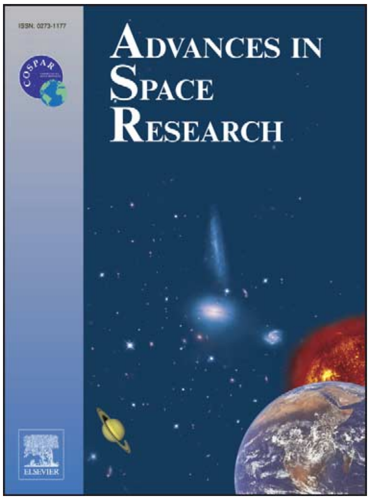

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Galileo and the IGS: Taking Advantage of Multiple GNSS Constellations

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Abstract

The paper reviews some objectives and preparatory activities of the International GNSS Service (IGS), in relation to the developing European Global Navigation Satellite System Galileo. Experience already acquired in the IGS in monitoring multiple global navigation satellite systems (GPS and GLONASS) is reviewed. Some significant features of the Galileo system are outlined, including constellation design, and some areas are identified in which Galileo will influence IGS operations in the future and in which the IGS and its active elements can continue to contribute to new GNSS developments. These include the IGS GNSS Working Group, the Galileo System Test Bed GSTB-V2 and the Galileo Geodetic Service Provider (GGSP) Prototype.

Keywords: Galileo; IGS; GNSS; International GNSS Service; GPS; GLONASS; IGLOS; IGEX

1. Introduction

In March 2005, in recognition of the fact that its activities encompass multiple Global Navigation Satellite Systems (GNSS), the IGS Governing Board changed the organization's name to the International GNSS Service. The acronym IGS, formerly the International GPS Service, was retained. IGS's pilot project using GLONASS (IGLOS) was officially terminated by the Board in December 2005, because GLONASS had been successfully and sufficiently incorporated into the routine daily IGS data collection, dissemination and processing cycles, and it had become a standard part of the IGS product offering. The IGS had indeed become an International GNSS Service.

The next step in this development is the introduction of Galileo into the IGS activities. A number of preparations have been already initiated in this direction. These will be the subject of this paper.

Through its unique experience and expertise in handling a very large global network of sensor stations and the complex data analysis required to produce on a routine basis high accuracy, short latency products, the International GNSS Service has already made a significant contribution to the development of the Galileo system. IGS products have been and are being used extensively as a reference in the development and verification of algorithms and systems, both ground and space. Data from the IGS station network was the basis of the Galileo System Test Bed, Version 1 (GSTB-V1), and Galileo receivers are currently being deployed at a number of IGS sites for support of the GSTB-V2 Mission activities. Several IGS Analysis Centres are working together on the Galileo Geodetic Service Provider (GGSP) Prototype, aimed at defining the reference frame for the Galileo products and the approach to maintaining that frame over the 20-year lifetime of the system. Within the IGS, Galileo is a focus of the GNSS Working Group's planning, as well as being a significant element of the IGS Strategic Plan for the years 2008-12.

2. International GNSS Service

The IGS provides, with a high reliability, accurate GNSS satellite orbit and clock solutions, both in near real-time and off-line, the latter with delays of 17 hours (rapid products) and 11 days (final products) respectively. Typical accuracies of the rapid and final products are 3 cm and 0.1 ns for orbits and clocks. The near real-time solutions are based on solutions made every 6 hours by combining solutions provided by a number of independent Analysis Centres, each based on pseudo-range and phase data collected from a global network of stations tracking the GNSS satellite constellations. The delay with respect to the latest data in these solutions is 3 hours. Real-time products (orbit and clock corrections) are provided through a 24 hour prediction from the combination solution with sub-decimetre and nanosecond-level accuracy.

These products are well suited to a wide range of applications, including:

- Access to and continued improvement of the International Terrestrial Reference Frame (ITRF), through highly accurate and continuous measurements of ground station positions and velocities and Earth Orientation Parameters (polar motion and length of day).
- Monitoring of deformations of the solid Earth
- Monitoring of sea level variations
- Orbit determination of satellites in low Earth orbit
- Continuous mapping of the variations in the electron content of the Earth's ionosphere
- Weather forecasting and climate research, through monitoring of troposphere zenith biases

A network of some 350 globally distributed ground stations equipped with geodetic quality GNSS antennas and receivers, of which many are driven by stable atomic clocks (rubidium, caesium, hydrogen masers), provides in near real-time the data needed to produce the IGS products and support these applications. Data are typically retrieved through the hierarchy of IGS Data Centres, mainly hourly but also daily, with 1 second or 30 second observation rates. A significant sub-set of stations is now providing data in real-time, with 1 second sampling rate.

Further background can be obtained from the IGS website (http://igscb.jpl.nasa.gov - includes the IGS Terms of Reference and current Strategic Plan, as well as network performance and much other information); the IGS Analysis Centre Coordinator website http://www.gfz-potsdam.de/pb1/igsacc/index_igsacc.html; the proceedings of the latest IGS Workshop, held in Darmstadt 8-12 May 2006 (Springer et al., 2006; see also http://nng.esoc.esa.de/ws2006/programme.html); Dow et al. (2005); and Beutler et al. (1999). Current information on the ITRF is provided by Altamimi et al. (2005).

3. GLONASS in IGS

The International GLONASS Service Pilot Project (IGLOS) was initiated by the IGS in February 2000 as a continuation of the International GLONASS Experiment (IGEX-98), which had been successfully completed in 1998 but had continued in a reduced mode thereafter through the continued involvement of several of the IGEX data providers and Analysis Centres; see Willis et al. (1999), Slater et al. (2000), Weber et al. (2001), Slater et al. (2004), Weber et al. (2005). A dedicated laser tracking campaign through cooperation with the International Laser Ranging Service (ILRS, see Pearlman et al., 2002) and collaboration with timing laboratories added to the value and relevance of the IGEX campaign.

The objectives of IGEX-98 were to:

- Set up a global network of GLONASS (or rather, combined GLONASS and GPS) receivers, with improved geographic distribution compared with the IGEX network
- Produce precise orbit and clock products with a delay of less than 3 weeks and orbit accuracy of 10-20 cm, for monitoring system performance and for geodetic applications
- Calibrate GLONASS receivers and antennas
- Monitor the accuracy and stability of the GLONASS geodetic reference frame and time system versus those of GPS.

The IGLOS project was of intrinsic interest, despite the small number of active GLONASS satellites available at the time, but was also considered a first step towards incorporation of additional GNSS's into the IGS processing cycle, looking in particular to the eventual deployment of Galileo. In the meantime, the GLONASS constellation is being built up again with more robust spacecraft; and there are excellent prospects of a complete constellation of 24 satellites again within a few years.

The objectives of the IGLOS Pilot Project were achieved and the project was concluded. The processing of GLONASS data in the IGS continues on a routine basis. A graphical summary of the orbit accuracy obtained over a period of several years is given in Fig. 1. It should be noted that results of the Russian Mission Control Centre (MCC) are based on satellite laser ranging (SLR) data only and apply to those few satellites of the GLONASS constellation which are regularly tracked by SLR.

4. Galileo orbit constellation

The Galileo spacecraft will fly in a Walker constellation 27/3/1, i.e. with 27 satellites distributed in 3 orbit planes separated by 120 degrees, with a phase angle of 360/27 = 13.3 degrees between the positions of the first satellite in consecutive planes. In addition, each plane will have a (normally active) spare satellite, bringing the total number of spacecraft to 30.

In order to avoid the gravitational resonance associated with a 12 hour orbital period, the Galileo satellites will have a semi-major axis of about 29600 km (altitude some 3000 km higher than GPS), and an orbital period of 14 hr 5 min, giving a repeat of the ground track in about 10 days, corresponding to 17 orbits. The relatively short repeat period is convenient for mission planning purposes. The constellation lifetime is 20 years, while individual satellites have a design lifetime of 12 years.

The requirements on constellation stability are as follows:

- Distance between consecutive satellites in one plane: variation within ±3 degrees
- Distance between satellites in adjacent planes: variation within ±3 degrees
- Inclination and ascending node: variations within ±3 degrees

In order to minimise the need for orbital manoeuvres, small offsets are applied to the nominal initial orbital elements of each satellite. In this way the above criteria can be satisfied for a period of years much longer than would otherwise be possible.

In view of the very long interval to be expected between correction manoeuvres (typically 12 years), it is of interest to use IGS (and ILRS) experience of GLONASS and radiation pressure modelling uncertainties to investigate the prediction uncertainty of a spacecraft in such an orbit. This has been carried out by fitting real laser data from an Etalon satellite (in a GLONASS-type orbit), showing that residuals of only a few km after 12 years can be expected. It is clear that, since Etalon is a spherical satellite with a very low area-to-mass ratio, radiation pressure modelling for Etalon is significantly simpler and more accurate than it can ever be for Galileo. However, the accuracy obtained in predicting over 12 years is about a factor 100 better than the Galileo in-orbit position deadband allows, so that we can be relatively confident that the orbit prediction accuracy will indeed be sufficient to allow a correct definition of the a priori orbit parameters for operation without frequent maintenance manoeuvres.

Further details about the Galileo orbit selection process can be found in Zandbergen et al. (2004).

5. IGS GNSS Working Group

A GNSS Working Group (WG) was established by the IGS in 2003, with the objectives to:

- Prepare a consolidated feedback to next generation navigation satellite systems (Galileo, GPS, GLONASS) based on relevant experience of providing highest accuracy products for the existing systems
- Reflect on opportunities of upcoming GNSS's to identify improvements in IGS products
- Establish information exchange and stimulate cooperation between IGS and entities involved in the management and technical set-up of Galileo, as well as modernisation of GPS and GLONASS

Typical technical tasks were to include study of:

- Standard formats (RINEX extension to Version 3, SP3, IONEX, SINEX, real-time, …) and their application to Galileo
- How to deal with intra- and inter-system biases
- Combined GPS/GLONASS processing
- Galileo System Test Bed (GSTB-V2) and In-orbit Validation (IOV): e.g. exploiting the analogy of GPS/Galileo-IOV constellation with GPS/GLONASS reduced constellation scenario for verification of navigation processing.

The issue of intra- and inter-system biases becomes much more complex for Galileo and future GPS satellites:

- Galileo will offer E1, E5a, E5b, E6
- GPS will have biases between C1A, P1, P2, L2C/CM, L5-Code
- GPS/Galileo as well as GPS/GLONASS system time offsets will have to be monitored
- Additional frequency-dependent antenna phase centre offsets and variations will have to be established and monitored

A central question for the WG will be: which biases can be monitored by the IGS?

In the GSTB-V2 and IOV phases of Galileo, it is expected that IGS, through its Analysis Centres, can contribute to improving orbital models, in particular radiation pressure models, and to monitoring the variation of offset between centre of mass and centre of phase, as well as differential group delay. Exploring the challenges of hybrid GNSS data processing during the Galileo IOV phase and identifying the possible improvements to IGS products will be key activities in this context.

Galileo will provide phase and pseudo-range measurements with lower measurement noise and multi-path errors (allowing more accurate precise point positioning, for example). Multi-frequency measurement combinations will give better integrity for kinematic applications, while the increased number of satellites (up to 60 with GPS and Galileo together) will increase navigation robustness in case of non-optimal horizon masking and allow derivation of better scientific products (e.g. ionosphere maps, horizontal gradients for troposphere zenith delays).

Information on the Galileo system design is provided by Oehler et al. (2006), and other contributions in the same Proceedings.

6. Galileo System Test Bed

The Galileo System Test Bed, Version 1 (GSTB-V1) utilised GPS signals to simulate critical aspects in a prototype Galileo ground segment. Central to this experimental operational activity, which was carried out in the Navigation Laboratory at ESA/ESTEC (The Netherlands), was the use of data from a subset of the global IGS network. A total of 41 stations, operated by GeoForschungsZentrum Potsdam (GFZ), the European Space Operations Centre (ESA/ESOC), the Centre National d'Etudes Spatiales (CNES) and other IGS contributors, were configured to provide 1 second data in near real-time (1 hour latency). A summary of the GSTB-V1 system and test results can be found in Falcone et al. (2004).

The Galileo System Test Bed, Version 2 (GSTB-V2) goes one step further, by incorporation of up to 2 Galileo test satellites (Giove-A and in future Giove-B), along with a network of 13 sites equipped with antennas and receivers able to track the Giove signals in addition to those of GPS; see Piriz et al. (2006). Two European IGS centres with long experience of operating global GNSS networks (GFZ and ESOC) were entrusted with the establishment of most of those new tracking sites, as part of a consortium led by Galileo Industries, with important contributions from the companies Alcatel, Indra, EADS Astrium UK, Septentrio and Space Engineering. Table 1 lists the sites, while Fig. 2 shows the geographic distribution of the network.

The network was nearing completion by November 2006, with the first data already beginning to flow into the GSTB-V2 Processing Centre in July 2006. An initial 1 year operational phase is foreseen, with a possible extension for a further year. Fig. 3 shows the station at New Norcia, near Perth in Western Australia.

7. Galileo Geodetic Service Provider Prototype

The establishment of the Galileo Reference Service Provider (GRSP) Prototype is a project funded within the sixth framework programme of the European Union. Call number 2420 of the second call for proposals asked for the "Implementation of Galileo Geodetic Service Provider Prototype". The Galileo Geodetic Service Provider (GGSP) aims to develop the Galileo Terrestrial Reference Frame (GTRF) and to establish a service with data, products and information for the potential Galileo users. A number of organisations actively involved in the IGS and in the International Earth Rotation and Reference Frame Service (IERS) formed a consortium which was awarded a contract to carry out the work, after a competitive bidding process. The organisations involved are: GeoForschungsZentrum Potsdam (D, Consortium leader); Astronomical Institute, University of Bern (CH); ESA/European Space Operations Centre, Darmstadt (D); Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt (D), Institut Géographique National, Paris (F); with additional support from Natural Resources Canada and the University of Wuhan (China). The project started in July 2005 and is planned to finish in 2009.

The realisation of a highly precise and stable Galileo Terrestrial Reference Frame (GTRF), the basis for all Galileo products and services, is the main function of the Galileo Geodetic Service Provider (GGSP), serving both the Galileo Core System (GCS) and the Galileo User Segment. This implies that the GGSP should enable all users of the Galileo System, including the most demanding ones, to rapidly access the GTRF with the precision required for their specific application. Furthermore, the GGSP must ensure the proper interfaces to all users of the GTRF, especially the application and scientific user groups. In addition, the GGSP must ensure the adherence to the defined standards of all its products. Last but not least, the GGSP will play a key role in creating awareness of the GTRF and in educating users about the realisation and application of the GTRF.

Although the prime task of the GGSP is to provide GTRF station positions and velocities for the Galileo Sensor Stations (GSS), its responsibilities will go well beyond this task. The GGSP responsibilities will include the generation of other precise products that are needed by the Galileo advanced geodetic user community to get full access to the GTRF. These products, which are generated simultaneously with the GTRF activities performed within the GGSP, will at least comprise Earth Orientation Parameters (EOPs) as well as Galileo satellite orbits and clocks. Only with such a complete and consistent set of high precision products can the GGSP fulfil its prime task of providing a reference frame to all relevant user communities, including the most demanding ones. In addition, these high precision products will be extremely valuable for the validation of the operational products generated by GCS.

The main objectives of the GGSP Prototype are:

- Consolidation of the GGSP Prototype: specification, definition and planning
- Realisation of the GTRF: concept, minimum network and data requirements
- Maintenance of the GTRF: assuring the long-term stability
- Validation of the GTRF: confirming the accuracy and stability
- Validation of satellite orbits, clocks and Earth orientation parameters
- Promotion and outreach
- Recommendations for the implementation and operation of the permanent GGSP

Several external inputs are needed for the realisation of the GTRF. The main interfaces for the GGSP are with the Galileo Ground Mission Segment (GMS) and with the IGS, as well as with the ILRS (for SLR data) and the IERS. The GMS is mainly responsible for providing access to the Galileo Sensor Station (GSS) data, both the station metadata and the Galileo/GPS observations. The IGS stations will be used to enable the expression of the GSS station coordinates in the International Terrestrial Reference Frame (ITRF). Furthermore, the IGS stations will increase the density of the GSS station network and thereby strengthen the overall network solution. As a first source of Galileo data for the GGSP, it is planned to use the outputs of the GSTB-V2 network, as soon as it is validated and operational.

8. Conclusion

Galileo and multi-constellation processing have been high priorities for the International GNSS Service (IGS) over the past few years, and will become even more so in the future, as will new developments in the GPS and GLONASS systems. The IGS and its contributing organisations are already active in applying to Galileo the lessons learned from the experience of more than a decade of producing high accuracy GNSS products from GPS and GLONASS. This is reflected in particular in the work of the IGS GNSS Working Group and in the participation of IGS centres in the Galileo System Test Bed activities and in the Galileo Geodetic Service Provider Prototype. A major campaign (equivalent to IGEX-98) can be foreseen for the period 2009-2010, once sufficient Galileo satellites and ground receivers have been deployed.

The incorporation of Galileo tracking and data processing into the IGS structures will imply in addition the further extension and application of IGS standards (equipment, calibrations, formats, delivery methods, products, etc.) and the generation of an even more valuable database and long term archive in support of geophysical and other research and applications.

9. Acknowledgement

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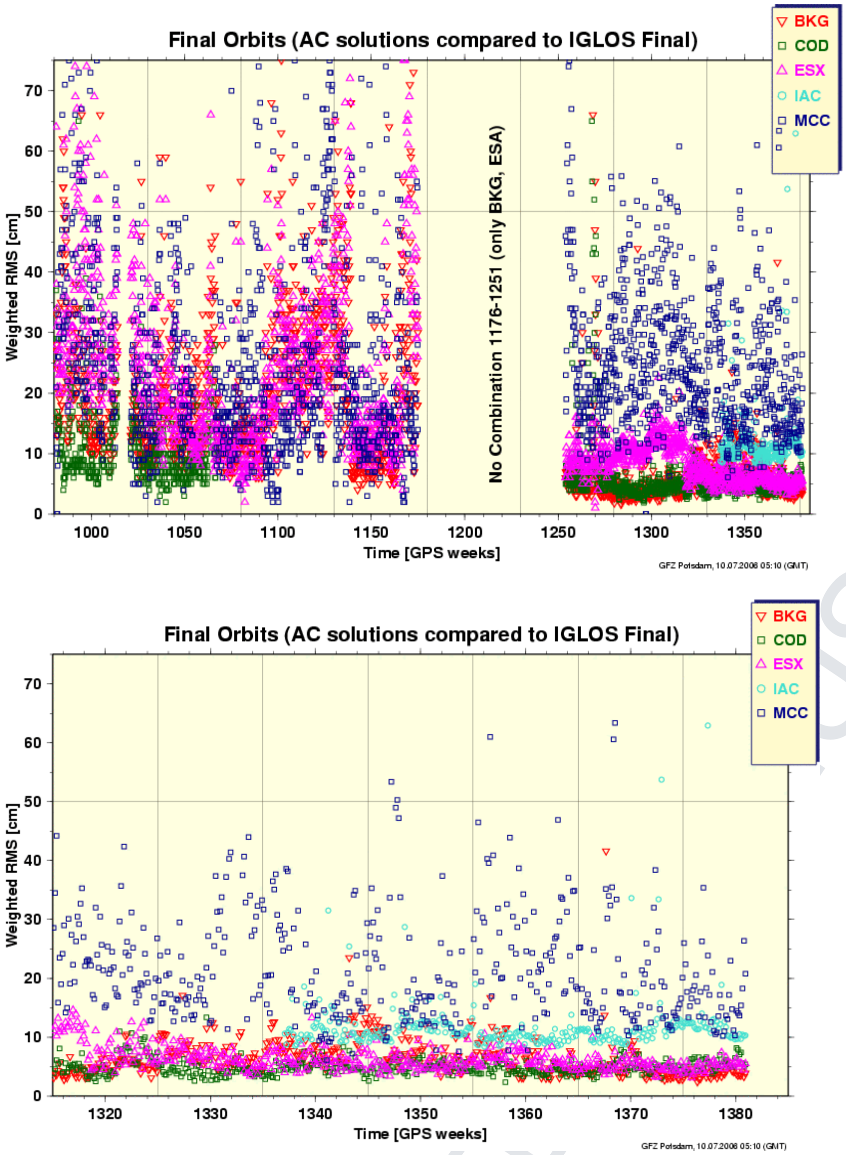
Figure captions

Fig. 1 (a & b). IGLOS (GLONASS) final orbit accuracy, till July 2006
Fig. 2. GSTB-V2 station network
Fig. 3. Galileo Experimental Sensor Station gnno at New Norcia, Australia

Table 1. GSTB-V2 station network

Number	Station	Country	Responsible agencies	Station code
1	Kourou	French Guyana	ESA/ESOC	gkou
2	Malindi	Kenya	ESA/ESOC	gmal
3	New Norcia	Australia	ESA/ESOC	gnno
4	Kiruna	Sweden	ESA/ESOC	gkir
5	Faaa, Papete	Tahiti	ESA/ESOC	gtht
6	Vesleskarvet	Antarctica	NSA, ESA/ESOC	gves
7	Washington	USA	USNO, ESA/ESOC	gusn
8	Mizusawa	Japan	GFZ	gmiz
9	La Plata	Argentina	GFZ	gpgm
10	Dunedin	New Zealand	GFZ	gous
11	Wuhan	China	GFZ	gwuh
12	Torino	Italy	INRiN	gien
13	Noordwijk	Netherlands	Indra, ESA/ESTEC	gnor



Final Orbits (AC solutions compared to IGLOS Final)

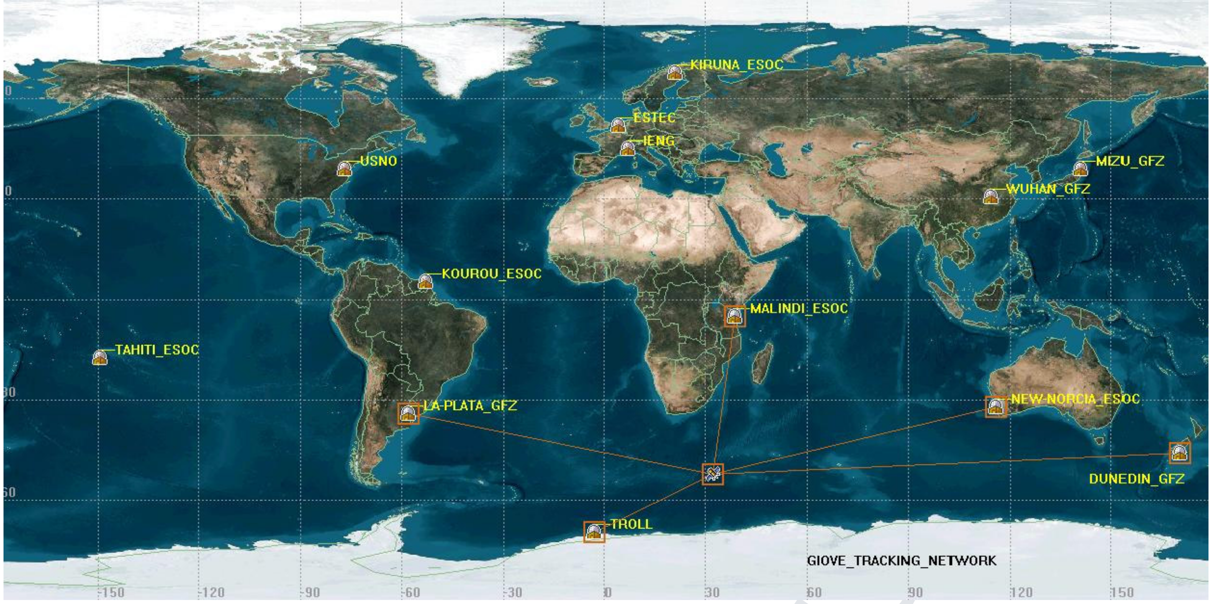
GFZ Potsdam, 10.07.2006 05:10 (GMT)

Final Orbits (AC solutions compared to IGLOS Final)

GFZ Potsdam, 10.07.2006 05:10 (GMT)

Fig. 1 (a & b). IGLOS (GLONASS) final orbit accuracy

Figure 2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MALINDI_ESOC
TAHITI_ESOC
LA-PLATA_GFZ
NEW-NORCIA_ESOC
DUNEDIN_GFZ
TROLL
GIOVE_TRACKING_NETWORK
-150
-120
-90
-60
-30
0
30
60
90
120
150

Figure 3