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An Overview of GPS, GLONASS, WAAS, MTSAT, EGNOS and Galileo Radionavigation Systems and Services

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Abstract

Radiolocation and radionavigation systems such as Global Positioning System (GPS), owned and operated by the US Department of Defense (DOD), and GLObal NAvigation Satellite System (GLONASS), of former USSR and now Russia, are providing a wide range of services to commercial and military users, worldwide. While some commercial applications might be satisfied with an availability of service of about 50%, some professional services such as aircraft navigation and landing require service availability in excess of 99%.
To improve availability and precision of GPS and GLONASS, additional satellite and terrestrial based systems have been already deployed and/or are planned, on the local and global scales. Satellite–Based Augmentation Systems (SBAS) such as Wide Area Augmentation System (WAAS) in the USA, Multi–functional Transport SATellite (MTSAT) system in Japan, European Geostationary Navigation Overlay Service (EGNOS) and European radionavigation system proposal Galileo, named after the famous Italian scientist, are providing and/or are intended to provide a wide range of radiolocation and radionavigation services to the most demanding users. These efforts should converge toward a Global Navigation Satellite System (GNSS).
In this contribution an overview of radionavigation, timing and positioning services and respective systems is presented. Applications in military, commercial and private fields, particularly suited to the Saudi Arabia are analyzed and discussed.

1 Introduction

Once upon the time there lived a wise and mighty ruler, Kronos — Father Time. From his royal palace at the northeastern cliff of the Sea of Kronos (modern Adriatic Sea) and the island of Elektris, Kronos' able son Zeus and grandson Dionysus went to conquer Ancient Egypt and distant Sarasvati–Sind. The age of prosperity of respective alliance, known as SynKronos, left memorable impressions on generations. About five thousand years old tablets from Ur in modern Iraq record the journeys of sailors from Sarasvati–Sind via Dilmun, now Bahrain, to Ur. Their navigation skills, accumulated knowledge and recording of natural events, known to us as Babylonian astronomy, spread back to the ancient Akkad, Phoenicia, Egypt, States of Macedons, Europe and beyond. Today, electronics, synchronization and precise timing are essentials of any navigation system.

The ancient peoples of Polynesia used stars, sun and moon as beacons to navigate across thousands of miles long stretches of the Pacific Ocean. Peoples of deserts used stars as beacons to navigate, on their mostly nighttime journeys, across desert areas. Ziggurats, pyramids, Colossus of Rhodes, Pharos, lighthouses and many natural markers served as navigation beacons to ancient travelers. We use markers while navigating through countryside, city streets and/or shopping mall areas.

In the twentieth century, radiolocation and radionavigation systems such as Omega an LORAN (LOng RAnge Navigation) were introduced. These systems use powerful low frequency radio transmitters as beacons, enabling respective users receivers to calculate time delays, distances and the two–dimensional (2D) positions with accuracy of hundreds of meters. In the past twenty years, Omega and LORAN systems have been augmented with satellite based radio beacons. The two best known satellite based radionavigation systems — GPS and GLONASS — allow for global 4D spacetime dynamic radionavigation uncertainties as low as tens of meters in space and a few microseconds in time, while static global 4D spacetime radiolocation uncertainties could be reduced to a few centimeters in space and hundreds of nanoseconds in time. Differential GPS/GLONASS systems and SBAS systems improved on GPS/GLONASS accuracies by an order of magnitude, at least.
Ease of use of these systems may require a simple operation such as reading of numbers from a display. However, a thorough understanding of systems details, necessary for precise measurements and user segment receiver design, requires a deep understanding of microelectronics, antennas, receiver design, radionavigation, relativistic orbital mechanics, geodesy, cartography, etc. In this contribution, an overview of some of systems characteristics with users needs in mind is given. Further details are available in references [1–35].

2 GPS + GLONASS Characteristics

Both GPS and GLONASS are providing and/or are intended to provide 4D radiolocation and radionavigation parameters, worldwide, i.e., globally. Both systems are owned and operated by respective military organizations. Both systems were planned and started their operation at approximately the same time. Both systems are intended to satisfy similar technical requirements. Both systems use 24 satellites in a full constellation, thus providing an instant view of at least five satellites from any point on the earth. Some of respective technical characteristics are summarized in Table **1**.
GPS employs 6 near–circular orbits with 4 satellites per orbit, for a full 24 satellites constellation. Each orbit is inclined by 55°, while respective orbital planes are spaced (rotated) by 60°.
GLONASS employs 3 near–circular orbits with 8 satellites per orbit, for a full 24 satellites constellation. Each orbit is inclined by 65° (a natural inclination), while respective orbital planes are spaced (rotated) by 90°.

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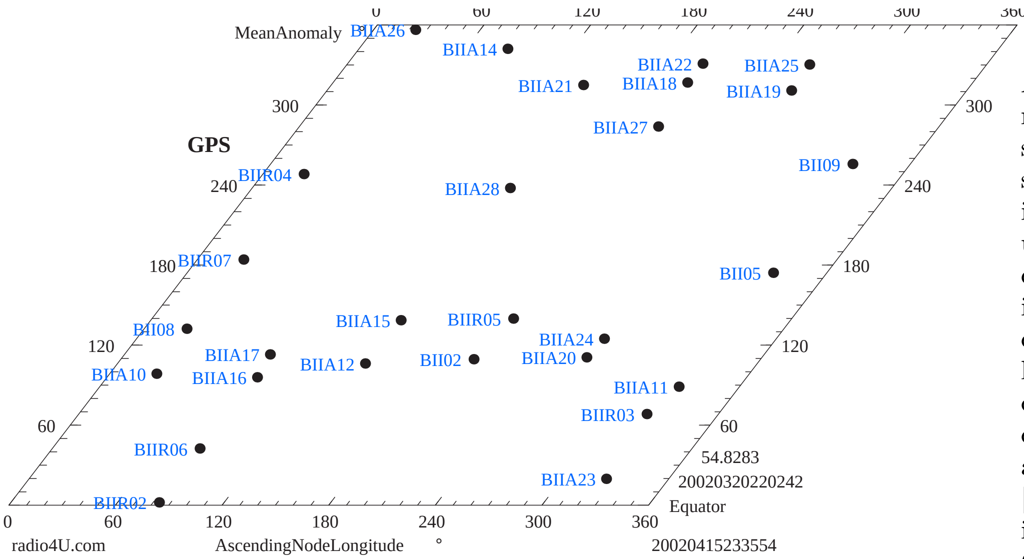

Figure 1: GPS Position Diagram for 20020320:220242.

The GPS (AscendingNodeLongitude, MeanAnomaly) position diagram is shown in Figure **1**; here, abscissa represents the AscendingNodeLongitude in the interval $(0, 360°)$, while ordinate represents the MeanAnomaly in the interval $(0, 360°)$. GPS satellites are placed in 6 obits, each orbit is inclined $54.8283°$ on average and spaced (rotated) about $60°$ apart. Each orbit contains four or five satellites for a total of 28 active satellites on the 20020320:220242, i.e., at the vernal equinox 2002. Names of the satellites are shown in the picture. As shown, satellites are neither evenly distributed along respective orbits nor having exactly the same inclinations. However, a total of 28 healthy satellites, four more than the full 24 satellites system, provide for high availability and fair coverage.

Similarly, GLONASS (AscendingNodeLongitude, MeanAnomaly) position diagram is shown in Figure **2**. GLONASS satellites are placed in 3 obits, each orbit is inclined $64.8886°$ on average and spaced (rotated) about $120°$ apart. The first orbit contains six satellites, the second orbit is void of any satellite, while the third orbits contains only three satellites. There was only 9 active satellites on the 20020320:220242, i.e., at the vernal equinox 2002. Names of the satellites are shown in the picture. A constellation of only 9 satellites could not provide an adequate global coverage. However, a user's receiver able to receive both GPS and GLONASS signals could provide an improved availability and precision.

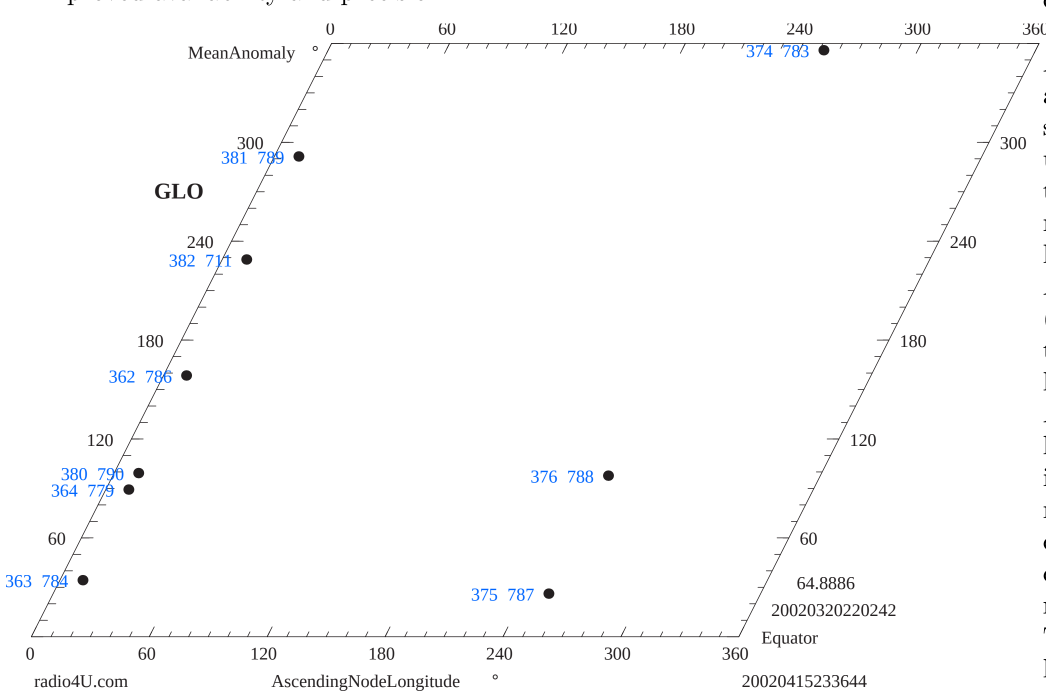

Figure 2: GLONASS Position Diagram for 20020320:220242.

At the vernal equinox 2002, a GPS user's receiver antenna located at the North Pole saw the GPS satellites constellation as shown in Figure **3**. In this figure, the cross in the center of the diagram represents the user's zenith direction. Each concentric circle, representing user's elevation angle, is $15°$ apart until the second last brown colored circle, which represents the user's horizon. The most outer concentric circle denotes an elevation of $-10°$, which also corresponds to a Fixed Earth Orbit (FEO), also known as GeoStationary Orbit (GSO) [24]. GPS satellites trajectories are shown in green. The North Pole user can see 10 GPS satellites above his horizon, 1 GPS satellite is just at the horizon, while 5 GPS satellites are less than $10°$ below the user's horizon. Also shown in Figure **3** is the FEO with respective Inmarsat satellites (magenta colored ellipses) transmitting WAAS and EGNOS signals. However, these signals are beyond the reach of the North Pole user's receiver. GPS orbits could reach only $55°$ in elevation, i.e., up to the orbital inclination values. There is no GPS satellites near the zenith of the North Pole user, which results in an increased Geometric Dilution Of Precision (GDOP) error. One could calculate the volume of a tetrahedron defined by the visible satellites and user's antenna for each satellite constellation and a particular time instant. A GDOP error is inversely proportional to this volume. Presence of 10 visible GPS satellites guarantees fair radiolocation and radionavigation conditions.

At 20020507:133000, a GPS user's receiver antenna located at KFUPM saw the GPS satellites constellation as shown in Figure **4**. There were 12 GPS satellites above the horizon, additional 2 satellites were near the horizon and 1 GPS satellite was located less than $10°$ below the horizon. Additionally, there were 4 FEO satellites (blue colored ellipses) within the user's antenna reach. These were excellent radiolocation and radionavigation conditions. A constellation of a zenith satellite and 3 horizon satellites spaced $120°$ apart minimizes the GDOP error. Signals from near horizon satellite travel longer and uncertain paths through troposphere, thus causing significant ranging errors in corresponding time and distance estimates. Thus, it is advisable to use only satellites located at elevation angles above $5°$.

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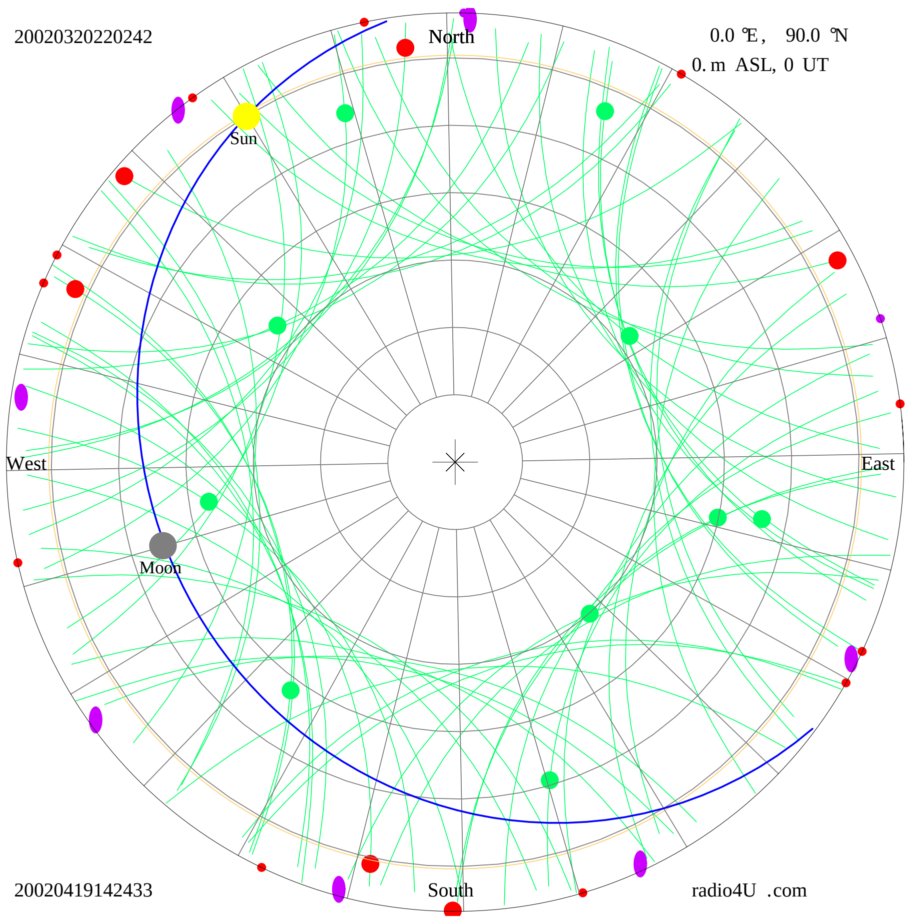

Figure 3: GPS Constellation: North Pole at 20020320:220242.

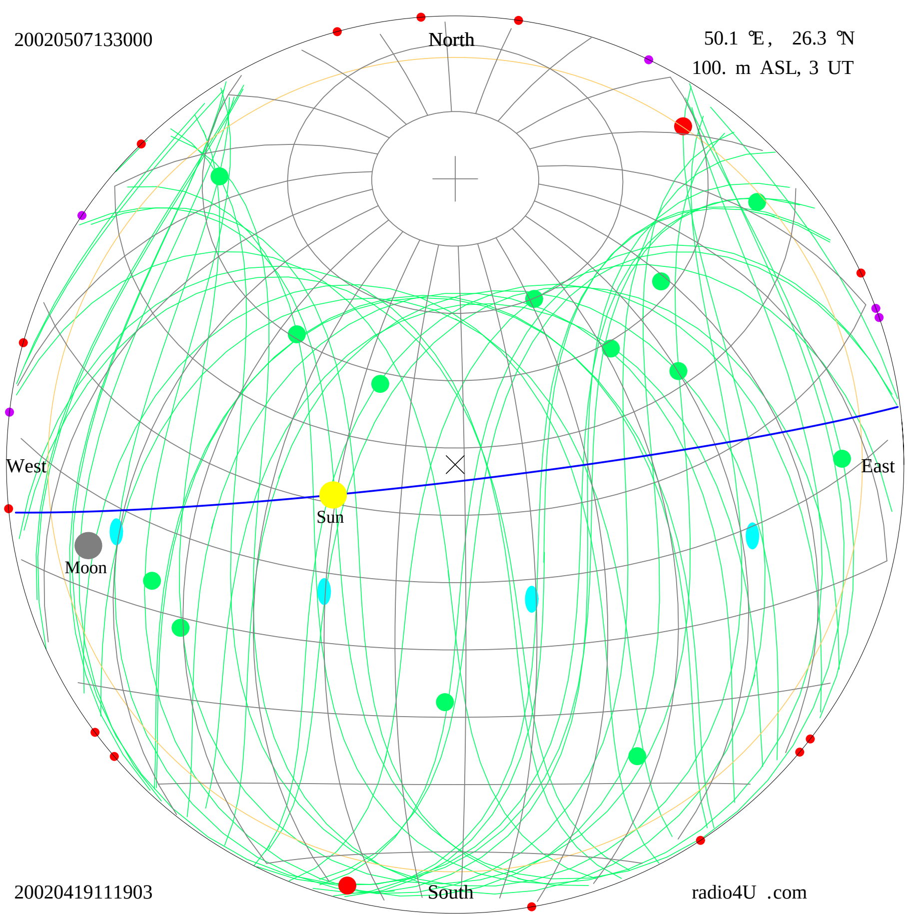

Figure 4: GPS Constellation: KFUPM at 20020507:133000.

Parameter	GPS	GLONASS
No. of satellites	24	24
No. of orb. planes	6	3
Satellites per plane	4	8
Orbit inclination, °	55	65
Orbit spacing, °	60	120
Orbital height, km	20180	19100
Semi–major axis, km	26558	25478
Period, hour	12.00	11.25
Gr.track period, day	8	1
Geodetic datum ECEF	WGS84	PZ90
Availability, hour	24	24
Broadcasting	CDMB	FDMB
Navigation data	t, X, Y, Z 3velocity	t, X, Y, Z 3velocity
Data rate, b/s	50	50
Data Period, s	30	30
Almanac time, min	12.5	2.5
C/A code rate, kchip/s	1023	511
wavelength λ, cm	29310	58620
period, ms	1	1
P code rate, kchip/s	10230	5110
wavelength λ, cm	2931	5862
period, day	7, 266	1 s
M code rate, kchip/s	10230	
wavelength λ, cm	2931	
period, day		
Satellite clocks	Rb+Cs	3 Cs
Clock freq. f_0, MHz	10.23	5.00
Freq: $L1 = 154 f_0$, MHz	1575.42	1602–1616
wavelength λ, cm	19.05	
$L2 = 120 f_0$, MHz	1227.60	1246–1257
wavelength λ, cm	24.45	
$L5 = 115 f_0$, MHz	1176.45	
wavelength λ, cm	25.50	
Polarization	RHCP	RHCP
Accuracy, PPS, m	20	20
(2σ, 95%) SPS,m	100	100

Table 1: GPS and GLONASS Characteristics.

GPS and GLONASS satellites transmit similar navigation data (almanac) about the position and status of every satellite, and similar pseudo random noise (PRN) spread spectrum codes: a coarse acquisition code C/A and a precise P code. C/A code, aimed toward civil users, and respective Standard Positioning Service (SPS) allow an accuracy of better than 100 m to be achieved with a simple receiver. P code, aimed toward military users, and respective Precise Position Service (PPS) allow an accuracy of better than 20 m. By using both L1 and L2 frequencies, C/A code and P code, military users are provided with better precision, higher availability, higher security and better anti–jamming and anti–spoofing properties, [6–7].

GPS transmits spread spectrum signals in Code Division Multiple Broadcast (CDMB) mode of operation. Each satellite transmits its own codes but at common sets of frequencies.
GLONASS transmits spread spectrum signals in Frequency Division Multiple Broadcast (FDMB) mode of operation. Each satellite transmits similar codes but at different sets of frequencies.

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The performance capabilities of any radiolocation and/or radionavigation system are affected by transmit beacons geometry and by ranging errors. The GPS and GLONASS satellite geometry, and the user receiver position, determine GDOP.

Causes of ranging errors include uncertainties in satellite ephemeris, satellite clocks, ionospheric and tropospheric group delays, multipath, and receiver measurements errors. In many practical situations an rms position error can be expressed as:

(rms position error) = GDOP $\times$ (ranging error)

Intuitively, a GPS/GLONASS receiver determines its own approximate 4D position (an exact time instant and a 3D spatial position) by analyzing navigation messages from at least four visible satellites. An average (GDOP = 3) is achieved for a full 24 satellites constellation. After acquiring the C/A (P) codes, a GPS/GLONASS receiver could estimate its position to within a fraction of the C/A (P) code wavelength, i.e., $\mathrm{GDOP}\times\lambda_{C/A}/400 \approx 2\,\mathrm{m}$ ($\mathrm{GDOP}\times\lambda_P/400 \approx 20\,\mathrm{cm}$), void of any other ranging error. In a kinematic mode, theoretically, tracking of a carrier phase could allow an estimate of a position $\mathrm{GDOP}\times\lambda_1/400 \approx 1.5\,\mathrm{mm}$. Usually, other ranging errors such as intentional dithering of satellite clocks and false satellite ephemeris, code noise, multipath, and ionospheric and tropospheric group delays in particular, limit the accuracy of either GPS or GLONASS, [6–7].

The smallest wrist watch size GPS receivers use simple and small antennas to receive satellites signals. Such receivers, with antennas having nearly hemispherical antenna pattern coverage, are particularly vulnerable to multipath ranging errors due to reflections from the ground and surrounding objects in the vicinity of the antenna. Sophisticated receivers may employ larger anti–multipath choke antennas, or the adaptive antennas for improved performance.
Tropospheric group delays caused ranging errors could be minimized by avoiding the low elevation satellite signals, employing more suitable antennas and/or using additional tropospheric correction data provided by other augmentation subsystems discussed in the following section. The ionospheric group delays related ranging errors could be minimized by processing signals from both L1 and L2 frequencies, by using appropriate ionospheric model correction algorithms and/or by using additional ionospheric correction data provided by other augmentation systems discussed in the following section.

Both GPS and GLONASS signals are rather weak (about $-160\,\mathrm{dBW}$ in front of the receiver antenna); thus, its use inside buildings, within city canyons or even below canopy is very limited to impossible. Such weak signals are also vulnerable to jamming. Planned military M–code signals on L5 frequency should alleviate most of these problems.

3 Users, TBAS, SBAS

Both military and civil users have been using GPS and/or GLONASS — single, hybrid GPS/GLONASS or augmented by other radionavigation means — for space, air, land and marine navigation and location purposes, dynamic and static positioning and timing, automatic vehicle location, tracking of precious cargo and endangered species, in geodesy, hydrology, architecture, oil explorations, archeological excavations, geographic information systems (GIS), precise farming, etc.
The existing, widely available receivers are achieving unaided positional accuracies many times better than respective GPS and GLONASS requirements for PPS $\leq 20\,\mathrm{m}$ and SPS $\leq 100\,\mathrm{m}$, respectively. However, in many applications, existing availability and precision of GPS and GLONASS services is inadequate.

Numerous Terrestrially–Based Augmentation Systems (TBAS) and Satellite–Based Augmentation Systems (SBAS) have been implemented and/or are in the process of implementation, see [1–35]. Essentially, these systems use additional beacons with improved location accuracy to transmit improved ephemeris of GPS/GLONASS satellites, satellites clocks data, tropospheric and ionospheric corrections, etc. TBAS are local in nature, while SBAS are global. Positional accuracies in dynamic and static mode, achieved by such TBAS/SBAS/GPS/GLONASS receivers, are in meter and centimeter range, respectively.

TBAS systems mostly include some form of Differential GPS/GLONASS solutions [7]. Examples of TBAS include Local Area Augmentation System (LAAS) and LORAN–C/EUROFIX/EGNOS solution known as LOREG. Additional radio beacons, employing frequencies below AM radio frequencies of 525 kHz, using LORAN–C transmitters, existing radio and TV stations, etc., to broadcast data, among others, on local ionospheric and tropospheric parameters, have sprung worldwide. Some of these systems are providing highly stable and precise time references, for example in digital cable and radio network, and spatial precision in cm range but over a spatial distances of few hundred kilometers.

Examples of SBAS include Wide Area Augmentation System (WAAS) in the USA [28, 29], Multi–functional Transport SATellite (MTSAT) system in Japan [19], European Geostationary Navigation Overlay Service (EGNOS) [16] and European radionavigation system proposal Galileo [17]. These efforts should lead toward a common Global Navigation Satellite System (GNSS).

The WAAS employs tens of terrestrial stations, located mostly in the USA, to collect GPS related data, among others, on local ionospheric and tropospheric parameters, and broadcast this data over additional L–band GPS–compatible beacons piggy–backed on the two FEO INMARSAT 3-F3, Pacific Ocean Region (POR) 178° E and INMARSAT 3–F4, Atlantic Ocean Region (AOR-W) 54° W satellites [15].

The EGNOS employs tens of terrestrial stations, located mostly in Europe, to collect GPS and GLONASS related data, among others, on local ionospheric and tropospheric parameters, and broadcast this data over additional L–band GPS/GLONASS–compatible beacons piggy–backed on the three FEO INMARSAT 3-F2, Atlantic Ocean Region (AOR-E) 15.5° W, INMARSAT 3-F1, Indian Ocean Region (IOR) 65.5° E [15], and ESA ARTEMIS satellite reaching FEO 21.5° E location at 2003.01.31, [18].

The signal coverage from these three FEO satellites includes many Arab countries. This fact suggest possible direct application of EGNOS system in the Arab countries and technical possibilities of addition of the local tropospheric and ionospheric corrections to future EGNOS like solutions.

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The EGNOS is perceived as a transitional project toward an European GNSS system called Galileo. Galileo, planned to be operational in 2006–2008, will employ 30 satellites in the near–circular orbit at the altitude of 23222 km above the earth. Expected positional accuracy is 10 m at 70% availability for *Mass Market*, and 4 m at 99% availability for *Safety Critical Market*, worldwide [17].

The MTSAT plans employing tens of terrestrial stations, located mostly in Japan, to collect GPS related data, among others, on local ionospheric and tropospheric parameters, and broadcast this data over additional L–band GPS–compatible beacons piggy–backed on the two FEO MTSAT-1R (planned start in 2003.08) at 140° E and MTSAT-2 (planned start in 2004.06), [19].

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