САМАРСКИЙ УНИВЕРСИТЕТ
SAMARA UNIVERSITY

Navigation in space

Igor Belokonov

Space Research Department

http://spaceresearch.ssau.ru/

CONTENT

- 1. Introduction. What is Navigation?
- 2. The theoretical aspects of space navigation
- 3. Nowadays methods of space navigation
- 4. Integrated navigation concept
- 5. GNSS technology for Moon missions
- CONCLUSION

1. What is Navigation?

Ever since primitive man wandered from his cave,
he has asked,
"where am I" (*the positioning problem*),
"which way leads me to my destination"
(*the guidance problem*),
or taken together
"how do I get from here to there"
(*the navigation problem*).

The navigation problem is a particular case of a more general problem *of identification the parameters of a dynamic system*

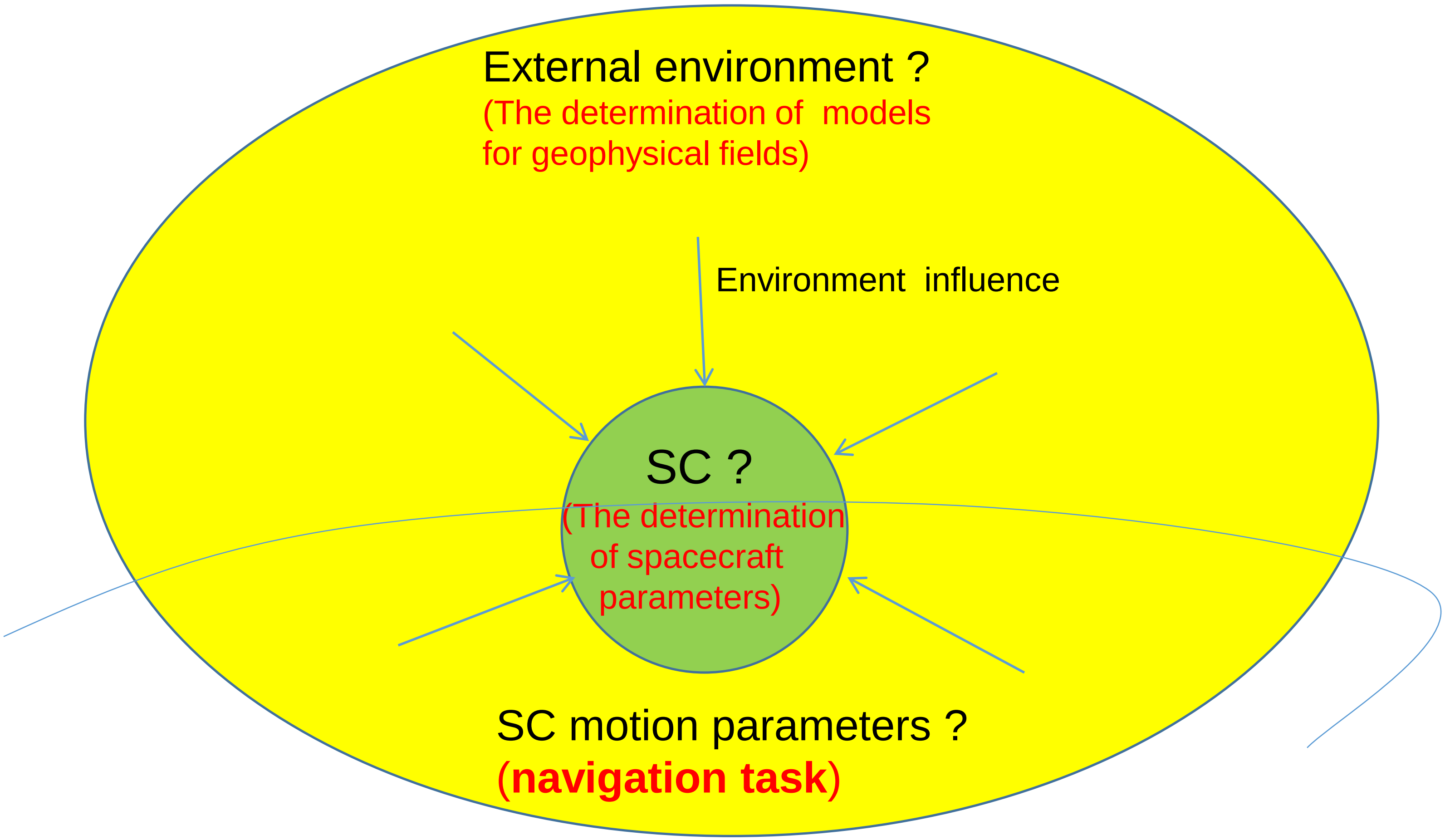
The problem of dynamic system identification includes three tasks:

- *- the determination of vector of parameters characterized present condition of dynamic system (vector of phase parameters*),
- *- the determination of constant parameters of dynamic system (dynamic system parameters),*
- *- the determination of parameters of environment in which dynamic system functions*.

ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

Applied to spacecraft these tasks may be named like:

- **Navigation task** : the determination of mass center motion parameters (for example, the projections of radius vector X,Y,Z and the projections of vector velocity Vx, Vy, Vz on the axis of geocentric coordinate system) and in some cases the motion parameters concerning of mass center (angels of pitch, yaw, roll and angles velocities)(orientation task),
- **The determination of spacecraft parameters** (for example, mass, inertia moments) and onboard systems parameters (for example, adjustment parameters of measurement devices),
- **The determination of the parameters of models of geophysical fields** (gravitational field, magnetic field, ionosphere, atmosphere etc.) in which the spacecraft is moved and which influence on SC motion.


External environment ?
(The determination of models for geophysical fields)
Environment influence
SC ?
(The determination of spacecraft parameters)
SC motion parameters ?
(navigation task)

In depend on how a navigation device operates to get the knowledge of the dynamic state of a platform (i.e., position, velocity, etc. with respect to a common reference frame), navigation can be categorized into three groups :

- ***Direct positioning systems*** use discrete measurements from external reference points whose locations in the space are well defined to determine the position and (in some cases) the velocity of the platform.

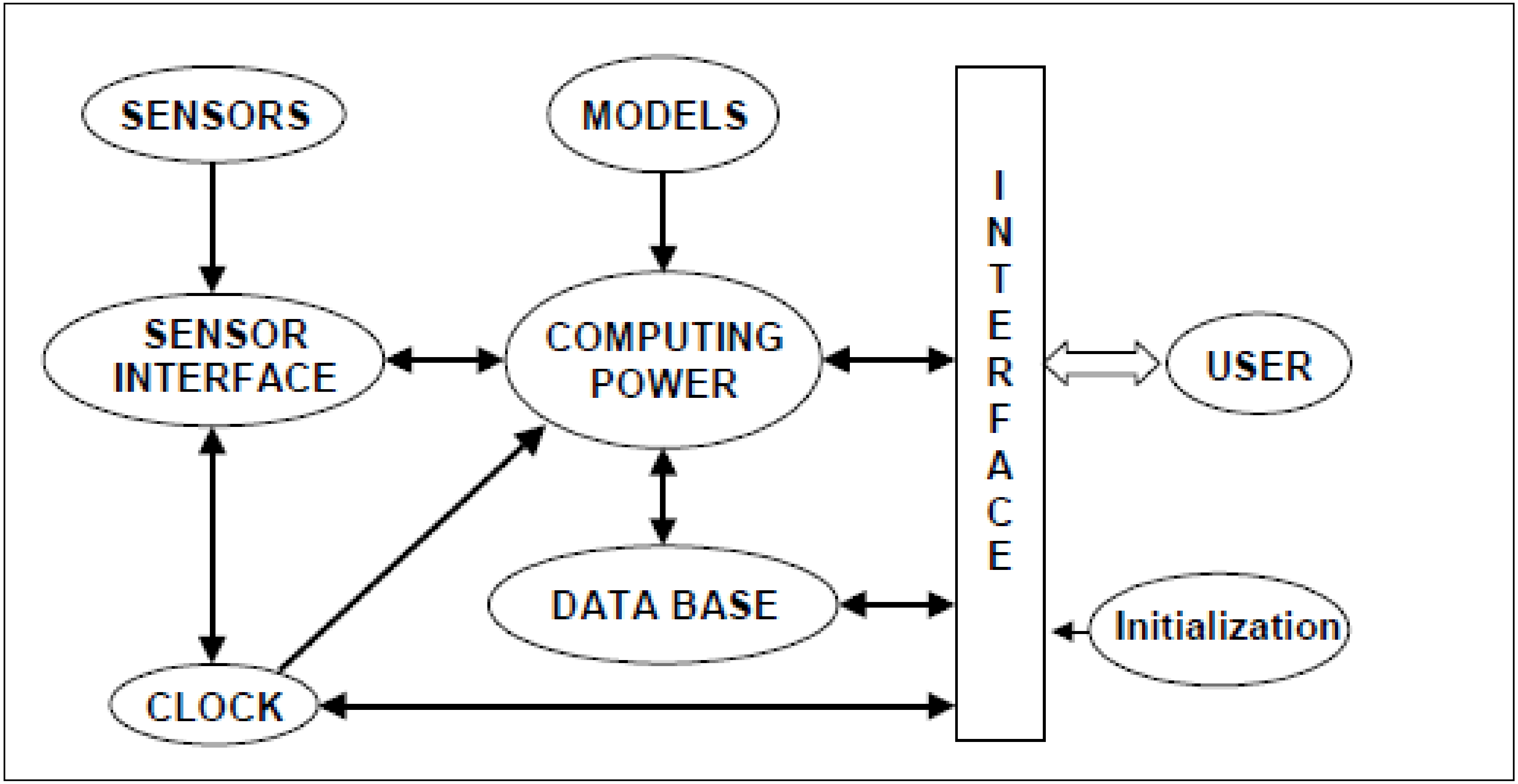
  Examples: stars (astronavigation), radio navigation satellite systems.

- ***Dead reckoning systems (autonomous system)*** use a known initial dynamic state of the platform at a known time and then continuously estimate its evolution, based on information provided by sensors of inertial information (for example, accelerometers, gyros).

  Examples: inertial systems.

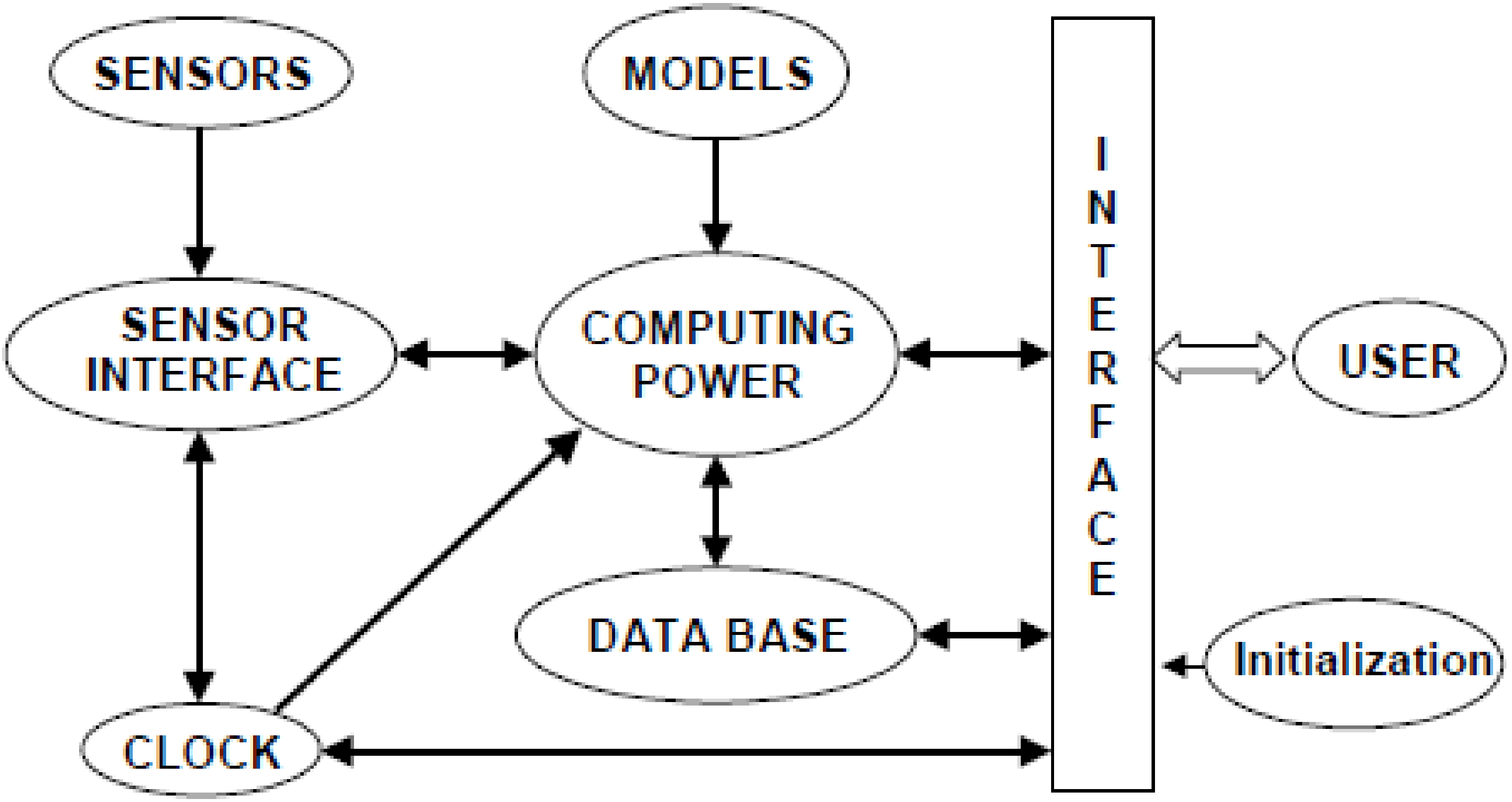
- ***Correlation systems*** sense and recognize some pre-defined and mapped characteristics of the environment and thus extract information related to the dynamic state of the platform.
- *Examples: terrain elevation, gravity variations, geomagnetic field*

Typical structure of any navigation device



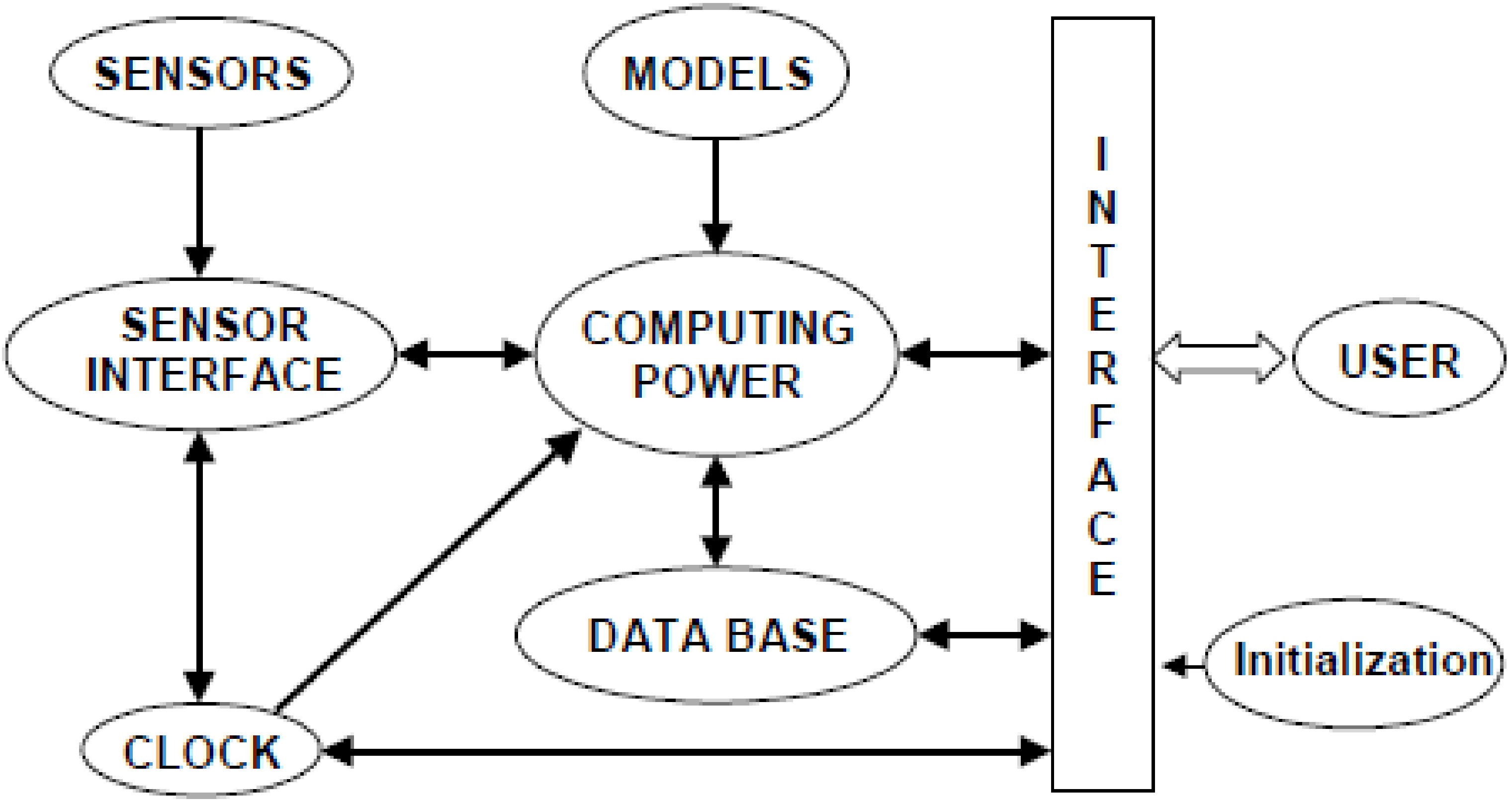
The **sensors** measure position and orientation or their rates of change (velocity and acceleration) or parameters of geophysical field (for example, intensity of strengths of magnetic field)

Typical structure of any navigation device



The **clock** provides precise time so the computer can coordinate the data from the sensors

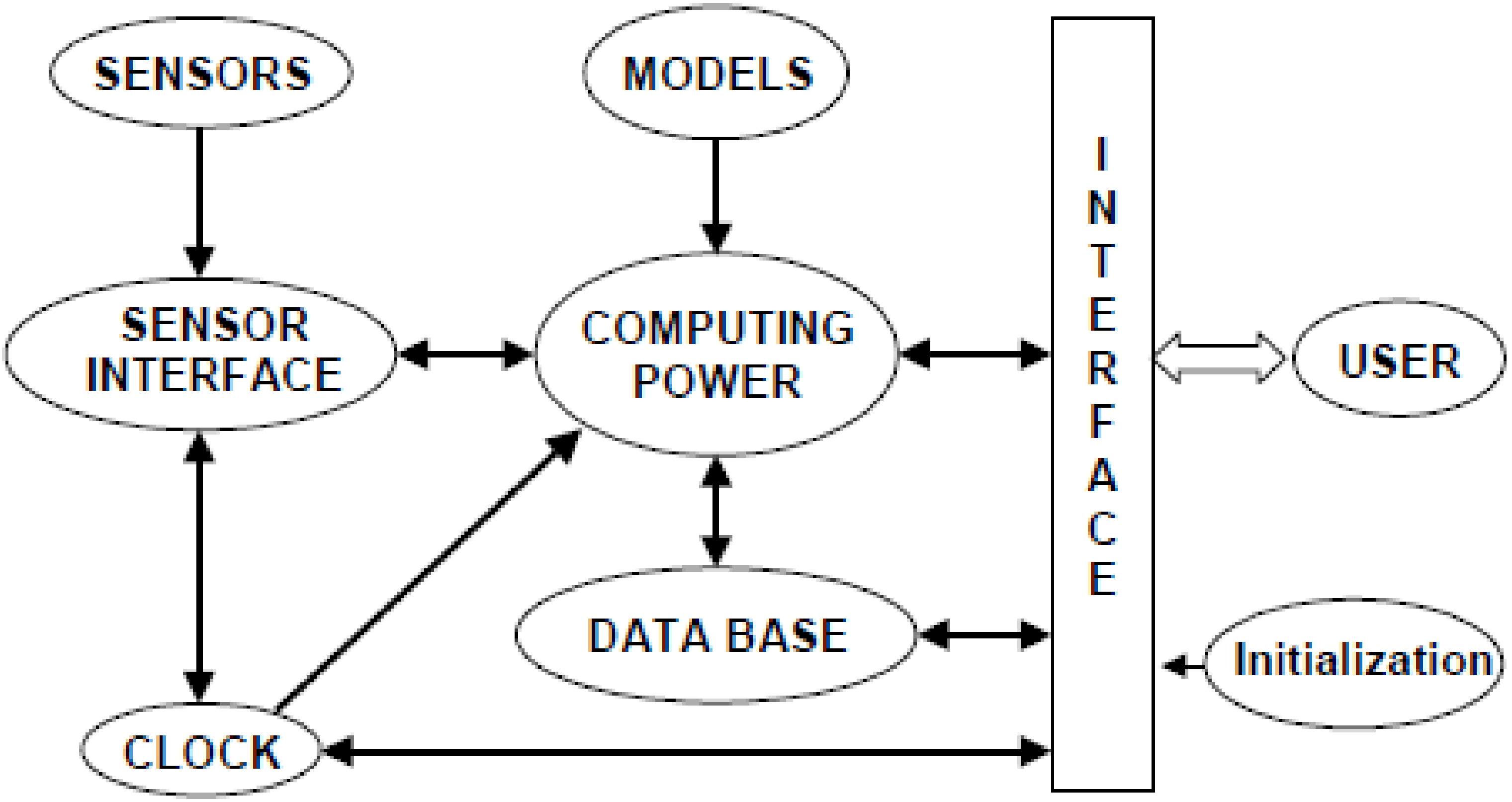
Typical structure of any navigation device



The **sensor interface** provides the measurements from the sensors to the computer

ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

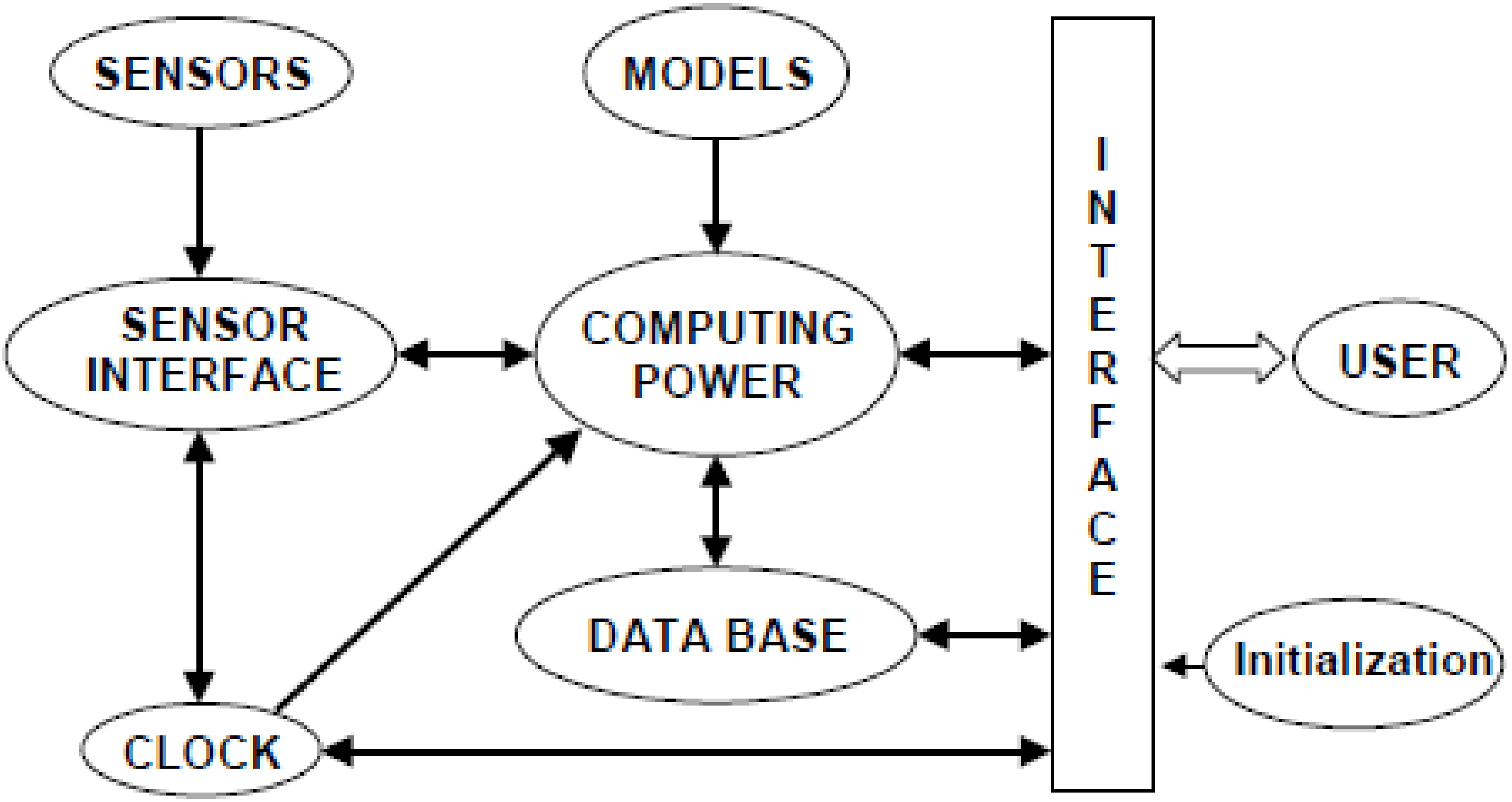
Typical structure of any navigation device



The **models**, which reside in the computer, compensate for environmental and dynamic effects on the sensors

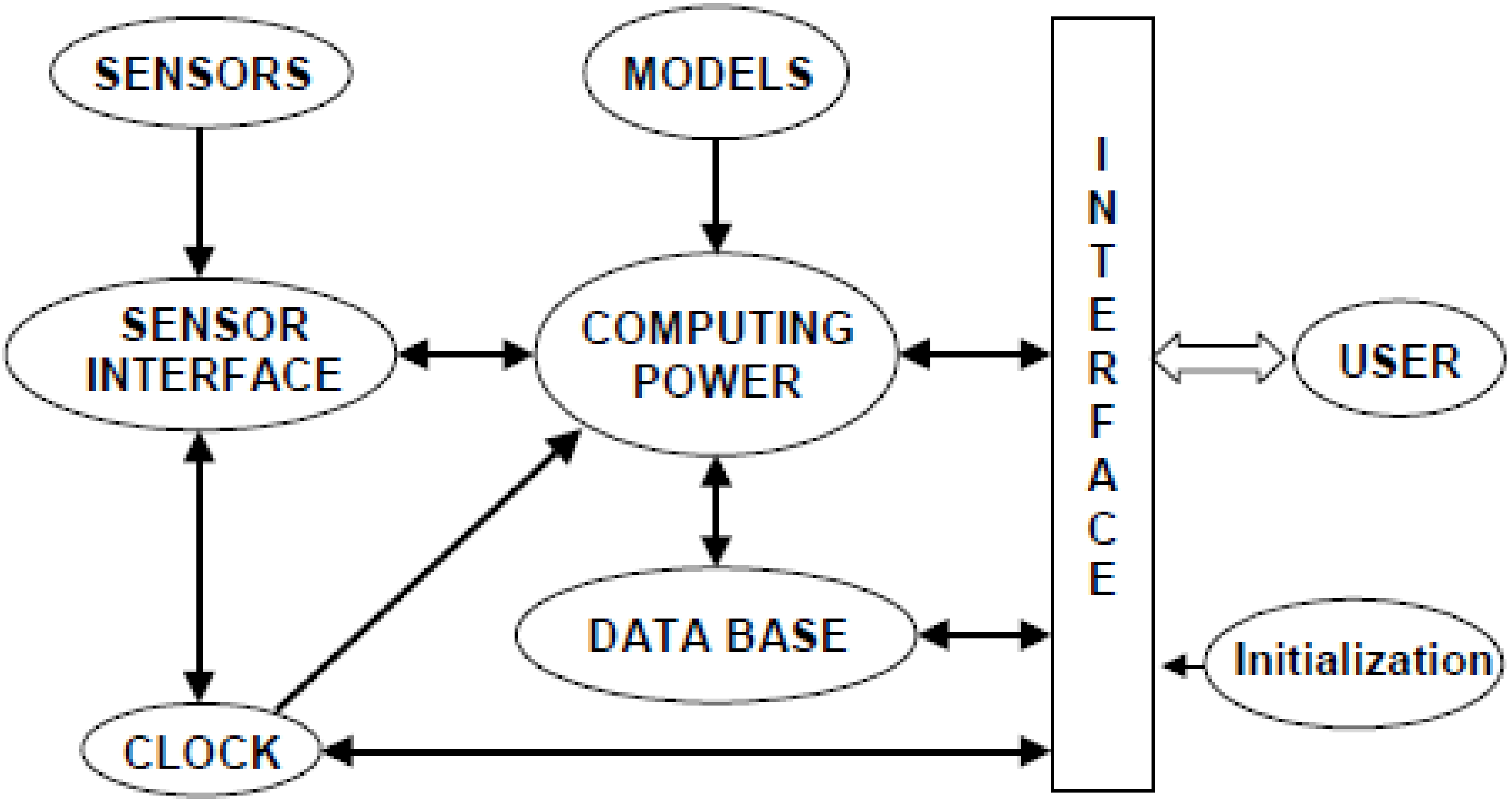
ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

Typical structure of any navigation device



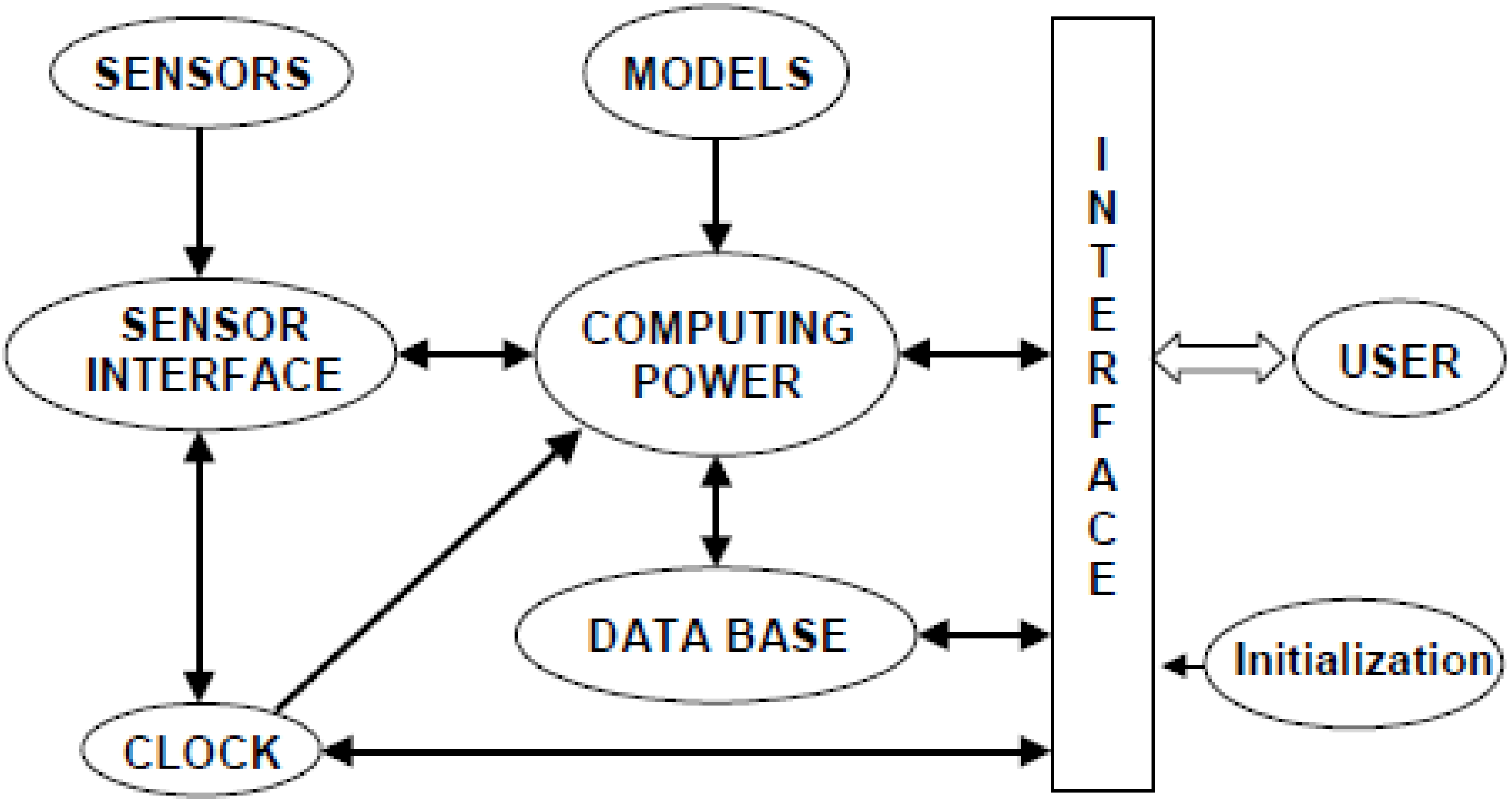
The **database** stores information related to the mission such as waypoints, maps, coordinate systems, jamming conditions, etc.

Typical structure of any navigation device



The **computer** performs the navigation computations based on models of the sensors, clock and environment.

Typical structure of any navigation device



Initialization is any process or data required to define and/or determine the initial position and alignment of the navigation system to a common reference frame.

2. The theoretical aspects of space navigation

1. Any measurement contains an errors (systematic and random types).
2. The aprioristic information about parameters to be determined can be present or absent.
3. Presence of the aprioristic information allows to simplify the decision of a navigation task.
4. The measurements can be received in one time and/or in different times:

if we have one time measurements it is a *kinematic navigation*,

if we have different times measurements it is a *dynamic navigation*.

5. In the algorithms of a kinematic navigation are used only models (equations) of measurements .
6. In the algorithms of a dynamic navigation are used models of motion together with models of measurements.

ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

7. The necessary conditions must be met to solve the navigation problem.

Necessary condition of navigation:

the number of determined parameters should be no more the numbers of measurements.

If the number of measurements is less than number of determined parameters, presence of the aprioristic information can allow in some cases to solve a navigation task.

Minimally necessary number of measurements have to be equally to number of determined parameters.

If the number of measurements exceeds number of determined parameters (a case of surplus measurements) it is possible to increase accuracy of a navigation task decisions, using statistical methods of measurements processing (for example, method of the minimum least squares, Kalman filtration, etc.)

Navigation Task formulation

- **Real motion:** $x^*(t), \quad t \in T$ $\quad x \in E^n$ **- vector dimension n**
- **Real measurements**: $\{r(t_1), r(t_2), \ldots, r(t_N)\} \in E^{m \times N}$ $\quad r \in E^m$ **- vector dimension m**
- **Subsystem of motion models:** $\dot{x} = f(t, x), \quad x(t_0) = x_0 \quad x_0 \subset X_0$
- **Subsystem of measurement models:**

$r(t) = y(t) + w(t)$ where $w(t)$ - random additive errors of measurements

$y = \varphi(t, x), \quad y \in E^r$

- **The criteria of quality of navigation solution :**

$$\alpha(\hat{x}_0, r) = \int_{X_0} \ldots \int W(x_0, \hat{x}_0) \cdot L(r, x_0) dX_0$$

where $\hat{x}_0$ - required vector of initial parameters of motion,

$W(x_0, \hat{x}_0)$ -loss function,

which characterizes difference of estimation $\hat{x}_0$ from real values X_0^*

$L(r, x_0)$- likelihood function, for example a conditional density function of probability

The result of navigational task $\quad \hat{x}_0^{opt} = \underset{\hat{x}_0 \in X_0}{arg\, min}\, \alpha(\hat{x}_0, r);$

ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

- The motion model should be *adequate* to real motion
- The measurements model should be *adequate* to real measurements
- The motion model and measurements model should satisfy to a condition of an *observability*,
- The criterion of quality of a navigational solution should be well-grounded in relation to measurements, ensure getting a unique solution $\hat{x}_0^{opt}$ and have a condition of a strong convergence to true values x_0^*

$$P\left\{\lim_{N\to\infty}\left\|\hat{x}_0^{opt} - x_0^*\right\| \geq \eta\right\} = 0$$

- For linear models of motion and measurements exist only two variants - observability and non-observability
- For non-linear models of motion and measurements exist concepts of global observability, local observability, and global non-observability

If there is no observability you can not solve navigational task using chosen models of motion and measurements

For check of an observability special criteria of an observability are used, for example for linear models of motion and measurements – Kalman criteria

Kalman criteria of observability for case of non-stationary linear models (motion and measurements):

- **Motion model** $$G : \dot{x} = \underset{n\times n}{A(t)} \cdot x; \qquad x(t_0) = x_0;$$
- **Measurement model** $$S : \quad y = \underset{m\times n}{C(t)} x$$

$$N_H = \left\| H_1(t) \vdots H_2(t) \vdots \ldots \vdots H_n(t) \right\|_{n\times mn}$$ - matrix of observability

where $H_1(t) = C^T(t)$

$$H_2(t) = A^T(t) H_1(t) - \dot{H}_1(t)$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$H_n(t) = A^T(t) H_{n-1}(t) - \dot{H}_{n-1}(t)$$

Rank $N_H(t) = n$

Kalman criteria of observability for case of stationary linear models:

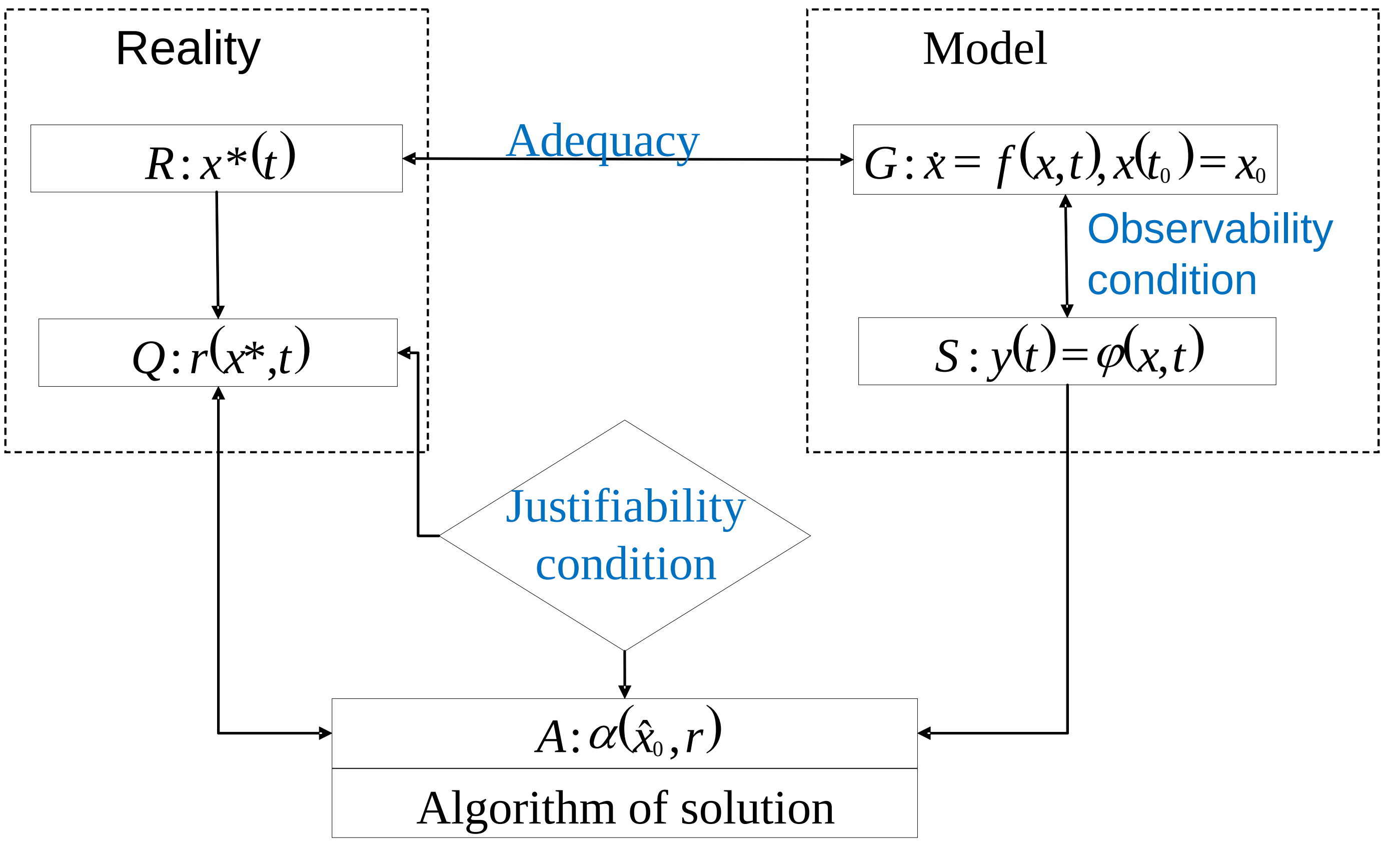
- **Motion model** $G: \dfrac{dx}{dt} = A\,x$ $x(t_0) = x_0$
- **Measurement model** $S: \; y(t) = C\,x(t)$

where

$N_H = \| \, C^T \,|\, A^T C^T \,|\, (A^T)^2 C^T \,|\, \ldots\ldots \,|\, (A^T)^{(n-1)} C^T \, \|$ - matrix of observability

$$\boxed{\text{Rank } N_H = n}$$

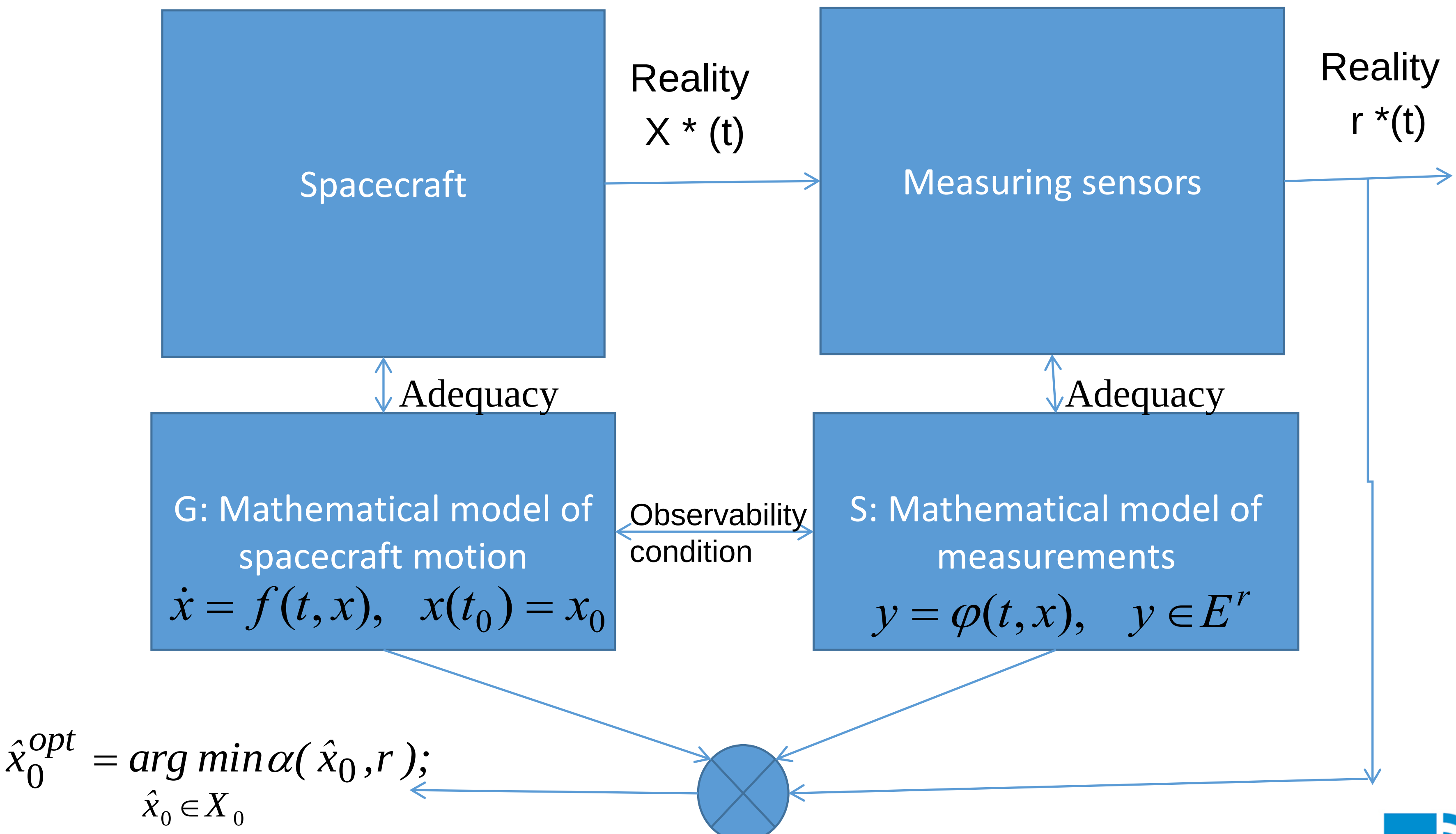
ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru



$$\hat{x}_0^{opt} = \arg\min_{\hat{x}_0 \in X_0} \alpha(\hat{x}_0, r);$$

ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

Scheme of navigation task



ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

3. The most popular methods of space navigation

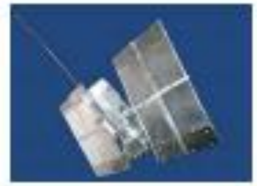
- 3.1 Satellite radio navigation
- 3.2 Inertial navigation

3.1 SATELLITE NAVIGATION SYSTEMS

Four satellite navigation systems have been designed to give three dimensional position, velocity and time data almost anywhere in the world with an accuracy of a few meters:

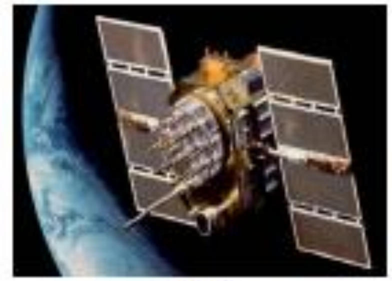
- The Global Positioning System – GPS (USA),
- The Global Navigation Satellite System – GLONASS (Russia),
- GALILEO (European Union) (under deployment),
- BEIDOW (China).

Exist regional satellite radio navigational systems, for example QZSS (Japan), IRNSS (India)



GLONASS

GALILEO



GPS

2. Satellites know their precise positions from data sent to them from the system controllers.

1. Each satellite has very accurate atomic clocks.

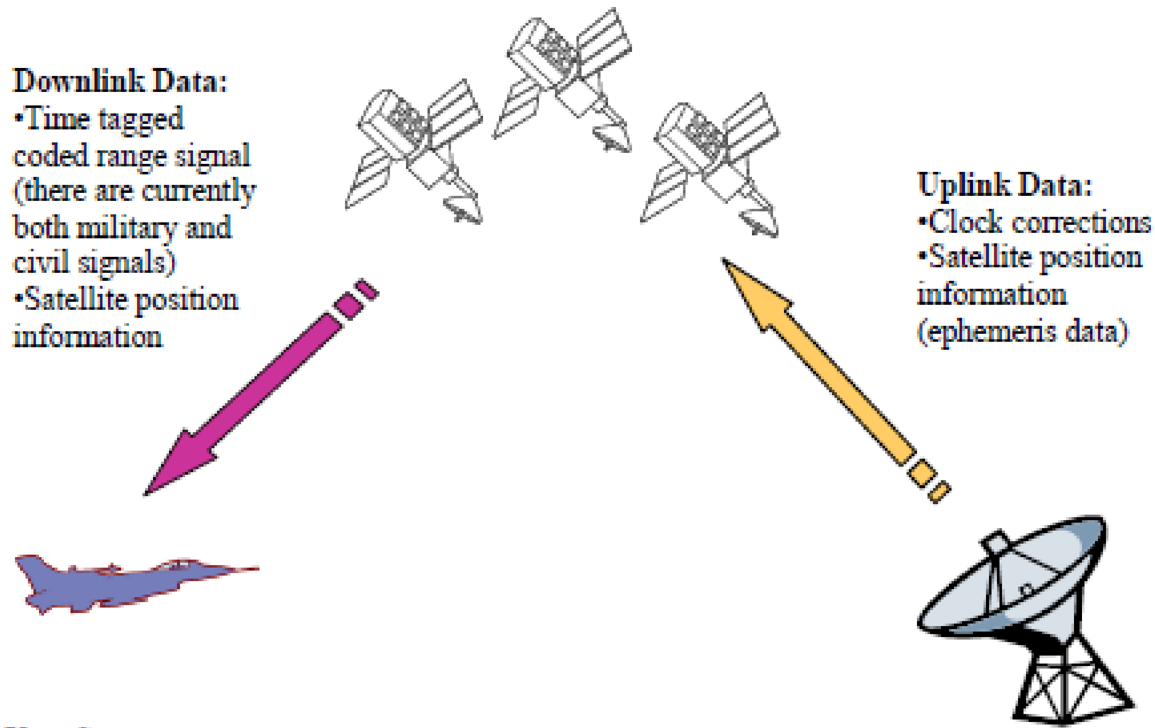
3. Each satellite broadcasts its position and time signal.

4. The signals travel to the receiver delayed by the distance travelled from the satellite to the user recever.

6. For 3-D position and time data the receiver needs to track a minimum of four satellites.

5. The receiver calculates the range to each satellite (from the time signal) and then calculates its own position.

Space Segment:
Constellation of nominal 24 satellites in six orbital planes around the earth (20200km altitude, each plane inclined at 55°). Each satellite is equipped with very precise atomic clocks.



User Segment:
GPS receivers detect, decode, and process the GPS satellite signals to calculate position.

Control Segment:
The ground control segment consists of antenna stations that track and monitor the GPS satellites. It computes and uploads corrections to the satellite constellation.

Space Segment

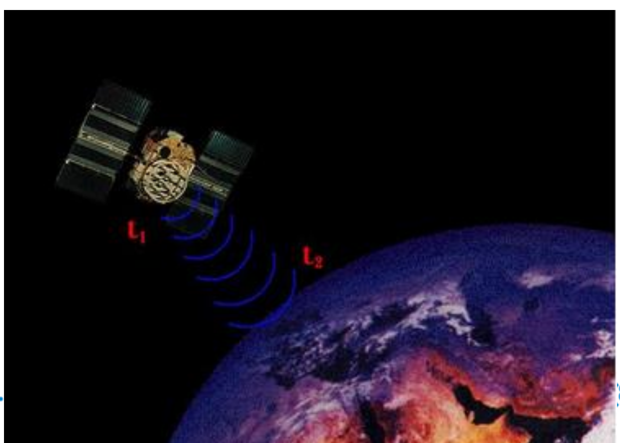
SRNS	GLONASS	GPS
The SV number in each plane	8	4
The number of orbit planes	3	6
The orbit inclination	64,8 °	55°
Orbital period	11 h 16 min	11 h 58 min
Orbital altitude	19100 km	20150 km

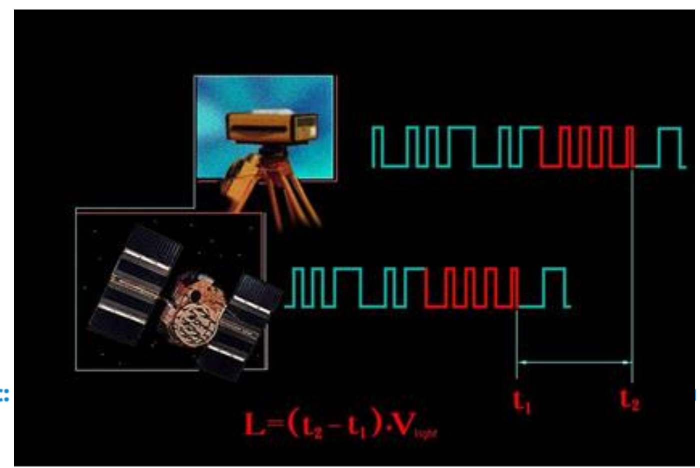
The basic idea: distances and speeds of their change between visible satellites and the receiver of signals are measured

Position is derived by computing the distance, or range, of the receiver from each satellite, by measuring the time taken for a radio signal transmitted from the satellite to travel to the receiver.

In order to make precise distance measurements, the accurate time tagging of the satellite signal is essential – this is achieved with the utilization of atomic clocks on each satellite, which are very expensive.

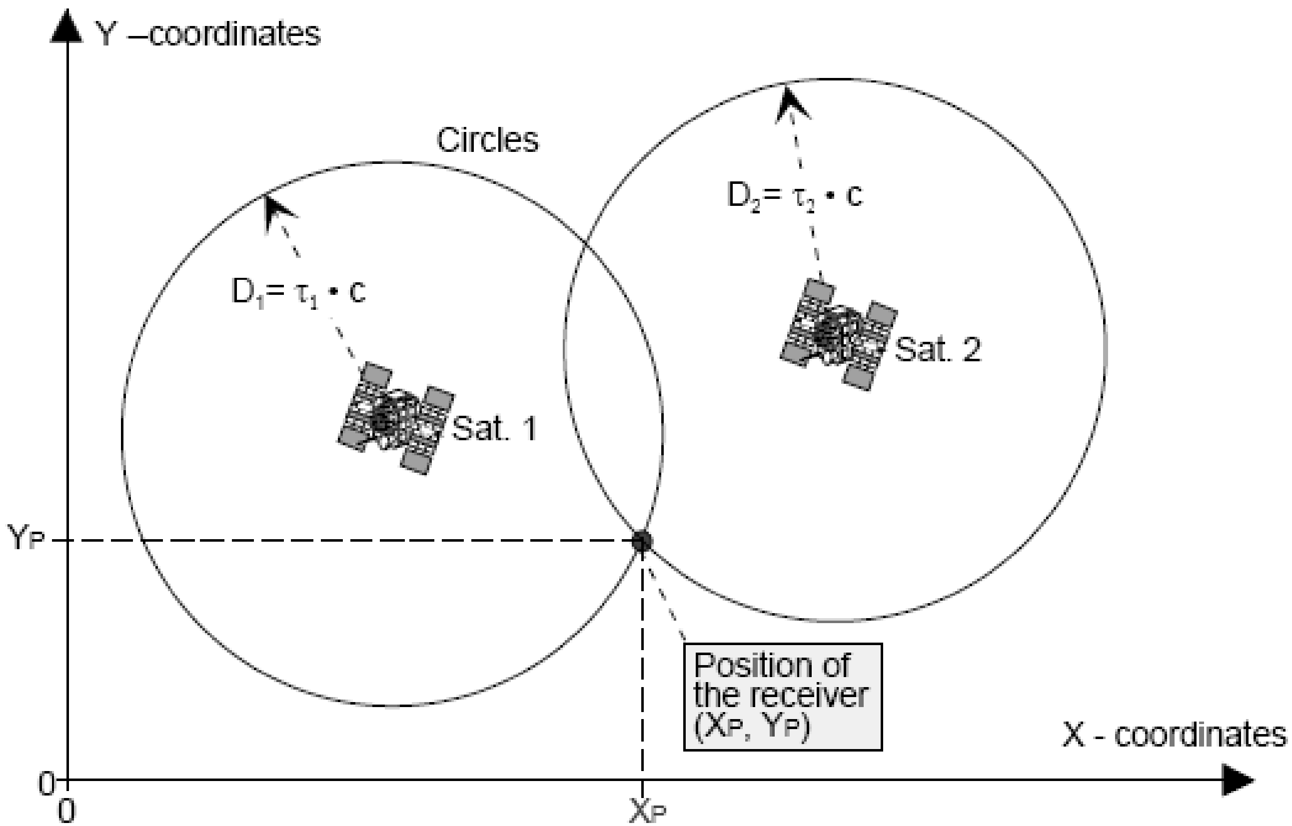
The clock used in the receiver is of lower cost and accuracy.



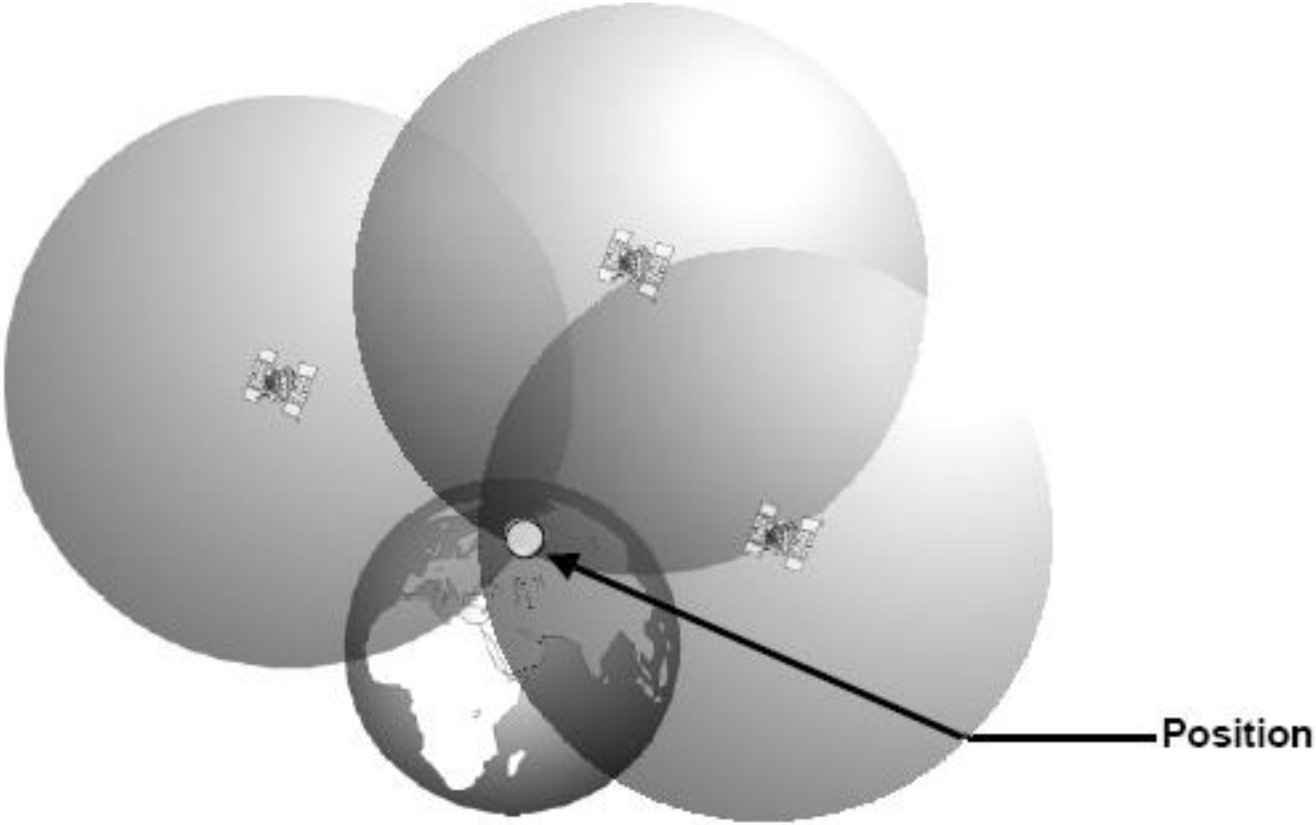


ул. … (846) 335-18-26, факс:

2D - satellite navigation



3D – satellite navigation



Measurement of range to at least four satellites is required to determine four unknowns parameters:

- three spatial co-ordinates (latitude, longitude, altitude),
- time.

By using the Doppler shift of the satellite signal, the range rate to each satellite can be computed in the receiver. It can be used to determine the vehicle's velocity.

• Measurement model

$$\begin{cases} D = \sqrt{(x - x_{NS})^2 - (y - y_{NS})^2 - (z - z_{NS})^2} \\ \dot{D} = \dfrac{1}{D}\left[(V_x - V_{xNS})(x - x_{NS}) + (V_y - V_{yNS'})(y - y_{NS}) + (V_z - V_{zNS})(z - z_{NS}) \right] \end{cases}$$

Errors budget:

- mistakes in satellites ephemerides,
- atmospheric delays of a signal,
- instability of the onboard standard clock and the standard of frequency generator,
- noise of the receiver

Advantages of satellite radionavigation

- Global coverage.
- Coordinates in Absolute Reference Frame.
- High accuracy (position to several meters, velocity to 0.1m/s, time to 0.1 millionth of a second).
- No error growth with time.
- Low cost receiver.

Disadvantages

- Not self-contained (dependent on external signals).
- Accuracy of position depend on geometry of visible constellation of navigating satellites
- May be discontinuities when antennas will be blocked by constructions/buildings/terrain
- Received satellite signals are very weak and therefore vulnerable to jamming.
- No real-time integrity

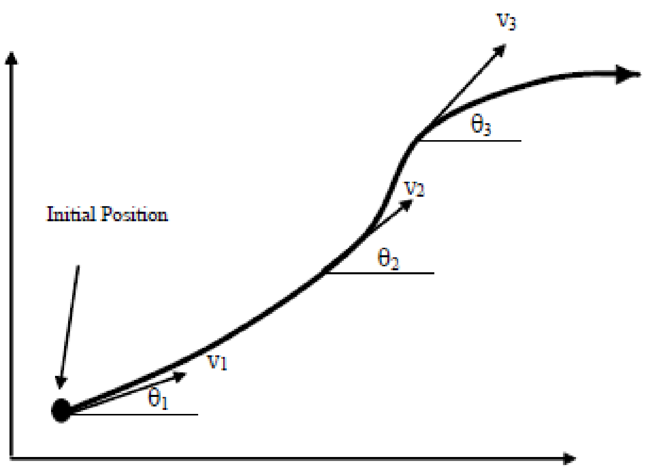
3.2 Inertial navigation

The basic idea: definition of position in space by means of integration measured accelerations

The basic sensors within an inertial navigation system are accelerometers (to measure linear motions) and gyroscopes (to measure rotational motion).

The budget of mistakes:

- mistakes of acceleration measurements,
- mistakes from discrepancy of axes of measurements with axes of the connected system of coordinates,
- mistakes of integration,
- a mistake of the using model of the Earth gravitational field



Among dead-reckoning systems, Inertial Navigation Systems (INS) are the most complex. They continuously measure linear motions (*vi)* and rotations (θ*i*), using on board accelerometers and gyroscopes respectively. Starting from a known position provided by the user or another system, the computer then computes the path followed, as depicted in the sketch below. In this process the velocity and attitude of the vehicle are also provided continuously.

The basic sensors of an INS are configured in either two ways:

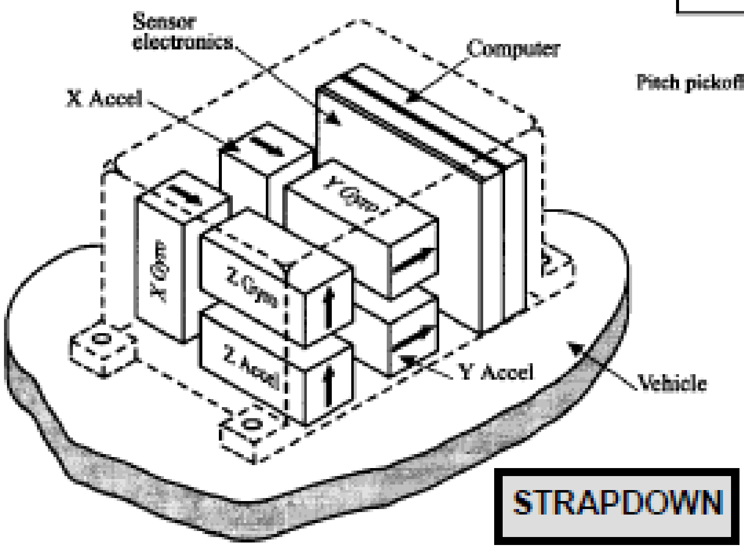
- Isolated from the vehicle rotations on served gimbals (“gimballed”),
- Mounted directly to the vehicle (“strapdown”).

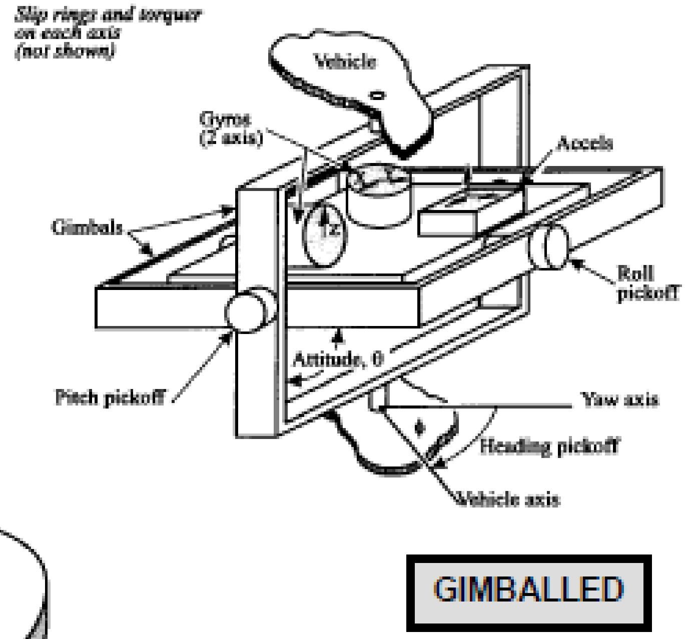
- Gimballed systems were the first to be developed and the most accurate systems today are still gimballed systems.

  The 3 accelerometers and 3 gyroscopes mechanical assembly is physically stabilized relatively the navigation reference frame. However their mechanical complexity and cost makes their use prohibitive in the large majority of applications.

- Strapdown systems appeared in the mid 70’s when the computation power on board became sufficient to compute a virtual reference frame in real-time.

  Strapdown systems are typically more reliable and lower cost than gimballed systems.


Sensor electronics
Computer
X Accel
Y Gyro
X Gyro
Z Gyro
Z Accel
Y Accel
Vehicle
STRAPDOWN


Slip rings and torquer on each axis (not shown)
Vehicle
Gyros (2 axis)
Accels
Gimbals
Roll pickoff
Attitude, θ
Pitch pickoff
Yaw axis
Heading pickoff
Vehicle axis
GIMBALLED

Accelerometers delete into two main categories:

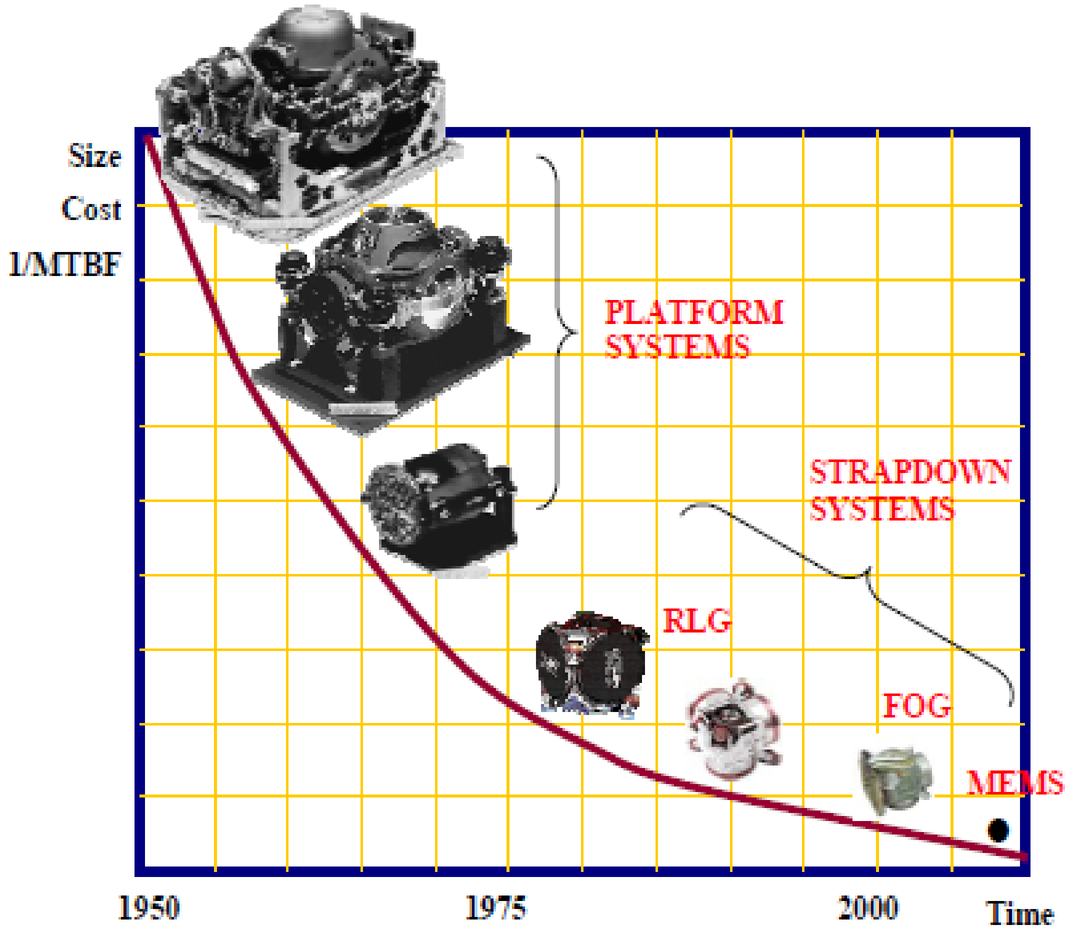
- force feedback or pendulous rebalanced accelerometers,
- vibrating beam accelerometers.

Gyroscopes are more diverse:

- Earlier designs consisted of metal wheels spinning in ball or gas bearings;
- Optical gyros were developed later and have counter-rotating laser beams either in an evacuated cavity (RLG: Ring Laser Gyro) or in an optical fiber (FOG: Fiber Optic Gyro);
- Other designs use resonators of different shapes (bars, cylinders, rings, hemispheres) and are known under the generic name of Coriolis vibrating gyros.

These sensors are generally moving from older construction methods consisting of assembling a great number of mechanical parts, to modern automatic mass production techniques. Currently the most advanced such technique uses Micro-Electro-Mechanical Systems (MEMS) technology, enabling true solid state sensors. MEMS offers the promise of a complete sensor and supporting electronics on a single integrated circuit chip. The basic materials often used by this technology are silicon or quartz.

Changes in Inertial Systems



Changes in technology and manufacturing process are the key factors to:

- Reduced cost,
- Improved reliability (higher Mean Time Between Failure),
- Reduced size

ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

Advantages INS

- Self contained – no external infrastructure required.
- Continuous information, including attitude.
- Available anywhere in any environment.
- Robust to jamming.

Disadvantages

- Accuracy degrades with time (unbounded error).
- Need for initial position parameters.
- Accurate systems are expensive.

INTEGRATED NAVIGATION CONCEPT

Not a single navigation system or sensor technology satisfies the whole range of technical, operational and cost requirements.

However, by combining several technologies, an integrated system can be formed that has superior performance and costs characteristics.

Such systems are called **Integrated Navigation Systems** (e.g., **INS/SRNS system**).

Since GPS and INS outputs and error characteristics are complementary to each other, integration of these sensors benefits both sensor systems resulting in a much better total navigation system

Since GPS and INS outputs and error characteristics are complementary to each other, integration of these sensors benefits both sensor systems resulting in a much better total navigation system.

INS

- Errors grow with time
- Needs initialization
- Continuous position and attitude output
- Low noise
- High bandwidth
- Self contained

GPS

- Bounded errors
- Self starting
- Slower output rate and limited attitude output
- Higher noise
- Lower bandwidth
- Dependent on external systems (satellites)

Benefits

INS

- Bounded errors
- On the move initialization
- Automatic sensor calibration

GPS

- Continuous output
- Improved resistance to jamming
- Improved dynamic performance
- Faster satellite re-acquisition

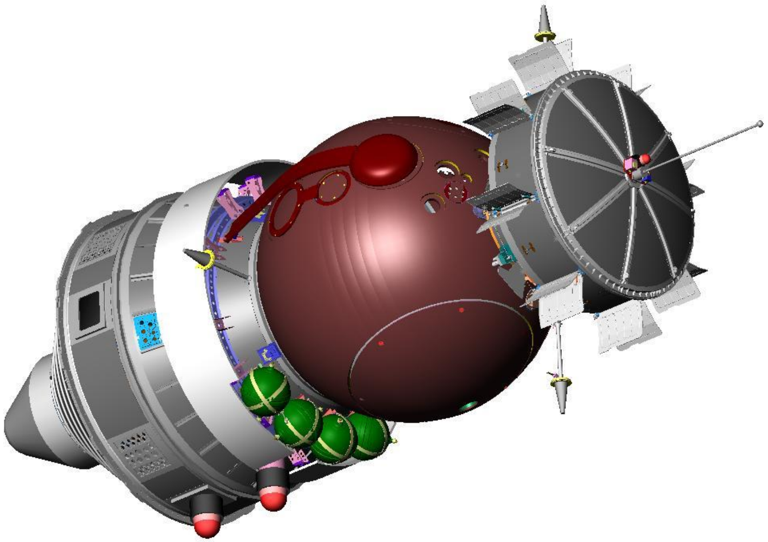
Satellite radio navigational technologies are basic tools for monitoring of geophysical fields (MGF)

- Upper atmosphere field – short-term variation of atmosphere density
- Ionosphere field – electronic concentration of ionosphere
- Earth observation - passive radiolocation via reflecting of GLONASS/GPS signals from Earth surface

ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

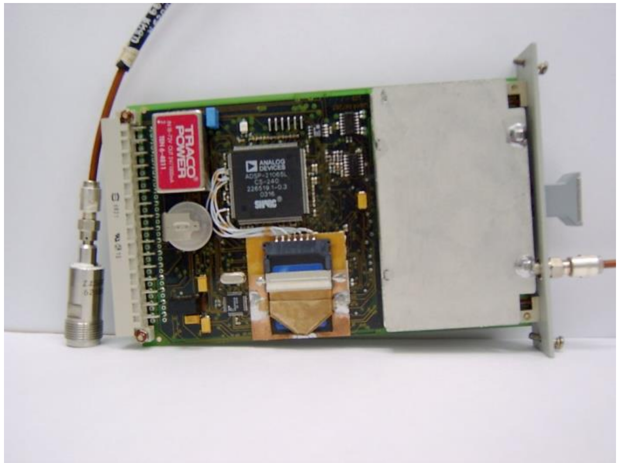
Navigation experiments on SV “Foton-M2”

SV Foton-M2 mission (2005)



Full mass – 6540 kg
Mass of recoverable payload – 650 kg
Daily average energy consumption – up to 800 W
Orbital parameters – 262 km x 304 km
Orbital lifetime – 16 days
Launch-vehicle – Soyuz
Launch site - Baikonur

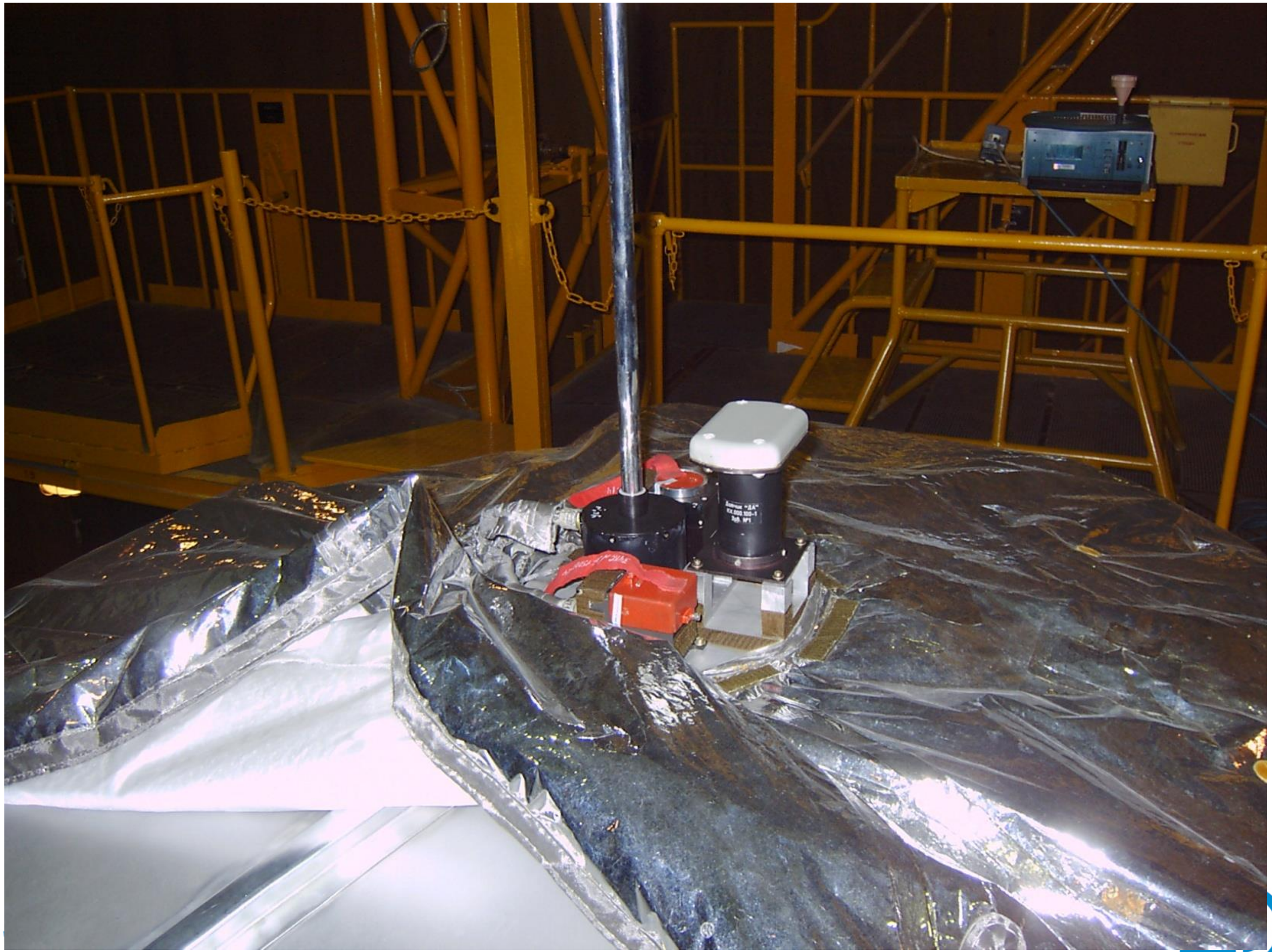
MIRAGE-M equipment: structure and characteristics



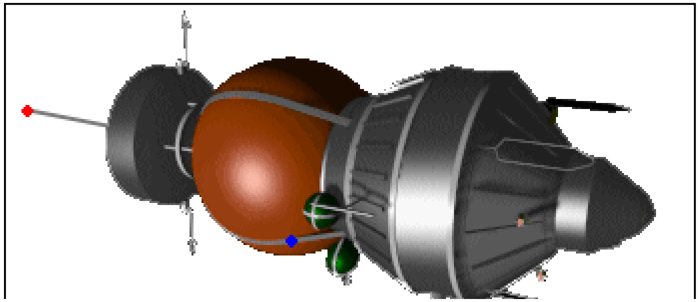
ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

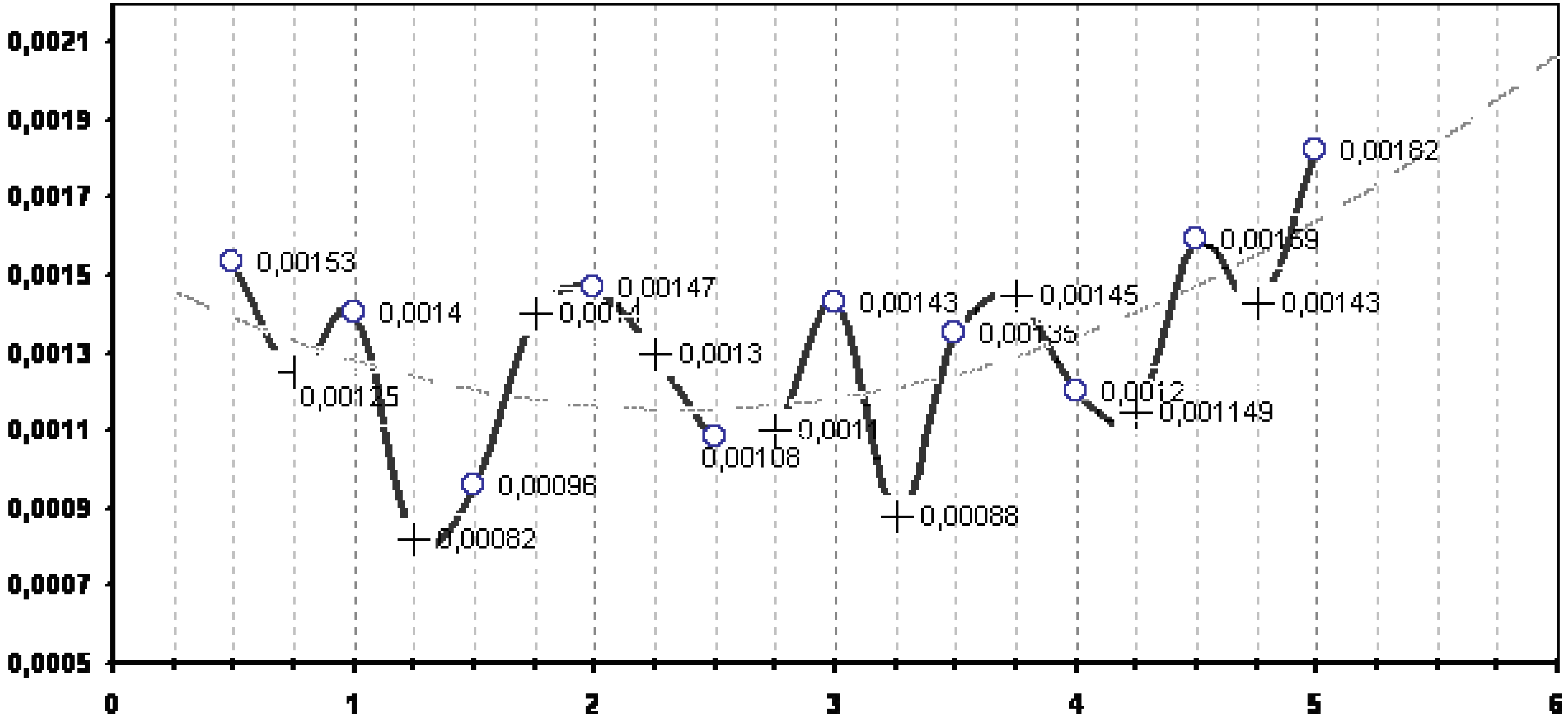
Experiment “NAVIGATOR”

Accommodation of antenna navigational receiver



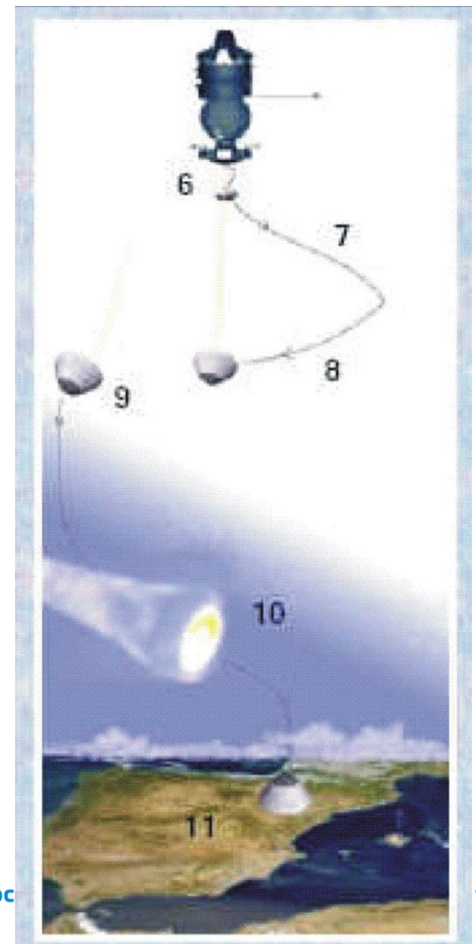
The results of experiment on spacecraft «Foton–M2»

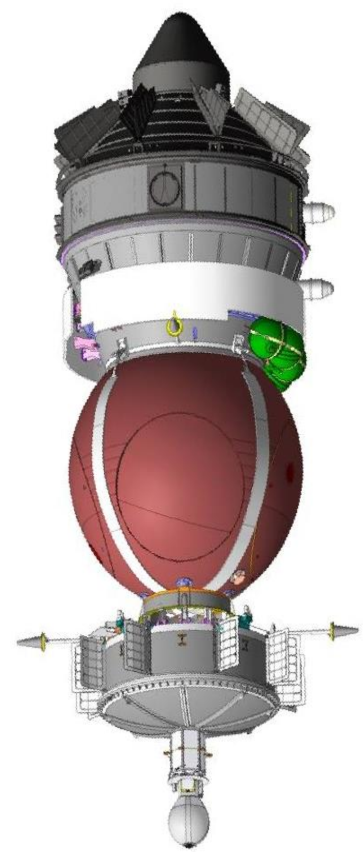




ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

Problems of navigational tracking of tether system deployment by an example of the experiment YES2

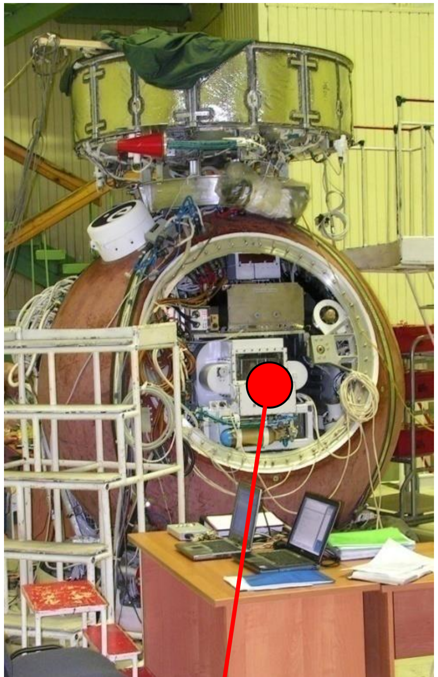




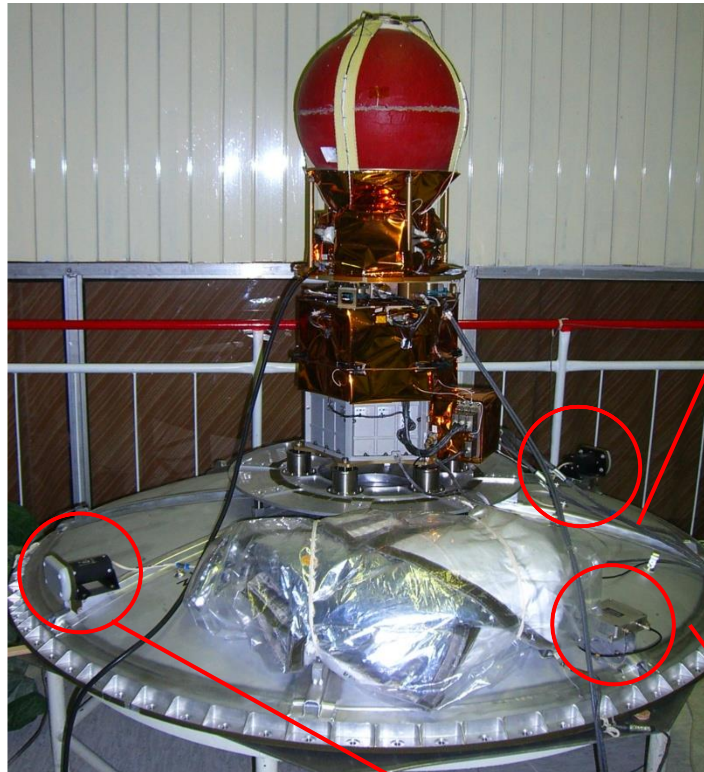
Goals of Samara University navigational experiment

- - testing of navigational tracking instrumentation;
- - improvement of technology of solving of navigational tasks with usage of two antennas;
- - research of influence of tether system on spacecraft Foton-M3 motion;
- - improvement of technology of restore of disturbance forces acting on spacecraft Foton-M3 by means of data processing from navigational receiver.

The description of auxiliary instrumentation SSAU-YES2



Electronic unit



Navigating antenna

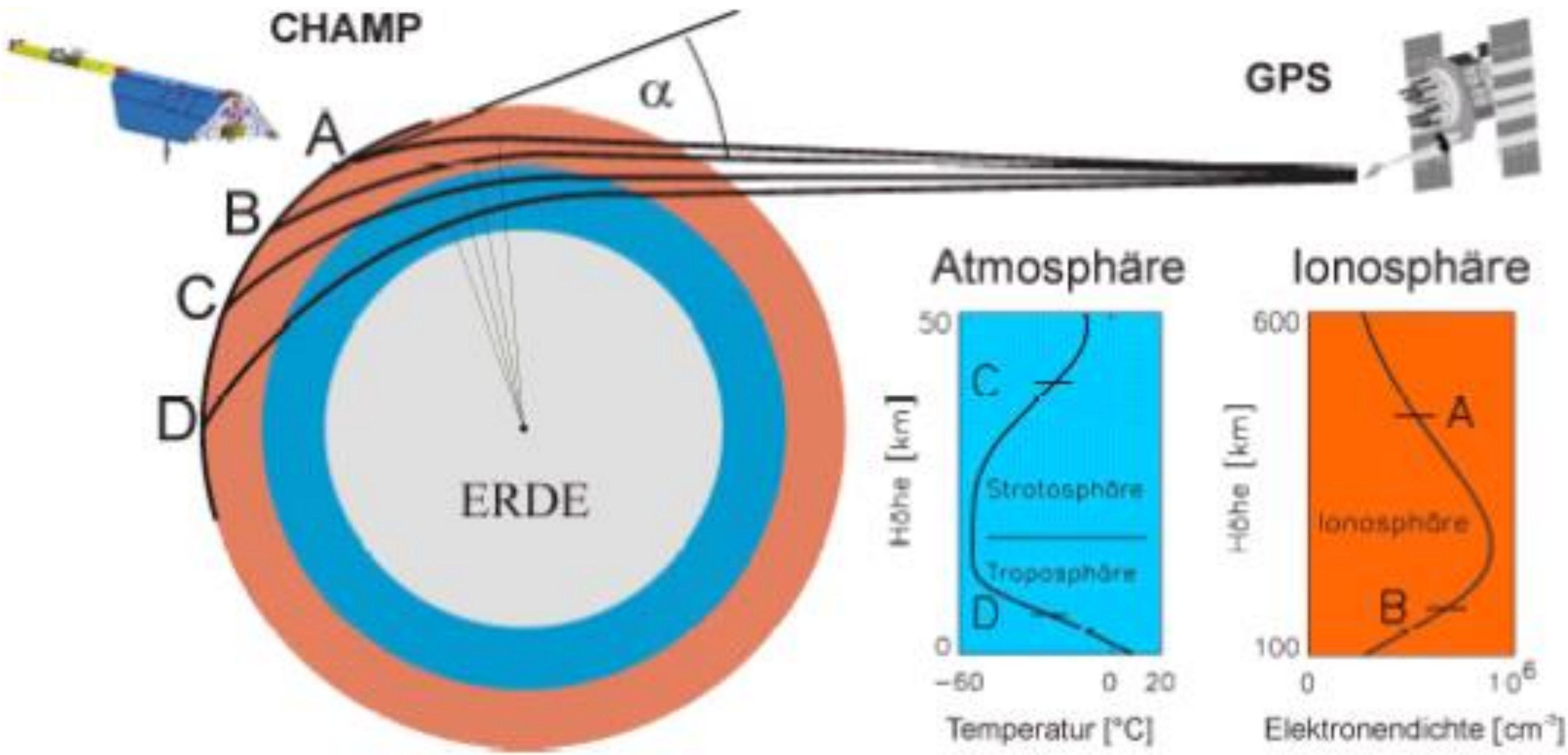
Navigating antenna

Summator of navigating signals

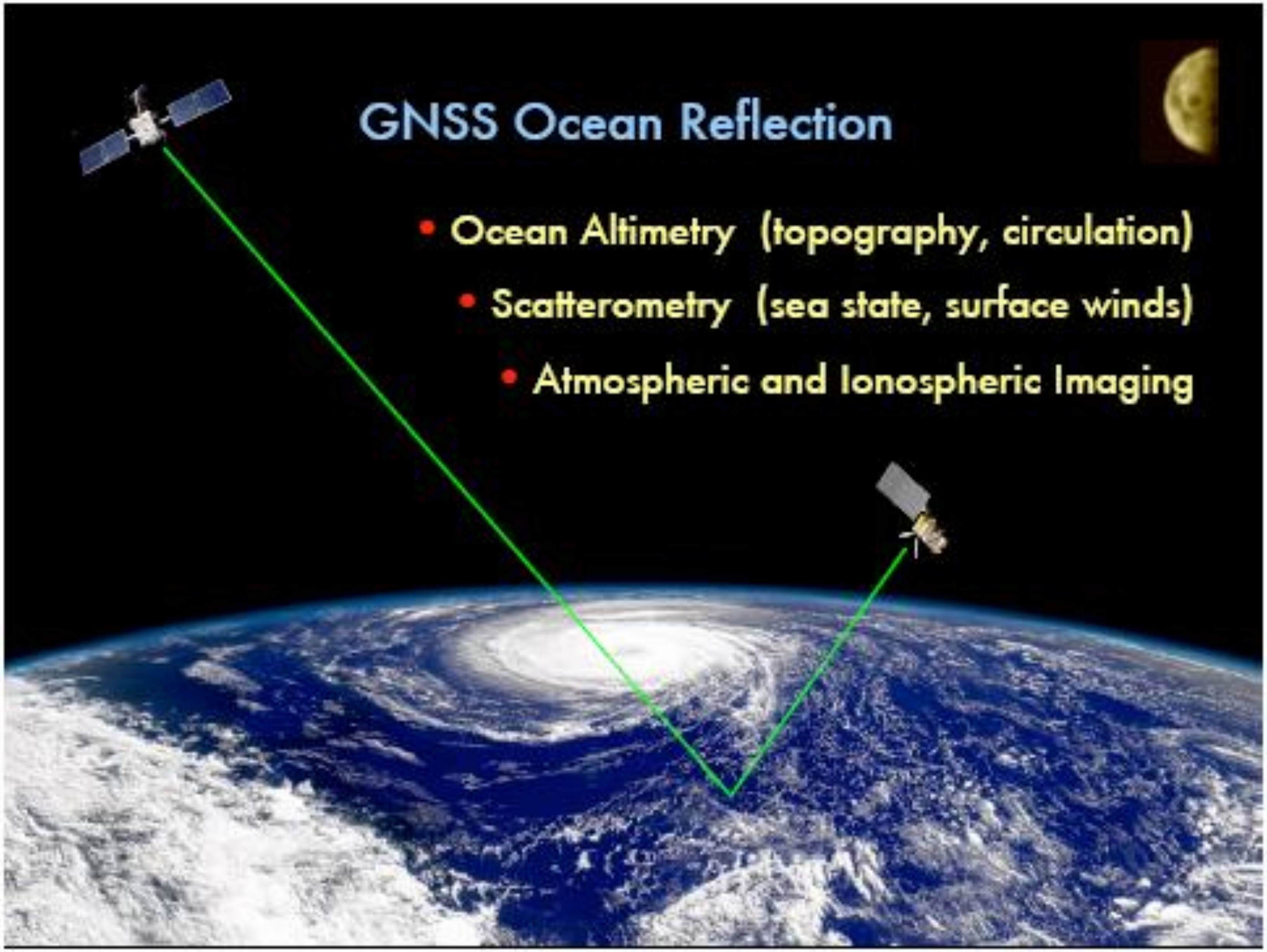
ул. Мос… г.Самара, 443086, тел.: +7 (846) 3… 35-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

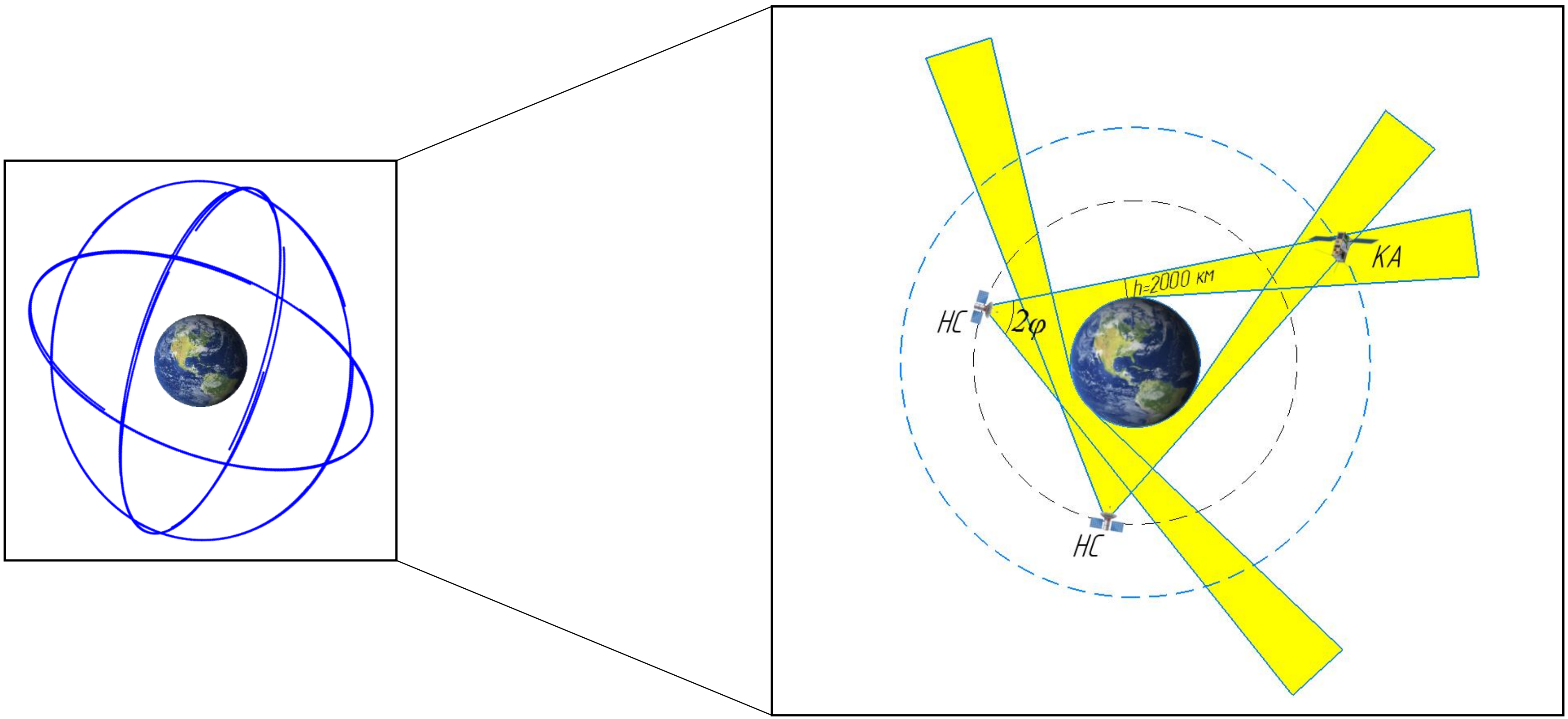
Satellite radio navigation as the method for research of geophysical fields

1. Navigational receiver can use as sensor for monitoring of geophysical fields

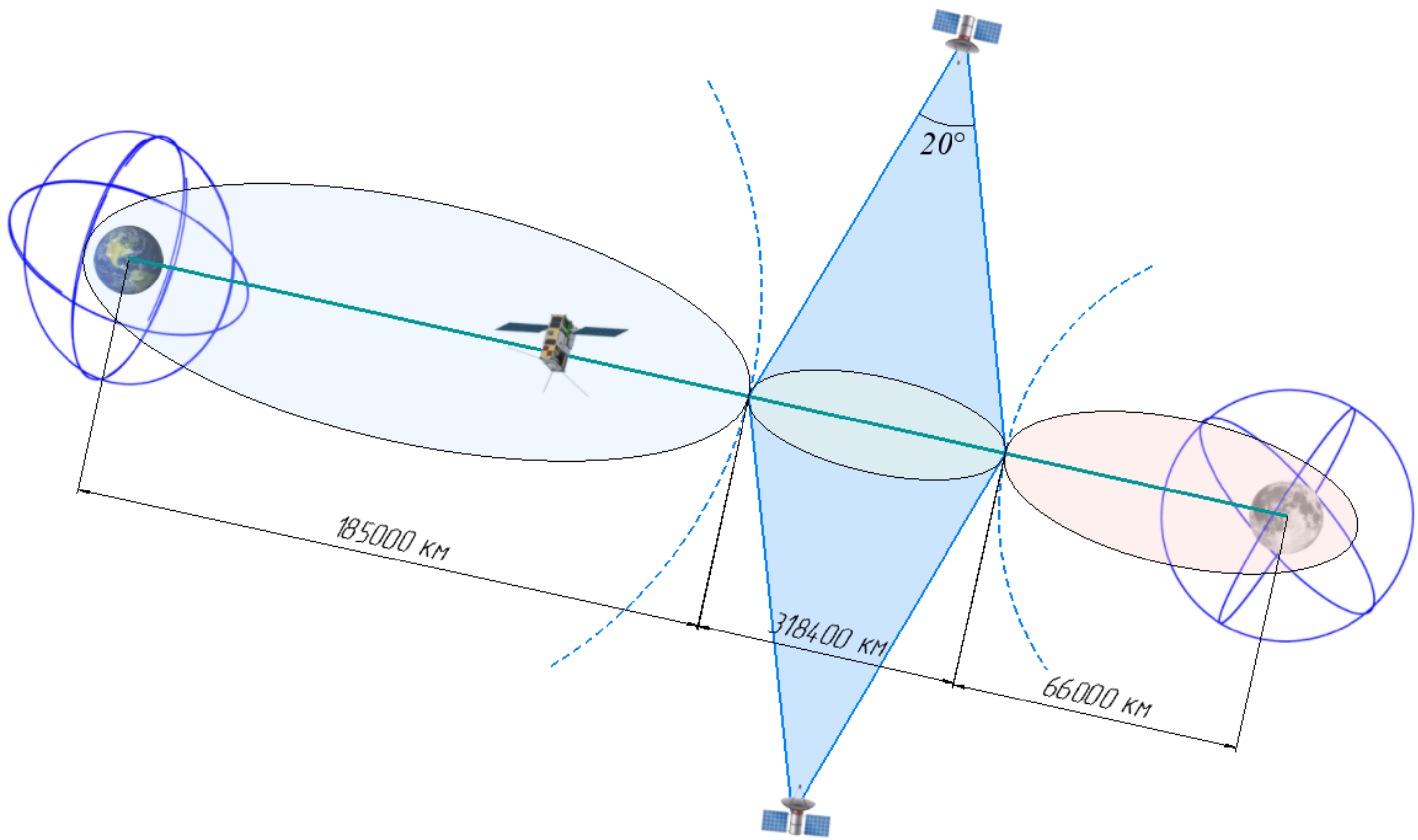


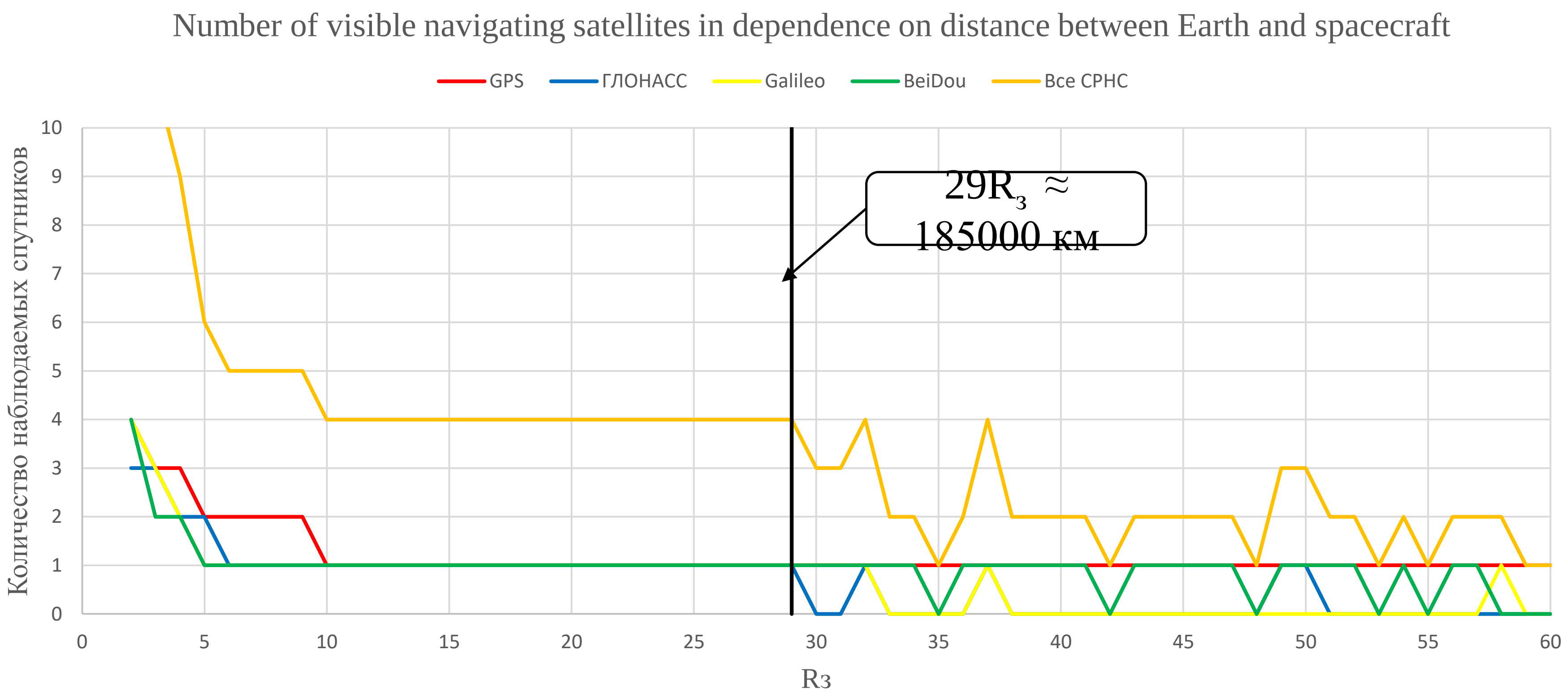
2. Navigational receiver can use for Earth radiolocation





ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

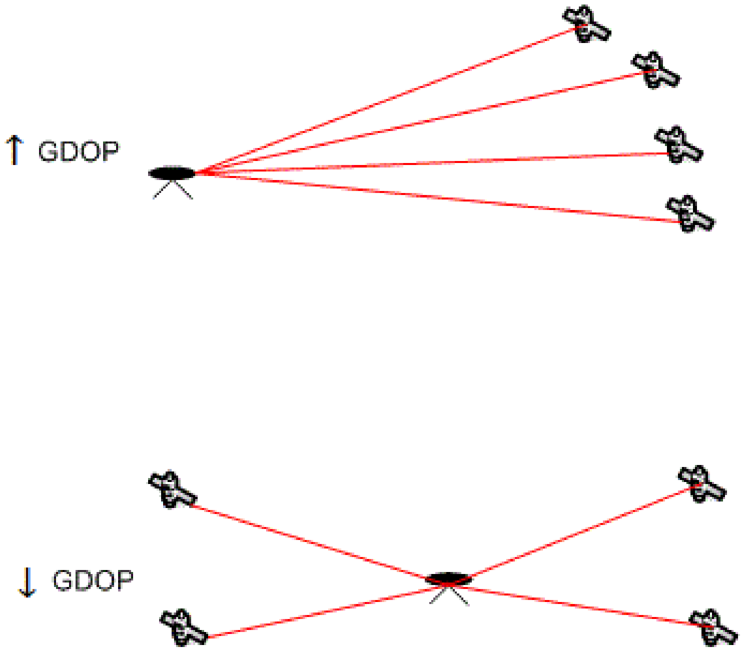

20°
185000 км
318400 км
66000 км

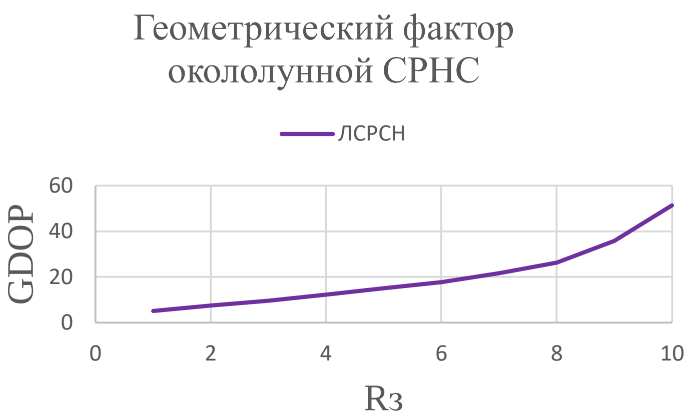


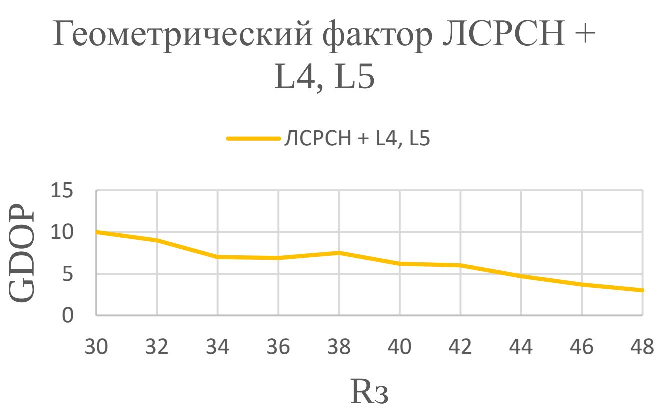
ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru

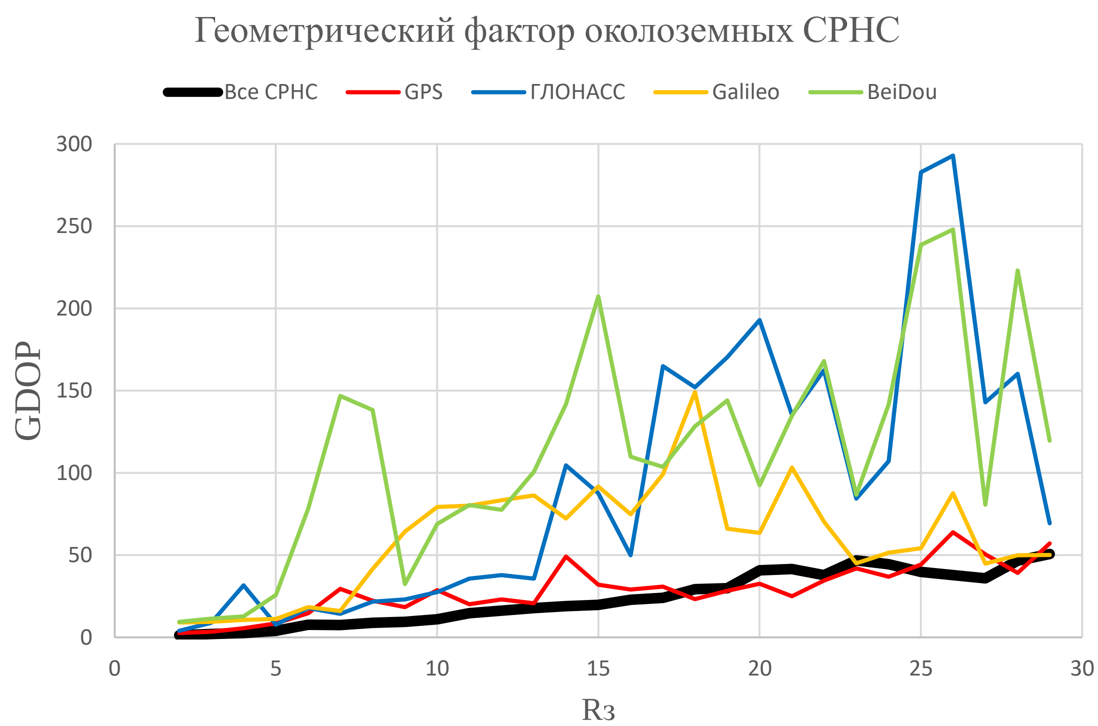
GDOP – this is the coefficient of deterioration of the accuracy of determining the spatial coordinates and velocity in comparison with the accuracy of measuring the range and its first derivative

$$D_1 = \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}$$
$$D_2 = \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2}$$
$$D_3 = \sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2}$$
$$A = \begin{bmatrix} \frac{\partial D_1}{\partial x} & \frac{\partial D_1}{\partial y} & \frac{\partial D_1}{\partial z} \\ \frac{\partial D_2}{\partial x} & \frac{\partial D_2}{\partial y} & \frac{\partial D_2}{\partial z} \\ \frac{\partial D_3}{\partial x} & \frac{\partial D_3}{\partial y} & \frac{\partial D_3}{\partial z} \\ \dots & \dots & \dots \end{bmatrix}$$
$$GDOP = \sqrt{Sp[(A^T \times A)^{-1}]}$$




Геометрический фактор окололунной СРНС
ЛСРСН
GDOP
60
40
20
0
0
2
4
6
8
10
Rз


Геометрический фактор ЛСРСН + L4, L5
ЛСРСН + L4, L5
GDOP
15
10
5
0
30
32
34
36
38
40
42
44
46
48
Rз


Геометрический фактор околоземных СРНС
Все СРНС
GPS
ГЛОНАСС
Galileo
BeiDou
GDOP
300
250
200
150
100
50
0
0
5
10
15
20
25
30
Rз

Thank you for attention

ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru