je naziv *Navy Navigation Satellite System* (skraćeno *NNSS*), a poslije se često koristio i naziv *TRANSIT*. Svaki satelit TRANSIT, zbog rotacije Zemlje oko svoje osi, sjekao je ekvator nakon svakoga kružnog ophoda oko Zemlje na mjestu udaljenom za 26° zapadno od mjesta gdje je prelazio ekvator u prethodnom ophodu. Tim je sustavom satelita postignuto da se na svakome mjestu na Zemlji moglo relativno često

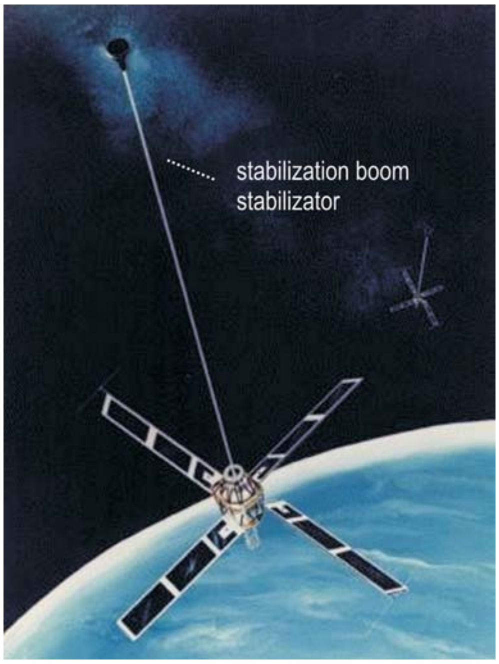


Fig. 8. Navigation satellite TRANSIT (URL 4)

Slika 8. Navigacijski satelit TRANSIT (URL 4)

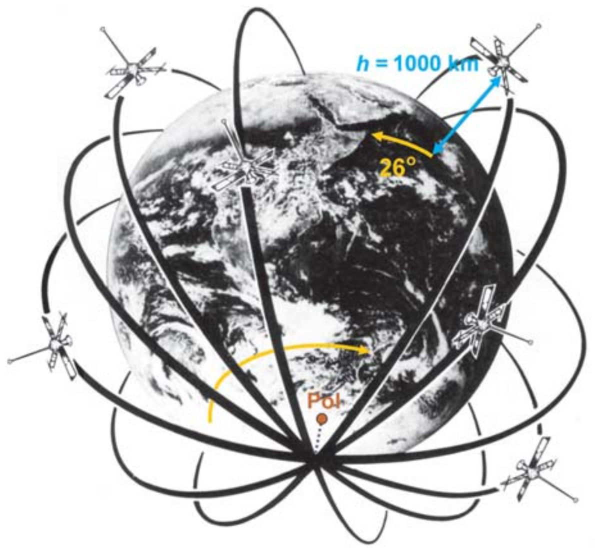


Fig. 9. Navy Navigation Satellite System (NNSS), i.e. TRANSIT (Stansell 1983)

Slika 9. Navy Navigation Satellite System (NNSS), tj. TRANSIT (Stansell, 1983)

trip. By using this satellite system, one could register passages of the TRANSIT satellites relatively often in any place on the Earth, i.e. by means of receiving their radio signals determine the position of a ship or a coordinate of a point on the Earth. The first results indicated errors with 1 km order of magnitude (Yionoulis 1998).

There were the following numbers of passages of NNSS-satellites, called TRANSIT (later also NOVA) above the horizon of a point on the Earth in a 24-hour period:

- at the *equator* 20-30
- at *middle latitudes* 40-50 and
- at the *pole* considerably more.

In so doing, 10-16 minute signals were received during the flight of every NNSS satellite above the antenna of the Doppler device (Stansel 1983, p. 7). The length of receiving the signal depended on maximum elevation the satellite reached during the passage above the antenna horizon. For a new ship's position determination, one had to wait the next passage of an NNSS satellite:

- at the *equator* about 1 hour
- at *middle latitudes* more than half an hour and
- at a *pole*, position determination could be repeated after a brief time period.

Each navigation satellite had a:

- radio receiver of commands and messages from the Earth
- memory in which all data were stored and broadcast to Earth by radio transmitters
- data decoder
- stable oscillator of 5 MHz (precision 10^{-12})
- 1.5 W radio transmitters, as well as various supporting devices.

A satellite's mass was only 68 kg, and its dimensions 46 cm × 30 cm without solar panels. The stabilizer (Fig. 8) enabled proper orientation of transmitter antennae (Decca 1978).

Radio transmitters from the satellites broadcast two very stable coherent carrier of frequencies of electromagnetic waves in ultra-short wave area of about 150 MHz (more precisely, 149.988 MHz) and 400 MHz (more precisely, 399.968 MHz). These two frequencies were selected so as to correct the ionosphere influence well. Both frequencies were phase modulated with phase shift of +60° or -60° forming the signal for bit "1" or "0" , which can be seen in (Fig. 10). Thus a binary number system also used in electronic computers was adopted in the NNSS system.

Messages about satellite positions, i.e. fixed elements of satellites' middle orbit and its disturbances in satellite movement, as well as other required information were broadcast by radio communication to users on the Earth. These messages, the so-called broadcast ephemeris in orbital coordinate system, were broadcast each even minute of the Universal Time (UT). This ensured the accuracy of relation of time on the satellite and in the receiver. This is very significant if one knows that TRANSIT satellites moved around the Earth with great speed of 7.37 km/s. In this way, TRANSIT satellites could be registrirati prolaze satelita TRANSIT, tj. uz pomoć prijama njihovih radiosignala odrediti položaj broda ili koordinate neke točke na Zemlji. Početni rezultati davali su pogreške reda veličine 1 km (Yionoulis, 1998).

Iznad horizonta neke točke na Zemlji u jednom danu (za vrijeme od 24 sata) bilo je prolaza NNSS-satelita, zvanih TRANSIT (a poslije i NOVA):

- na *ekvatoru* 20 do 30
- na *srednjim geografskim širinama* 40 do 50 i
- na *polu* znatno više.

Pritom su prigodom nadlijetanja svakog NNSS-satelita iznad antene doplerovskog uređaja primani signali 10 do 16 minuta (Stansel, 1983, str. 7). Dužina primanja signala ovisila je o maksimalnoj elevaciji satelita do koje je došao satelit pri prolazu iznad horizonta antene. Za novo određivanje položaja broda trebalo je čekati sljedeći prolaz jednog od NNSS-satelita:

- na *ekvatoru* oko 1 sat,
- na *srednjim geografskim širinama* nešto više od pola sata i
- na *polu* moglo se određivanje položaja ponoviti s manjim vremenskim razmakom.

Svaki navigacijski satelit imao je:

- radioprijamnik naredbi i poruka sa Zemlje,
- memoriju u koju su pohranjeni svi podaci koje su poslije radioodašiljači odašiljali na Zemlju,
- dekoder podataka,
- stabilan oscilator od 5 MHz (preciznosti 10^{-12}),
- radioodašiljače od 1,5 W, kao i različite pomoćne uređaje.

Masa satelita bila je samo 68 kg, a njegove dimenzije 46 cm × 30 cm bez ploča za skupljanje sunčane energije i njezino pretvaranje u električnu. Stabilizator (sl. 8) je omogućavao da su antene odašiljača pravilno orijentirane (Decca, 1978).

Radioodašiljači sa satelita emitirali su dvije vrlo stabilne koherentne noseće frekvencije elektromagnetskih valova u ultrakratkom valnom području od 150 MHz (točnije 149,988 MHz) i od 400 MHz (točnije 399,968 MHz). Te dvije frekvencije bile su izabrane tako da se može dobro korigirati utjecaj ionosfere. Obje frekvencije bile su fazno modulirane s pomakom faze za +60° ili -60° tvoreći na taj način signal za bit ''1'' ili ''0'', kao što se vidi na (sl. 10). Tako je u NNSS-sustavu prihvaćen binarni sustav brojeva kakav se koristi i u elektroničkim računalima.

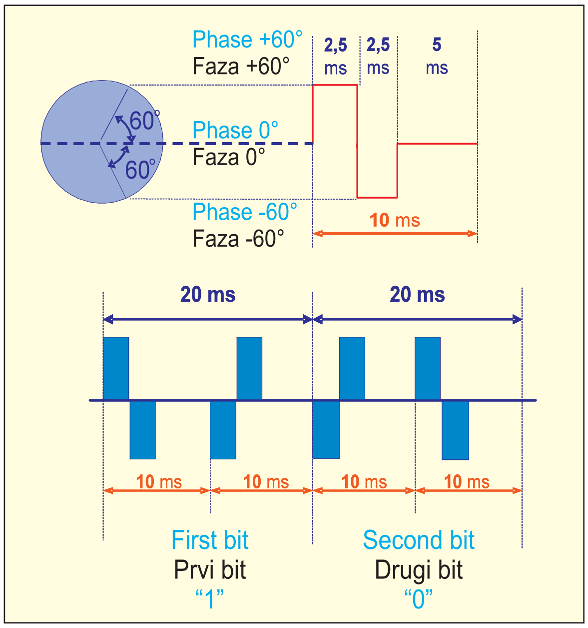


Fig. 10. Signal for bit 1 and 0 (Decca, 1978)
Slika 10. Signal za bit 1 i 0 (Decca, 1978)

Na taj su način korisnicima na Zemlji radiovezom prenošene poruke o položajima satelita, tj. o fiksnim elementima srednje orbite satelita i poremećajima u gibanju satelita, kao i ostale potrebne informacije. Te poruke, tzv. odaslane efemeride (Broadcast Ephemeris) u orbitalnom koordinatnom sustavu, počele su se odašiljati svake parne minute Svjetskog vremena (Universal Time – UT). Tako je bilo osigurano da je vrijeme na satelitu i u prijamniku međusobno što točnije povezano. To je vrlo značajno kada se zna da su se sateliti TRANSIT gibali oko Zemlje velikom brzinom od 7,37 km/s. Na taj se način satelite TRANSIT moglo smatrati nosiocima vlastitih koordinata položaja u orbitalnom koordinatnom sustavu u trenutku mjerenja.

Položaj satelita na Keplerovoj elipsi određen je u prostoru sa šest parametara.

Orijentacija ravnine putanje satelita u prostoru određena je s tri kuta:

Ω – longitudom uzlaznog čvora,

ω – argumentom perigeja i

i – nagibom orbite satelita (sl. 11),

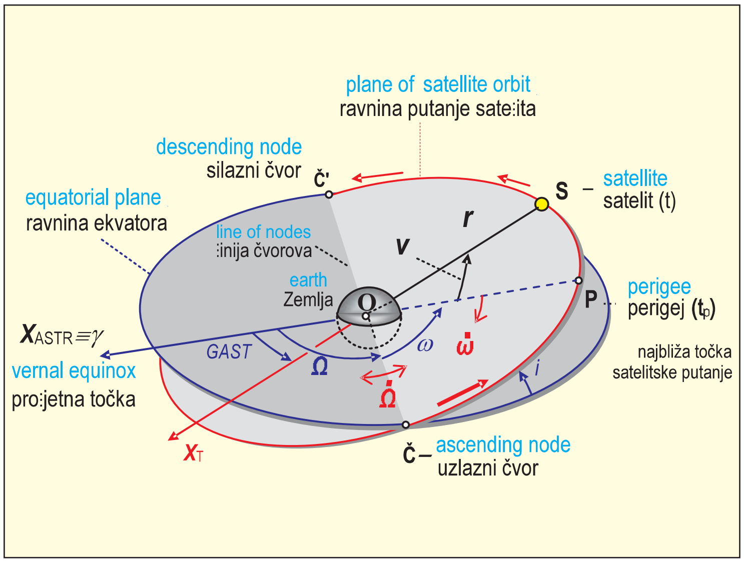
a dimenzije eliptičke putanje određene su još sa:

a – velikom poluosi elipse i

e – numeričkim ekscentricitetom.

Osim toga, važno je definirati i položaj satelita na putanji srednjom anomalijom M, tj. kutnom udaljenosti od točke perigeja ili istinitom anomalijom v. Srednja anomalija izračuna se s pomoću srednjega gibanja n i vremenskog intervala $(t-t_p)$ trenutačnog vremena t minus vrijeme kada je satelit prošao kroz perigej t_p.

To bi bilo dovoljno da je Zemlja homogena kugla. Međutim, Zemlja ima približno oblik rotacijskog elipsoida, a i nehomogena je. Zato dolazi do pomicanja (precesije) uzlaznog čvora i točke perigeja, te najbliže točke eliptičke satelitske putanje od središta Zemlje. Tako su definirani



t_p – time of satellite perigee / vrijeme u perigeju

ω – argument of perigee at t_p / argument perigeja u t_p

Ω – right ascension ascending node at t_p
longituda uzlaznog čvora u t_p

i – inclination of orbit / nagib orbite

a – semi-major axis of ellipse / velika poluos elipse

e – eccentricity of orbit ellipse
ekscentricitet eliptičke putanje

n – mean motion / srednje gibanje

M – mean anomaly / srednja anomalija $M=n(t-t_p)$

$\dot{\omega}$ – precession rate of perigee / brzina precesije perigeja

$\dot{\Omega}$ – precession rate of ascending node
brzina precesije uzlaznog čvora

GAST – Greenwich apparent sidereal time at t_p
Greenwichko prividno zvjezdano vrijeme u t_p

v – true anomaly / istinita anomalija

Fig. 11. Satellite trajectory plane and satellite orbit parameters in orbital coordinate system

Slika 11. Ravnina putanje satelita i parametri orbite satelita u orbitalnom koordinatnom sustavu

considered bearers of their own coordinates in the orbital coordinate system at the time of measurement.

Satellite position on a Kepler ellipse is determined in space by six parameters.

Satellite trajectory plane orientation in space is determined by three angles:

Ω – longitude of ascending node

ω – argument of perigee and

i – inclination of orbit (Fig. 11),

and dimensions of the elliptic trajectory are determined by:

a – semi-major axis of the ellipse and

e – numerical eccentricity of ellipse.

It is also important to define the satellite position on the trajectory by mean anomaly M, i.e. angular distance from the perigee point or true anomaly v. The mean anomaly is calculated with mean movement n and the time interval $(t-t_p)$ of current time t minus the time when the satellite passed through the perigee t_p.

If Earth was a homogeneous ball, this would be enough. However, Earth is approximately a rotational ellipsoid in shape, and is also heterogeneous. This leads to precession of the ascending node and point of the perigee, which is the nearest point of elliptic satellite trajectory from the centre of the Earth. Thus angular speed of node $\dot{\Omega}$ point precession and angular speed of perigee $\dot{\omega}$ point precession are defined, so it was possible to derive angular shifts of those points by multiplying with the time interval $(t-t_p)$.

Influences of other coefficients of the Earth's gravitational field and other anomalies are not compensated with node and perigee precessions, so corrections for the semi-major axis, eccentric anomaly and deviation from the trajectory plane are done.

The GAST angle, i.e. Greenwich Apparent Sidereal Time is introduced in order to relate the orbital coordinate system to the coordinate system bound to the centre of the Earth.

These numerous data, as well as other were broadcast by 6103 bits in two minutes by a radio connection from an NNSS satellite to users on the Earth. This means a bit was exactly 19.662461 ms, i.e. rounded 20 ms.

One could thus calculate and transform the orbital coordinate system into the World Geodetic Coordinate System WGS'72 (Fig. 12). It is a fixed geocentric coordinate system bound to the centre of the Earth's mass O. The semi-major axis of the Earth was a = 6 378 135 m and the flattening 1/f = 298,26 for broadcast ephemeris, and the semi-major axis of the Earth a = 6 378 145 m and the flattening 1/f = 298.25 for precise ephemeris.

Broadcast ephemeris were calculated on the basis of previous 36 hours of measuring signal frequency Doppler shifts broadcast from satellites TRANSIT and NOVA in four stations (Hawaii, California, Minnesota and Maine) (Fig. 13). They broadcast their measurements by special lines to the computer centre in California. These measurement data were processed on the basis of celestial mechanics and broadcast ephemeris for 12 hours in advance calculated, which the computer centre then broadcast to two injection stations on the Earth. Thereafter, these injection stations broadcast the messages (ephemeris) by radio connection to the satellites' memory, which they after broadcast by radio messages to users on the Earth. The NNSS satellites could thus broadcast their coordinates by radio messages to users on the Earth. These positions are not real, they are calculated in advance on the basis of previous measurements.

Besides broadcast ephemeris, there were also precise ephemeris, which were only available to NATO member countries. They were subsequently determined on the

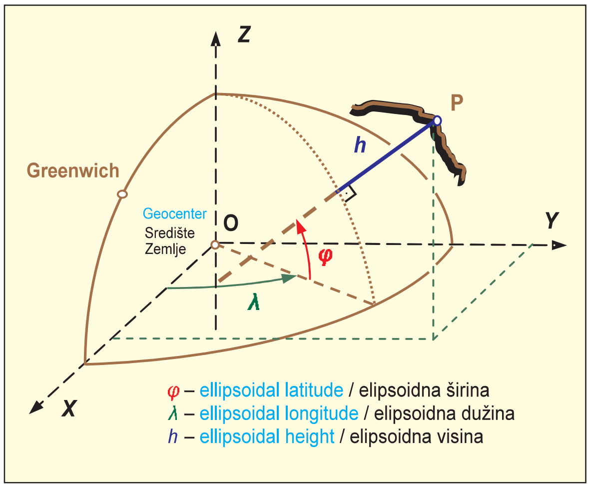


Fig. 12. The World Geodetic Coordinate System WGS'72 from 1972

Slika 12. Svjetski geodetski koordinatni sustav WGS'72 (World Geodetic System) iz 1972. godine

kutna brzina precesije točke čvora $\dot{\Omega}$ i kutna brzina precesije točke perigeja $\dot{\omega}$, pa se množeći s vremenskim intervalom (t-t_p) dobiju kutni pomaci tih točaka.

Samo s precesijama čvora i perigeja nisu kompenzirani utjecaji ostalih koeficijenata gravitacijskog polja Zemlje i ostalih poremećaja, te se uzimaju popravke za veliku poluos, ekscentričnu anomaliju i odstupanje od ravnine putanje.

Da bi se mogao povezati orbitalni koordinatni sustav s koordinatnim sustavom čvrsto vezanim sa središtem Zemlje, uvodi se kut *GAST*, tj. Greenwichkog prividnog zvjezdanog vremena.

Svi ti brojni podaci, kao i još neki drugi, bili su odašiljani s NNSS-satelita korisnicima na Zemlji s pomoću 6103 bita u dvije minute radiovezom. To znači da je bit bio dug točno 19,662461 ms, tj. približno 20 ms.

Tako se moglo računskim putem prijeći iz orbitalnog koordinatnog sustava u Svjetski geodetski koordinatni sustav WGS ’72 (World Geodetic System) (sl. 12). To je fiksni geocentrički koordinatni sustav vezan za središte masa Zemlje O. Za odaslane efemeride (Broadcast Ephemeris) velika poluos Zemlje bila je a = 6 378 135 m i spljoštenost 1/f = 298,26, a za precizne efemeride (Precise Ephemeris) velika poluos Zemlje a = 6 378 145 m i spljoštenost 1/f = 298,25.

Odaslane efemeride bile su izračunane na osnovi prethodnih 36-satnih mjerenja doplerovskih pomaka frekvencije signala odaslanih sa satelita TRANSIT i NOVA na četiri stanice (Havaji, Kalifornija, Minesota i Maine) (sl. 13). One su slale svoja mjerenja u računsko središte u Kaliforniji po posebnim linijama. Ti su podaci mjerenja obrađeni na osnovi nebeske mehanike i tako izračunane odaslane efemeride za 12 sati unaprijed, koje je računsko središte slalo na dvije injekcijske stanice na Zemlji. Zatim su te injekcijske stanice, radiovezom, poslale poruke (efemeride) u memoriju satelita, koje su oni potom odašiljali u radioporukama korisnicima na Zemlji za njihovu uporabu. Tako su NNSS-sateliti mogli u radioporukama

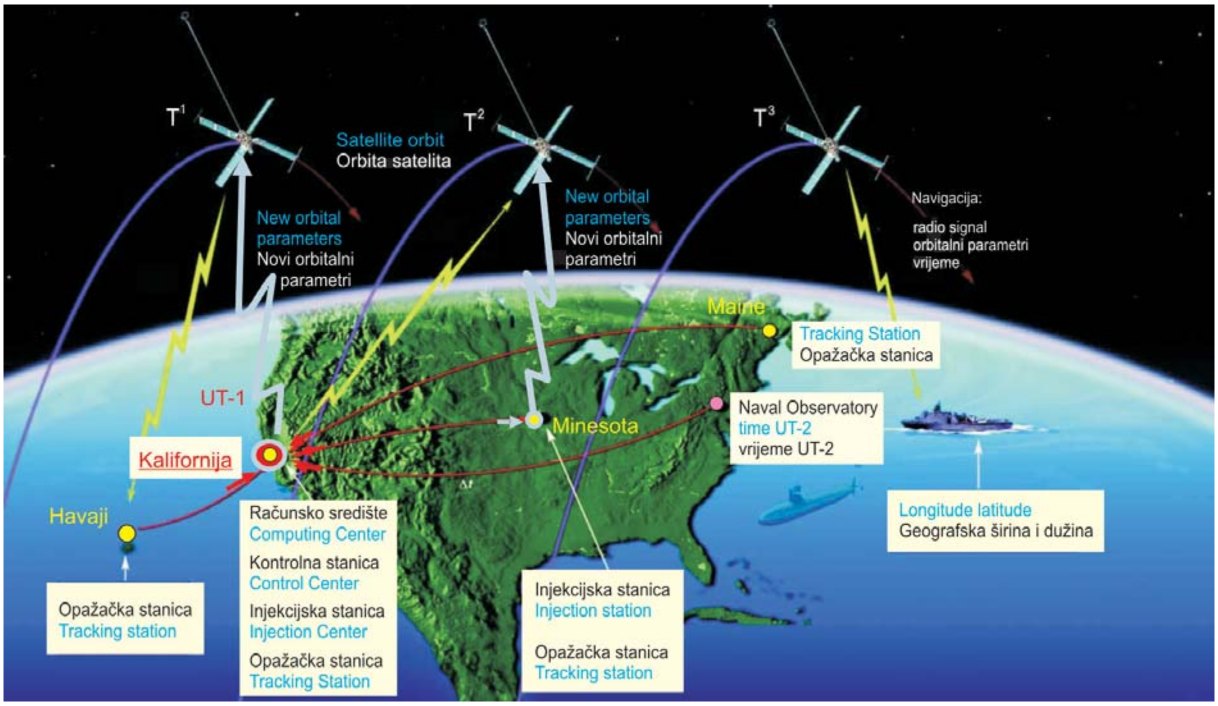


Fig. 13. Network of observational Doppler stations (Hawaii, California, Minnesota and Maine) illustrated by Jacob Elbaz, according to Pisacane

Slika 13. Mreža opažačkih doplerovskih stanica (Havaji, Kalifornija, Minesota i Maine) čija su mjerenja uključena u računanje odaslanih efemerida za satelite TRANSIT i NOVA (ilustracija Jacoba Elbaza prema Pisacane)

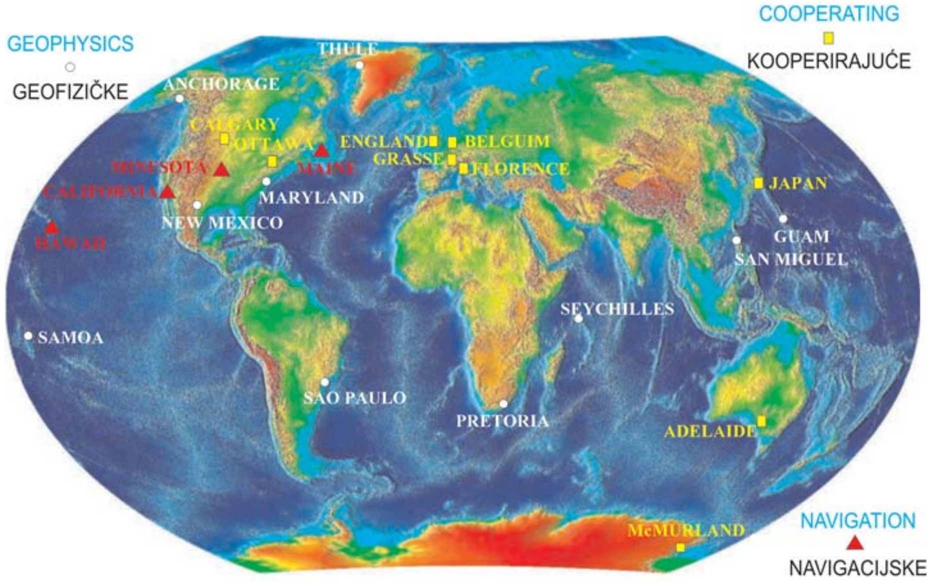


Fig. 14. Networks of Doppler stations (navigation, geophysical and cooperating) sent to the computer centre their measurement data of the TRANSIT and NOVA satellites for calculating precise ephemeris

Slika 14. Mreže doplerovskih stanica (navigacijskih, geofizičkih i kooperirajućih) slale su u računsko središte svoje podatke mjerenja satelita TRANSIT i NOVA za računanje preciznih efemerida

basis of 48-hour observations with as many as 22 globally distributed permanent Earth stations from several networks (Fig. 14). These ephemeris were defined by rectangular coordinates *X*, *Y* and *Z* and their changes $\dot{X}$, $\dot{Y}$ *and* $\dot{Z}$, and for every minutes, and could only be obtained 14 days after the measurements. Their precision was around 1 m.

The complete device for receiving signals from a TRANSIT type satellite based on the Doppler principle consisted of following elements:

1) antenna with an amplifier (which receives at the same time both radio wave frequencies broadcast from the TRANSIT)
2) radio receiver (for both frequencies)
3) measurement data registry unit
4) process computer (microcomputer) for preparing, that is editing collected data, computing geocentric position coordinates and storing measurement data.

Devices were usually powered by electrical energy from a 12 V accumulator or by standard 220 or 110 V alternating current.

The working process of the device was mostly automated, so antenna coordinates could be read directly from the display at any time:

φ – ellipsoidal latitude, λ – ellipsoidal longitude and h – ellipsoidal height or rectangular coordinates *X*, *Y* and *Z*.

It should be noted that the device measured (determined) the so-called Doppler count $N_{j\text{-}k}$. The Doppler count $N_{j\text{-}k}$ represented the area between the referent frequency f_{ref} produced in the receiving Doppler device and the received frequency of radio waves f_{pr} broadcast from satellites during the time interval $\Delta T_{j\text{-}k}$ (Fig. 15). In so doing, f_{sa} was the frequency of radio waves broadcast from satellite. The minimum integration time interval was 4.6 seconds, and usually 23-30 seconds were taken in geodesy for the integration time interval $\Delta T_{j\text{-}k}$. This integral enabled the determination of the difference of distances of satellite position radius vectors $\Delta r_{j\text{-}k}$ from the observational station P at the beginning "j" and the end of the measurement interval "k". According to (Solarić, Čolić 1981) it follows:

$$r_k - r_j = \frac{c}{f_{ref}} N - c\frac{f_{ref} - f_{sa}}{f_{ref}}\left(t_k - t_j\right). \qquad (2)$$

The calculated distance difference r_k-r_j determined the hyperboloid as a geometric location of possible points, where station of the device or, more accurately - its antenna should have been. Further Doppler counts formed other hyperboloids as station surfaces, and their intersection finally determined the position of the observational station P, which can be seen in Fig. 16. For the sake of simplicity, only cross sections of two hyperboloids are represented, while a minimum of three hyperboloids and their cross sections should be drawn passing through points P_1 and P_2.

It should be noted that two solutions (two points) were obtained, but it was certain which of them provided the real solution, because the two points were at great distances (Fig. 17).

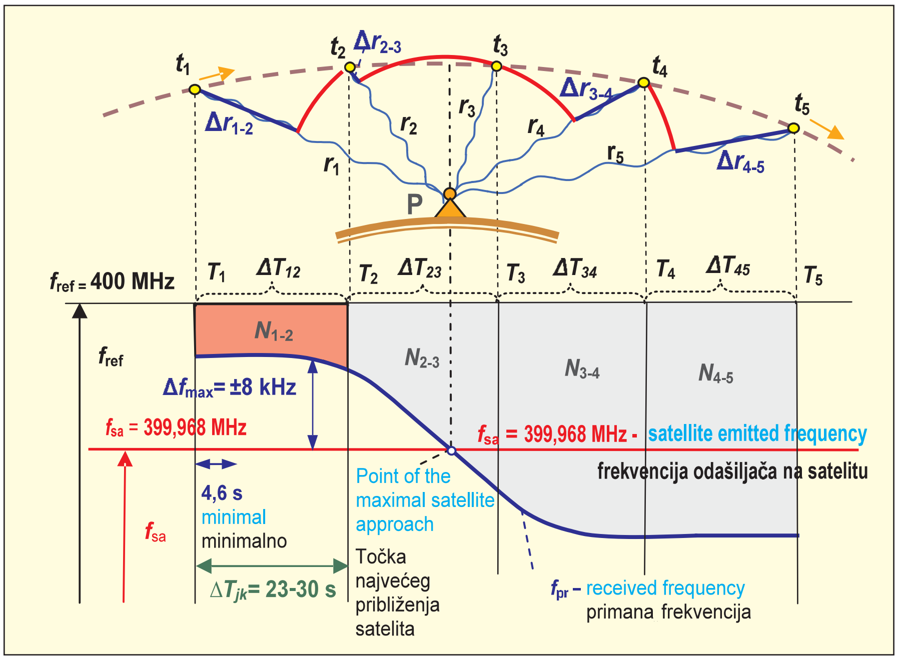


Fig. 15. Integrated Doppler Count N_{j-k}
Slika 15. Doplerovski zbroj N_{j-k}

odašiljati korisnicima na Zemlji, za njihovu uporabu, koordinate svojega položaja gdje se trenutačno nalaze. Ti položaji nisu stvarni već su računskim putem predviđeni unaprijed na osnovi prethodnih mjerenja.

Osim *odaslanih efemerida* postojale su i *precizne efemeride*, koje su bile dostupne samo državama članicama NATO-a. One su naknadno određene na temelju 48-satnih opažanja sa čak 22 globalno raspoređene stalne zemaljske stanice iz nekoliko mreža (sl. 14). Te efemeride bile su izražene pravokutnim koordinatama *X, Y i Z* i njihovim promjenama , $\dot{X}$, $\dot{Y}$ *i* $\dot{Z}$, i to za svaku minutu, a mogle su se dobiti tek 14 dana nakon mjerenja. Njihova preciznost bila je oko 1 m.

Kompletni uređaj za prijam signala sa satelita tipa TRANSIT na Dopplerovu principu sastojao se od sljedećih elemenata:

1) antene s pojačalom (koja prima istodobno obje frekvencije radiovalova odaslanih sa satelita TRANSIT)
2) radioprijamnika (za obje frekvencije)
3) jedinice za registriranje podataka mjerenja
4) procesnog računala (mikroračunala) za pripremu, odnosno sređivanje skupljenih podataka, računanja geocentričnih koordinata stajališta i spremanje podataka mjerenja.

Uređaji su obično napajani električnom energijom iz akumulatora napona 12 V ili standardnom električnom izmjeničnom strujom od 220 V ili 110 V.

Cijeli proces rada uređaja bio je uglavnom automatiziran, tako da su se na ekranu uređaja mogle izravno očitati koordinate položaja antene u bilo kojem trenutku: φ – elipsoidna širina, λ – elipsoidna dužina i *h* – elipsoidna visina ili pravokutne koordinate *X, Y* i *Z*.

Treba naglasiti da je uređaj mjerio (određivao) tzv. *Doppler count - doplerovski zbroj* N_{j-k}. Doplerovski zbroj N_{j-k} predstavljao je površinu između referentne frekvencije f_{ref} proizvedene u prijamnom doplerovskom uređaju i primljene frekvencije radiovalova f_{pr} odaslanih sa satelita u vremenskom intervalu ΔT_{j-k} (sl. 15). Pritom je f_{sa} bila frekvencija radiovalova odaslanih sa satelita. Minimalni vremenski interval integracije bio je 4,6 sekundi, a obično se u geodeziji uzimalo za vremenski interval integracije ΔT_{j-k} 23 – 30 sekundi. Iz tog integrala omogućeno je određivanje razlike duljina radijus-vektora položaja satelita Δr_{j-k} od opažačke stanice P na početku ''j'' i na kraju mjerenog intervala ''k''. Tako je, prema (Solarić, Čolić, 1981), dobiveno:

$$r_k - r_j = \frac{c}{f_{ref}} N - c\frac{f_{ref} - f_{sa}}{f_{ref}}\left(t_k - t_j\right). \tag{2}$$

Izračunana razlika dužina r_k-r_j određivala je hiperboloid kao geometrijsko mjesto mogućih točaka, na kojem se moralo nalaziti i stajalište uređaja, točnije – njegove antene. Daljnji Dopplerovi zbrojevi tvorili su druge hiperboloide kao stajališne plohe, a njihov presjek određivao je konačno prostorni položaj opažačke stanice P, kao što se vidi na sl. 16. Zbog jednostavnosti na slici je nacrtan samo presjek dvaju hiperboloida, a trebalo bi nacrtati najmanje tri hiperboloida i njihove presjeke, koji će prolaziti točkama P_1 i P_2.

Treba naglasiti da su dobivena dva rješenja (dvije točke), ali se sigurno moglo reći koja je od točaka davala

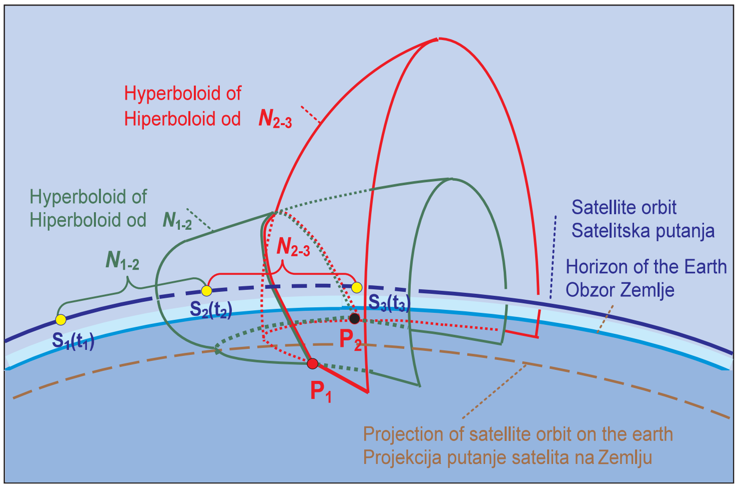


Fig. 16. Determined point P_1 or P_2 is located in the cross section of the hyperboloid. For the sake of simplicity, only cross sections of two hyperboloids are represented, while a minimum of three hyperboloids and their cross sections should be drawn.

Slika 16. Određivana točka P_1 ili P_2 nalazi se u presjeku hiperboloida. Zbog jednostavnosti na slici je nacrtan samo presjek dva hiperboloda, a trebalo bi nacrtati najmanje tri hiperboloida i njihove presjeke

A ship's position could be determined from Doppler measurements in one passage of a TRANSIT satellite, but its speed had to be taken into consideration (Fig. 18). The first position of the ship P_1 could be determined only after the first three measurement intervals, i.e. the Doppler count $N_{j\text{-}k}$. The accuracy of determining a ship's coordinates if the NNSS satellite passed for 10-14 minutes was 200 m at night, and 400 m at day. Ionosphere's influence on measurement accuracy was much greater during the day. This can be explained by Sun's radiation influence, especially when it is more active, i.e. when there are more sunspots, when there are magnetic storms and polar light.

The NNSS navigation system, also known as TRANSIT, played a significant historical role for mariners, as well as geodesists. Unfortunately, maintenance of this navigation system ended on December 31, 1996, and its role was taken by the Global Positioning System (GPS) (URL 4). Nowadays, the TRANSIT system is used by USA Navy for researching the state of the ionosphere. In fact, TRANSIT satellites contain transmitters with two frequencies, which can be used to draw conclusions about the state of the ionosphere.

5. Application of Satellite Doppler Measurements in Croatia for Needs of Geodesy

The TRANSIT navigation system had gradually become more accurate, and as such geodesists have begun to use it to solve their tasks during the 1970s. Doppler receivers have become more precise, ephemeris better, and more disturbances in satellite movement have been taken into account.

In geodesy, where devices are stationary, following equations were used for the functional model of Doppler satellite geodesy (Solarić, Čolić 1981):

$$N_{j\text{–}k}=\frac{f_{ref}}{c}\left\{\sqrt{(X_k-X_o)^2+(Y_k-Y_o)^2+(Z_k-Z_o)^2}-\right.$$
$$\left.-\sqrt{(X_j-X_o)^2+(Y_j-Y_o)^2+(Z_j-Z_o)^2}\right\}+(f_{ref}-f_{sa}). \tag{3}$$

where only geocentric coordinates X_0, Y_0 and Z_0 of observational stations P_0 were unknown. According to that, the equation (3) contained three unknowns, and at least three Doppler counts needed to be measured with a device in a station during one passage of the satellite. Since geodesists had never content with the minimum number of measurements, efforts were made to measure as many Doppler counts, i.e. distance differences as possible. Then, by solving error equations with the least squares method, one could calculate the most probable coordinate values of the observational station. In addition, there was a possibility of equalization to determine at the same time unknown coordinates of the Doppler device antenna (φ, λ and h or X, Y and Z) and the frequency residuals.

The idea to organize a Doppler measurement campaign with the goal of integration into the World Geodetic Coordinate System WGS'72 for the first time in Croatia (and the former country) started in 1980. Thus the first permission for collaboration in the international project IDOC'82 (Italy Doppler Observation Campaign '82) (Fig. 19) was received. Since we didn't have our own Doppler device, we borrowed the Magnavox device (Fig. 20 and 21) from Prof. Dr. Herman Seeger from Bonn (Germany). Measurements were done continuously from July 15 to July 26, 1982, and the measurement data with 12 pravo rješenje, jer su se te dvije točke nalazile na velikim udaljenostima (sl. 17).

Iz doplerovskih mjerenja u jednom prolazu satelita TRANSIT moglo se odrediti položaj broda, ali se u račun morala uzeti i brzina njegova kretanja (sl. 18). Tek nakon prva tri intervala mjerenja, tj. doplerovskog zbroja $N_{j\text{-}k}$ mogao se odrediti prvi položaj broda P_1. Točnost određivanja koordinata položaja broda pri 10 do 14 minutnom prolazu NNSS-satelita bila je po noći 200 m, a po danu 400 m. Po danu je utjecaj ionosfere na točnost mjerenja mnogo veći nego po noći. To se može pojasniti utjecajem Sunčeva zračenja, posebice pri njegovoj povećanoj aktivnosti, odnosno povećanom broju Sunčevih pjega, kada se pojavljuju magnetske oluje i polarna svjetlost.

Navigacijski sustav NNSS, također poznat kao TRANSIT, odigrao je značajnu povijesnu ulogu u pomorstvu, ali i geodeziji. Na žalost, servisiranje toga navigacijskog sustava završeno je 31. prosinca 1996., a njegovu ulogu preuzeo je Globalni pozicijski sustav (GPS) (URL 4). Danas sustav TRANSIT upotrebljava američka vojna mornarica za istraživanje stanja ionosfere. Naime, na satelitima TRANSIT nalaze se odašiljači s dvije frekvencije, te se s pomoću njih mogu izvesti zaključci o stanju ionosfere.

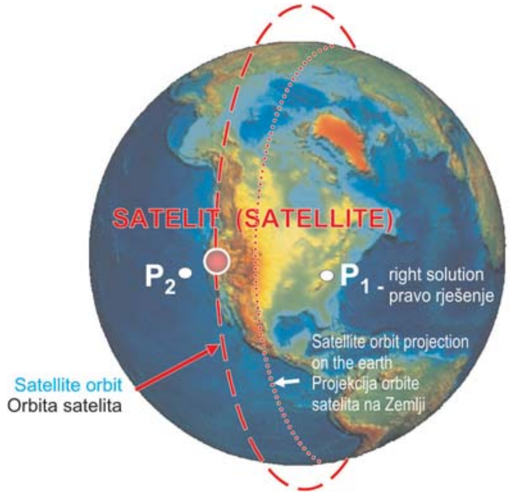


Fig. 17. Two points P_1 and P_2 of hyperboloid cross sections are at great distances, so it was possible to know which point P really determines the position of the Doppler device antenna

Slika 17. Dvije točke presjeka hiperboloida P_1 i P_2 nalaze se na velikim udaljenostima tako da se već prema stvarnom položaju određivane točke sigurno znalo koja točka P je određivala pravi položaj antene doplerovskog uređaja

5. Primjena satelitskih doplerovskih mjerenja u Hrvatskoj za potrebe geodeta

Navigacijski sustav TRANSIT postupno je postao sve točniji, pa su ga geodeti 1970-ih počeli koristiti za rješavanje svojih zadataka. Naime, doplerovski su prijamnici postali sve precizniji, efemeride isto tako sve bolje, a u račun se uzimalo sve više poremećaja u gibanju satelita.

U geodeziji, gdje uređaji stoje mirno, za funkcionalni model doplerovske satelitske geodezije koristile su se jednadžbe (Solarić i Čolić, 1981):

$$N_{j-k} = \frac{f_{\text{ref}}}{c}\left\{\sqrt{(X_k - X_o)^2 + (Y_k - Y_o)^2 + (Z_k - Z_o)^2} - \sqrt{(X_j - X_o)^2 + (Y_j - Y_o)^2 + (Z_j - Z_o)^2}\right\} + (f_{\text{ref}} - f_{\text{sa}}). \tag{3}$$

U toj jednadžbi nepoznanice su bile samo geocentrične koordinate X_o, Y_o i Z_o opažačke stanice P_o. Prema tome u jednadžbi (3) nalazile su se tri nepoznanice, te je tako za jednog prolaza satelita bilo potrebno izmjeriti najmanje tri Dopplerova zbroja s uređajem na stanici. Budući da u geodeziji nikada nije zadovoljavao samo minimalnim broj mjerenja, nastojao se izmjeriti što veći broj Dopplerovih zbrojeva, odnosno razlika udaljenosti. Zatim su se postavljanjem jednadžbi pogrešaka i njihovim rješenjem po metodi najmanjih kvadrata mogle izračunati najvjerojatnije vrijednosti koordinata opažačke stanice. Osim toga postojala je mogućnost izjednačenja kojim se uz nepoznate koordinate položaja antene doplerovskog uređaja (φ, λ i h ili X, Y i Z) određuje i popravka frekvencije.

Ideja da se prvi put u Hrvatskoj (a i bivšoj državi) organizira doplerovska kampanja mjerenja s ciljem povezivanja u svjetski geodetski koordinatni sustav WGS (World Geodetic System) '72 započeta je 1980. godine. Tako je primljena prva dozvola za sudjelovanje u međunarodnom projektu IDOC '82 (Italy Doppler Observation Campaign '82) (sl. 19). Budući da nismo imali svoj doplerovski uređaj, posudili smo uređaj Magnavox (sl. 20 i 21) od prof. dr. Hermana Seegera iz Bonna (Njemačka). Mjerilo se kontinuirano od 15. do 26. srpnja 1982; podaci mjerenja s 12 točaka obrađeni su s pomoću programa GEODOP (verzija III) u više varijanti, a rezultati su objavljeni u časopisima te na domaćim i međunarodnim simpozijima (Solarić, Čolić, 1983), (Baldi i dr., 1984) i (Čolić i dr., 1984).

Tako su koordinate Opservatorija Hvar (stupa trigonometrijske točke 209_z) određene sa standardnim odstupanjem od 0,48 m. Takva visoka preciznost na velikim udaljenostima nije se do tada mogla ostvariti klasičnim geodetskim mjerenjima, ali ni optičkim opažanjima umjetnih Zemljinih satelita. Treba naglasiti da su provedene različite varijante računanja s istim podacima mjerenja, ali i izbacivanjem iz izjednačenja mjerenja s jedne od točaka. Rezultati izjednačenja tih varijanti bili su dosta različiti.

Nekoliko identičnih točaka iz projekta IDOC '82 sudjelovalo je i u projektima: EDOC-2, ERIDOC i ALGEDOP-82, gdje su bile određene koordinate točaka u sustavu preciznih efemerida. Tako su se na osnovi 7-parametarske transformacije koordinata mogle izračunati

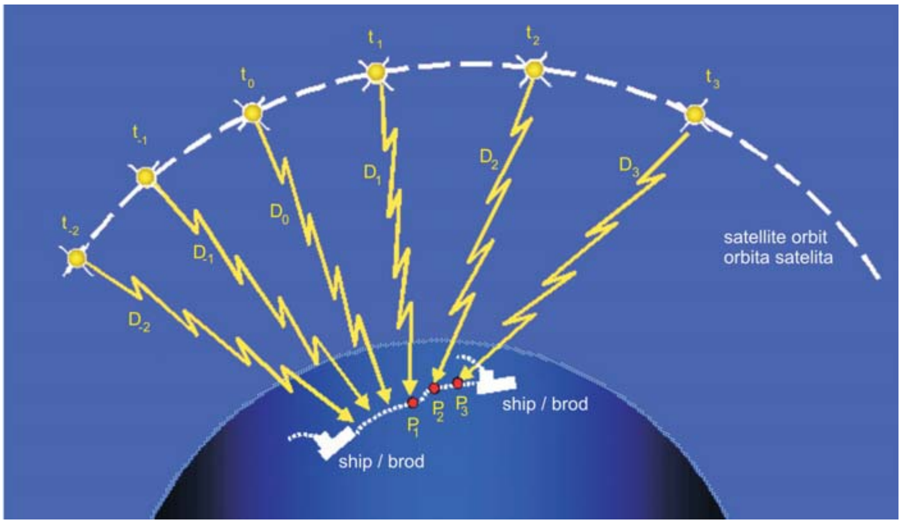


Fig. 18. Representation of determining a ship's position by means of Doppler frequency shifts measurements of received signals broadcast from TRANSIT and NOVA satellites

Slika 18. Prikaz određivanja položaja broda s pomoću doplerovskih mjerenja pomaka frekvencije primljenih signala odaslanih sa satelita TRANSIT i NOVA

points were processed using the GEODOP (version III) program in several variants and the results were published in journals at national and international symposia (Solarić, Čolić 1983), (Baldi et al. 1984) and (Čolić et al. 1984).

Thus coordinates of the Hvar Observatory (pillar of trigonometric point 209_z) were determined with a standard deviation of 0.48 m. At the time, such a high precision on great distances couldn't have been obtained neither by classic geodetic measurements nor by optical observations of Earth's artificial satellites. However, it should be noted that various variants of calculating were done with same measurement data, but also by not taking into account measurements from one of the points. Equalization results of those variants were quite different.

Several identical points from the IDOC'82 project also participated in projects: EDOC-2, ERIDOC and ALGEDOP-82, where point coordinates in the system of precise ephemeris were determined. Thus, on the basis of 7-parameter transformation of coordinates, one could calculate coordinates for the pillar of trigonometric point 209_z of the Hvar Observatory in the system of precise ephemeris (PE), which were published in (Čolić et al. 1984).

The Hvar Observatory also participated in the other international scientific Doppler project WEDOC-2 (West East European Doppler Observation Campaign) (Fig. 22). In this project by countries of the former western and eastern block, as many as 27 points from September 5 to September 19, 1983 participated, and the Hvar Observatory among them. The Magnavox Doppler device borrowed from Trieste from Prof. R. Antonio Marussi. The final results of processed measurement data for the referent point of antenna from that observational campaign were processed with the GEODOP (version V) and SADOSA programs, and the results were published in (Pesec et al. 1985). Standard deviations of coordinates in that measuring campaign were about 0.28 m.

Analysis of the achieved results of Doppler measurements was done in papers (Solarić, M. and N. 2000 and 2001). Results of Doppler measurements were compared to the results of GPS measurements from several international campaigns at the Hvar Observatory. It should be noted it wasn't as simple to compare the results. This is because coordinates in Doppler measurements are expressed in the WGS'72 coordinate system, while those in GPS measurements are expressed in the WGS'84 coordinate system, i.e. in ITRF'90 (International Terrestrial Referent Frame). This is why Doppler measurements needed to be converted to the ITRF'90 coordinate system on the basis of relation of coordinate systems. In addition, coordinates of the Hvar Observatory from the WEDOC-2 measurement campaign had to be reduced previously to a brass mark in the pillar of trigonometric point 209_z from the referent point of the Doppler device antenna.

GPS measurements can certainly be considered much more accurate in comparison to Doppler measurements. Therefore, results of the Hvar Observatory coordinate determination by Doppler measurements and GPS measurements were compared. Thus, results from the Doppler measurement campaign IDOC'82 with precise ephemeris are determined by errors:

❑ on coordinate X from 0.83 to 0.91 m

❑ on coordinate Y from 0.75 to 0.82 m

❑ on coordinate Z from 0.39 to 0.51 m

❑ on ellipsoidal height h from 0.68 to 0.83 m.

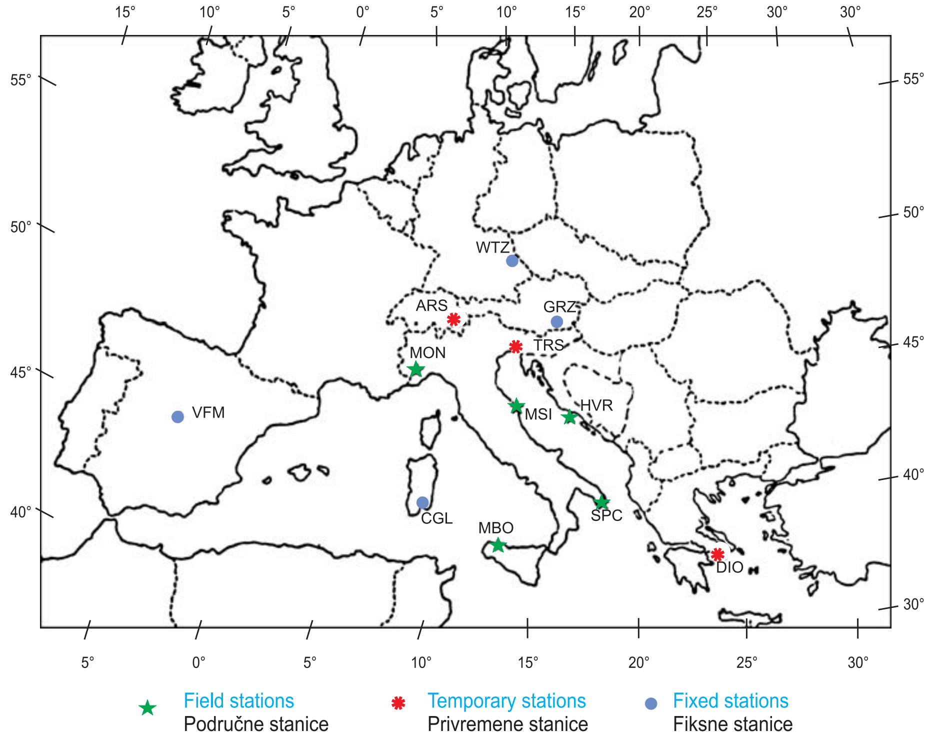


Fig. 19. Network of points included into the IDOC'82 project (ARS-Arosa, CGL-Cagliari, DIO-Dionysos, GRZ-Graz, HVR-Hvar, MBO-Monte Bonifato, MON-Mondovi, MSI-Monte Sicuro, SPC-Specchia, TRS-Trieste, VFM-Villa Franco del Castillo and WTZ-Wettzell) (Baldi et al. 1984)

Slika 19. Mreža točaka uključenih u projekt IDOC' 82 (ARS-Arosa, CGL-Cagliari, DIO-Dionysos, GRZ-Graz, HVR-Hvar, MBO-Monte Bonifato, MON-Mondovi, MSI-Monte Sicuro, SPC-Specchia, TRS-Trieste, VFM-Villa Franco del Castillo i WTZ-Wettzell) (Baldi i dr., 1984).

koordinate za stup trigonometrijske točke 209_z Opservatorija Hvar u sustavu preciznih efemerida (PE), koje su i objavljene u radu (Čolić i dr., 1984).

Opservatorij Hvar sudjelovao je i u drugom međunarodnom znanstvenom doplerovskom projektu WEDOC-2 (West East European Doppler Observation Campaign) (sl. 22). U tom projektu zemalja tadašnjega zapadnog i istočnog bloka sudjelovalo je čak 27 točaka od 5. do 16. rujna 1983. Doplerovski uređaj Magnavox posuđen je iz Trsta od prof. dr. Antonija Marrussija. Konačni rezultati obrade podataka mjerenja za referentnu točku antene iz te opažačke kampanje obrađeni su s pomoću programa GEODOP (verzija V) i SADOSA, a rezultati su objavljeni u radu (Pesec i dr., 1985). Standardna odstupanja određenih koordinata u toj mjernoj kampanji iznosila su oko 0,28 m.

Analiza ostvarenih rezultata doplerovskih mjerenja učinjena je u radovima (Solarić, M. i N., 2000. i 2001). Uspoređeni su rezultati doplerovskih mjerenja s rezultatima GPS-mjerenja iz više međunarodnih kampanja na Opservatoriju Hvar. Treba naglasiti da se ti rezultati nisu mogli tako jednostavno usporediti. Naime, u doplerovskim mjerenjima koordinate su izražene u koordinatnom sustavu WGS'72, a u GPS-mjerenjima u koordinatnom sustavu WGS'84, tj. u ITRF'90 (International Terrestrial Referent Frame). Zato je na osnovi povezanosti koordinatnih sustava doplerovska mjerenja trebalo svesti na koordinatni sustav ITRF '90. Osim toga koordinate Opservatorija Hvar iz mjerne kampanje WEDOC-2 trebalo je prethodno reducirati od referentne točke antene doplerovskog uređaja na mjedenu oznaku (mesinganu bolcnu) u stupu trigonometrijske točke 209_z.

Sigurno je da se GPS-mjerenja mogu u usporedbi s doplerovskim mjerenjima smatrati mnogo točnijima. Zato su i uspoređeni ostvareni rezultati određivanja koordinata položaja Opservatorija Hvar s pomoću doplerovskih mjerenja i oni dobiveni GPS-mjerenjima. Pokazalo se da su rezultati iz doplerovske mjerne kampanje IDOC'82 s preciznim efemeridama određeni s pogreškama:

☐ po koordinati *X* od 0,83 do 0,91 m

☐ po koordinati *Y* od 0,75 do 0,82 m

☐ po koordinati *Z* od 0,39 do 0,51 m

☐ po elipsoidnoj visini *h* od 0,68 do 0,83 m.

Dakle, sve su tri koordinate određene u prosjeku s pogreškom oko 0,70 m. Pritom je najbolje određena koordinata *Z*, a koordinata *X* s nešto većom pogreškom.

To je izvrstan rezultat za tu točku, kada se zna da je u to vrijeme u Europi bilo samo tridesetak točaka kojima su bile tako dobro određene koordinate položaja. Osim toga treba imati na umu da su Opservatoriju Hvar prvi

Fig. 20. (upper left) Magnavox Doppler device with accumulator at the Hvar Observatory in the IDOC'82 campaign

Slika 20. (gore lijevo) Doplerovski uređaj Magnavox s akumulatorom na Opservatoriju Hvar u kampanji IDOC' 82

Fig. 21. (right) Antenna of the Doppler device at the Hvar Observatory trigonometric point 209_z

Slika 21. (desno) Antena doplerovskog uređaja na Opservatoriju Hvar na trigonometrijskoj točki 209_z

Therefore, all three coordinates are determined on average with an error of about 0.70 m. The coordinate Z is determined very well, and the coordinate X with somewhat greater error.

This is an excellent result for this point if one takes into consideration that there were only about thirty points in Europe whose coordinates were determined so well at the time. In addition, one should note that the Hvar Observatory was the first place in Croatia (and the former country) where coordinates in the World Geodetic Coordinate System WGS'72 were determined.

6. The TSIKLON Satellite Doppler Navigation System in the Former Soviet Union

An experimental satellite Doppler navigation system called Tsiklon was proposed in the Soviet Union in 1962. Therefore, four years after Americans. They planned a satellite system with an altitude of 800 to 1000 km and angle in relation to the equator of i=74° to i=83°. The first experimental flight of their navigation satellite was performed in 1967.

At the beginning, Russians had a problem with calculating the ephemeris, i.e. predicting the position of their navigation satellites, so they achieved very low precision of up to 3 km. However, already in 1969 they considerably improved in predicting the position of their navigation satellites and achieved 10 to 30 times more precise predictions of their navigation satellites' positions. The improved software in 1969 had an average precision of 100 m during a 5-day period. This Soviet Union navigation system was designed by Mikhail Fedorovich Reshetnev (1924 -1996) (Fig. 23) with collaborators. Testing of the Tsiklon navigation system lasted until 1972, when it was accepted for military purposes. As many as 20 satellites for military purposes were launched within this project until 1978 (according to the chronology in URL 5).

Production and testing of the Parus/Tsiklon-B system (Fig. 24) was started in 1974. The following can be seen from the Parus chronology:

- ☐ they launched 29 military navigation satellites between 1974 and 1980
- ☐ they replaced 30 of them until 1986
- ☐ they launched 13 additional satellites until 1990 and
- ☐ they launched about 20 more navigation satellites into various planes between 1991 and 2005 (URL 6).

The second generation of the Soviet navigation system was created in collaboration between the Maritime Academy of Sciences and the Ministry of Shipping. It was started in 1974 and named Tsikada (Fig. 25), and was accepted in military use in the Soviet Union in 1979. From the Tsikada chronology (URL 7), one can see that 12 satellites were launched for military purposes, and 6 for civilian navigation and they were launched until 1995. They also had as many as 13 planes in which their navigation satellites circulated.

Fig. 22. Network of Doppler stations included into the WEDOC (West East European Doppler Observation Campaign) projects:

- ■ *Doppler stations included into the WEDOC-1 and WEDOC-2 projects*
- ▣ *Doppler stations included into the WEDOC-2 project (Pesec et al. 1985)*

Slika 22. Mreža doplerovskih stanica uključenih u projekte WEDOC (West East European Doppler Observation Campaign):

- ■ *doplerovske stanice uključene u projekte WEDOC-1 i WEDOC-2*
- ▣ *doplerovske stanice uključene u projekt WEDOC-2 (Pesec i dr., 1985)*

put u Hrvatskoj (a i bivšoj državi) bile određene koordinate položaja u svjetskom geodetskom koordinatnom sustavu WGS'72.

6. CIKLON - satelitski doplerovski navigacijski sustav u bivšem SSSR-u

U SSSR-u je predložen eksperimentalni satelitski doplerovski navigacijski projekt pod imenom *Ciklon* (*Tsiklon*) 1962. godine. Dakle, u zaostatku od četiri godine za Amerikancima. Rusi su planirali sustav satelita na visini od 800 do 1000 km pod kutom nagiba prema ekvatoru od i=74° do i=83°. Prvi eksperimentalni let njihova navigacijskog satelita ostvaren je 1967. godine.

Na početku su Rusi imali problema s računanjem efemirida, tj. s prediciranjem položaja svojih navigacijskih satelita, pa su tako postizali vrlo nisku preciznost od čak 3 km. Međutim, već u 1969. godini znatno su poboljšali predviđanje (prognoziranje) položaja svojih navigacijskih satelita, pa su postigli 10 do 30 puta veću preciznost predviđanja njihova položaja. Poboljšani softver u 1969. godini pokazao je prosječnu preciznost od 100 m u periodu od 5 dana. Taj navigacijski sustav u SSSR-u projektirao je Mihail Fedorovič Rešetnev (1924-1996) (sl. 23) sa svojim suradnicima. Testiranje navigacijskog sustava Ciklon potrajalo je do 1972. godine, kada je bio prihvaćen za vojsku. Unutar tog projekta lansirano je čak 20 satelita za vojnu upotrebu do 1978. godine (prema kronologiji u URL 5).

Proizvodnja i testiranje sustava Parus/Ciklon-B (sl. 24) započeti su 1974. godine. Iz kronologije Parusa uočava se:

- ☐ da su lansirali 29 vojnih navigacijskih satelita od 1974. do 1980.
- ☐ zamijenili su ih 30 do 1986.
- ☐ lansirali su ih još 13 do 1990. i
- ☐ lansirali još oko 20 navigacijskih satelita u razne ravnine od 1991. do 2005. godine (URL 6).

Druga generacija sovjetskog navigacijskog sustava nastala je u suradnji Pomorske akademije znanosti i Ministarstva brodarstva. Ona je započeta 1974. godine i dobila je naziv Cikada (sl. 25), a prihvaćena je u vojnoj uporabi u SSSR-u 1979. godine. Iz kronologije Cikada u (URL 7) vidi se da je za vojnu uporabu bilo lansirano 12 satelita, a za civilnu navigaciju 6 i da su ih lansirali sve do 1995. godine. Također se iz te kronologije vidi da su imali čak 13 ravnina u kojima su kružili njihovi navigacijski sateliti.

7. Daljnji razvoj satelitskih navigacija

Doplerovski satelitski navigacijski sustavi imali su nedostatak da se s pomoću njih mogao odrediti položaj broda samo u određeno vrijeme, tj. nije bilo moguće odrediti položaj broda u bilo kojem trenutku, već samo onda kada je iznad horizonta broda nadlijetao navigacijski satelit. Zato se planirala izgradnja naprednije satelitske navigacije, kojom se može odrediti položaj broda ili neke točke na Zemlji u bilo kojem trenutku i s većom preciznosti.

Postojeći i planirani navigacijski sustavi:

Globalni pozicijski sustav (*GPS*) izgradile su Sjedinjene Američke Države od 1978. do 1993. godine. Taj sustav danas se koristi kako u navigaciji, tako i u vođenju vozila na kopnu, ali i u geodeziji.

Globaljnaja navigacionaja sputnjikovaja sistema (*GLONASS*) počela se izgrađivati 1980. u SSSR-u. Taj je sustav sličan američkom GPS-u, ali do danas nije, na žalost, izgrađen do kraja.

Beidou, komunikacijsko-navigacijski sustav s četiri geostacionarna satelita postavili su Kinezi. Ti sateliti

Fig. 23. Mikhail Fedorovich Reshetnev (1924-1996), designer of communication and navigation satellites in the Soviet Union (URL 8)

Slika 23. Mihail Fedorovič Rešetnev (1924-1996) projektant komunikacijskih i navigacijskih satelita u SSSR-u (URL 8)

7. Further Development of Satellite Navigation

The Doppler navigation systems had a flaw, they could be used to determine a ship's position only when the satellite was overhead. Using Doppler navigation systems, it was not possible to determine the position anytime, only when the navigation satellite was flying above the ship's horizon. This is why efforts were made to produce more advanced satellite navigation, using which one could determine the position of a ship or a point on the Earth anytime and with greater precision.

There are following existing and planned navigation systems:

Global Positioning System (GPS) was created by USA from 1978 to 1993. It is nowadays used in navigation, as well as guiding land vehicles, but also in geodesy.

Global Navigation Satellite System (GLONASS) was started by the Soviet Union in 1980. This satellite system is similar to the American GPS, but unfortunately hasn't been finished yet.

Beidou communication-navigation system with four geostationary satellites was posted by Chinese. These satellites were used for telecommunication, as well as for navigation. In addition, Chinese plan to establish the navigation system Beidou-2, also called COSMOS, which would be similar to GPS and GLONASS and with 5 geostationary satellites and 30 satellites at medium altitudes. It is predicted that its precision of determining coordinates is going to be 10 m (URL 9).

Galileo is a planned European navigation system similar to GLONASS and GPS. It is going to be more accurate than GPS and GLONASS, and is going to have the possibility of SAR (Search and Rescue). It is going to be a significant advantage over GPS and GLONASS, and it is planned to be finished in 2012. The first satellite from that system was launched in 2006.

ARGOS (*Advanced Research and Global Observation Satellite*) system works on the principle of the Doppler effect and helps researching, for example the movement of dolphins. USA and France are collaborating on this project. A radio transmitter is located e.g. on a dolphin, and the Doppler device on a satellite, and the dolphin's position to a 5 m depth are determined on the basis of frequency shift measured on the satellite (this data is taken from the Internet). This is then sent to telemetric station on the Earth, which forwards it to the user.

COSPAS-SARSAT (*Search and Rescue Satellite - Aided Tracing*) is a satellite system for searching and rescuing in situations of ship and airplane breakdowns, etc. This project is a collaboration of Canada, France, Russia and USA, and works on the Doppler principle. The ship or airplane contains a radio transmitter, and the satellite measures the frequency shift caused by the Doppler effect, and the position of the ship or airplane is determined similar as with the TRANSIT satellite system. The result is sent by radio to a telemetric station on the Earth, where rescue is organized.

EUTELTRACS is a European satellite communication and navigation system intended for needs of large European transport companies. By using it, tugs and trucks can communicate with their company administrations, but they can also determine their position with somewhat lower accuracy, i.e. precision up to 1000 m.

QZSS - Quasi-Zenith Satellite System is a satellite communication and navigation system consisting of three 24-hour satellites which are going to alternately circle above Japan, so one of them is always going to be approximately in zenith (Solarić 2007). These 24-hour satellites, as their name suggests, circle around the Earth in 24 hours, the same as geostationary satellites. They are located 35700 km above the Earth's surface, the same as geostationary satellites. However, their orbit is not in the equator plane as those of geostationary satellites, but they have an angle in relation to the equator plane. They are therefore going to help position determination with GPS in cities where horizons are blocked by high buildings, but are also going to help mobile communications, as well as radio program broadcasts without repeaters on the surface of the Earth.

INMARSAT -The International Maritime Satellite Organization. This international organization of mariners was established in 1979, and 80 countries were its members in 1997. Four geostationary satellites enabled communication to all types of ships in all oceans and seas.

Nowadays, it can be concluded that satellite navigation has become a prestige of certain countries and groups of countries and that further boundaries of expanding this contemporary technology can not be predicted.

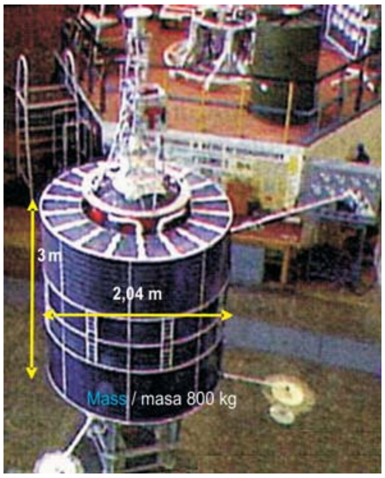


Fig. 24. Parus navigation satellite (URL 5)
Slika 24. Navigacijski satelit Parus (URL 5)

Fig. 25. Tsikada navigation satellite (URL 7)
Slika 25. Navigacijski satelit Cikada (URL 7)

korišteni su za telekomunikacije, ali i za navigaciju. Osim toga Kinezi planiraju uspostaviti navigacijski sustav *Beidou-2*, kojeg nazivaju i COSMOS (sličan GPS-u i GLONASS-u), u kojem bi bilo 5 geostacionarnih satelita i 30 satelita na srednjim visinama. Predviđa se da će se postići preciznost određivanja koordinata položaja točaka 10 m (URL 9).

Galileo je planirani europski navigacijski sustav, najsličniji GLONASS-u i GPS-u, ali će biti točniji od njih, a imat će mogućnost SAR-a (Search and Rescue, tj. traženja i spašavanja). To će biti znatna prednost pred GPS-om i GLONASS-om, a planiran je završetak izgradnje tog sustava 2012. godine. Prvi satelit iz tog sustava izbačen je 2006. godine.

ARGOS (*Advanced Research and Global Observation Satellite*) je sustav koji radi na principu Dopplerova efekta i pomaže pri istraživanju, na primjer kretanja dupina. U tom projektu surađuju SAD i Francuska. Radioodašiljač se nalazi na primjer na dupinu, a doplerovski uređaj na satelitu, te se na osnovi pomaka frekvencije izmjerene na satelitu određuje položaj dupina do 5 m dubine (podatak je preuzet s interneta). Taj podatak šalje se na telemetrijsku stanicu na Zemlji, koja ga prosljeđuje korisniku.

COSPAS-SARSAT (*Search and Rescue Satellite – Aided Tracing*) je satelitski sustav za traženje i spašavanje kod havarija brodova, zrakoplova itd. Taj je projekt nastao u suradnji Rusije i SAD-a i radi na doplerovskom principu. Na brodu ili zrakoplovu nalazi se radioodašiljač, a na satelitu se mjeri pomak frekvencije izazvan doplerovskim efektom, te se kao kod satelitskog sustava TRANSIT određuje položaj broda ili zrakoplova. Rezultat određivanja položaja šalje se radioputem telemetrijskoj stanici na Zemlji, koja organizira spašavanje unesrećenih.

EUTELTRACS je europski satelitski komunikacijski i navigacijski sustav namijenjen za potrebe velikih europskih transportnih poduzeća. Preko njega šleperi i kamioni mogu komunicirati sa svojim upravama u poduzećima, ali mogu odrediti i njihov položaj s nešto nižom točnosti, tj. preciznošću do 1000 m.

QZSS (*Quasi-Zenith Satellite System*) satelitski je komunikacijski i navigacijski sustav sastavljen od tri 24-satna satelita koji će kružiti naizmjenično iznad Japana, pa će uvijek jedan od njih biti približno u zenitu (Solarić, 2007). Ti 24-satni sateliti, kako im ime kaže, obiđu oko Zemlje za 24 sata, isto kao geostacionarni sateliti, te se i oni nalaze na visini 35 700 km iznad površine Zemlje. Međutim, njihova orbita ne leži u ravni ekvatora kao što leže orbite geostacionarnih satelita, već zatvaraju neki kut nagiba prema ravnini ekvatora. Zato će oni pomoći pri položajnim određivanjima s GPS-om u gradovima gdje su horizonti zaklonjeni visokim zgradama, ali će pomoći i mobilnim komunikacijama, kao i emitiranju radioprograma bez repetitora na površini Zemlje.

INMARSAT (*The International Maritime Satellite Organization*), međunarodna organizacija pomoraca osnovana 1979. godine, a 1997. u nju je bilo uključeno 80 država. Uz pomoć četiriju geostacionarnih satelita omogućena je komunikacija svima vrstama brodova sa svih oceana i mora.

Može se ustvrditi da su danas satelitske navigacije postale i prestiž pojedinih zemalja i grupa zemalja i da se ne mogu predvidjeti daljnje granice ekspanzije te suvremene tehnologije.

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