

# User Manual

Version V1.0-20170609

## Interface Control Document

For INS-T Inertial Navigation System

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## 1. INTRODUCTION

### 1.1. Description of the System

The **Tersus Inertial Navigation System, INS** is high-performance GPS-aided strapdown system that calculates absolute orientation (heading, pitch and roll) and position (latitude, longitude, altitude) for any device on which it is mounted. Orientation and position are determined with high accuracy for both motionless and dynamic applications.

The Tersus INS utilizes 3-axes each of precision accelerometers, magnetometers and gyroscopes to provide accurate heading, pitch and roll of the device under measure. Integration of gyroscopes' output provides high frequency, real-time measurement of the device rotation about all three rotational axes. Accelerometers and Fluxgate magnetometer measure absolute Pitch, Roll and magnetic Azimuth at INS initial alignment as well as providing ongoing corrections to gyroscopes during operation.

The Tersus INS has an onboard high-grade Global Navigation Satellite System (GNSS) receiver, which provides high accurate position using the next GNSS systems:

- GPS L1, L2;
- GLONASS L1;
- BeiDou B1, B3;

Tersus provides three models of INS products:

- INS-B (Basic model) – uses MEMS grade magnetometers, high grade IMU and high grade single antenna GNSS receiver;
- INS-P (Professional model) – uses high-grade Fluxgate magnetometers, high grade IMU and high grade single antenna GNSS receiver;
- INS-D (Dual antenna model) – uses high grade IMU, dual-antenna GNSS receiver and measures static and dynamic Heading, independent on magnetic field disturbance.

For INS operations it is necessary to connect one (for INS-B, INS-P) or two (for INS-D) active antennas to the TNC connector(s) on the back side of the Tersus INS (see Fig.1.1, Fig.1.2).



**Fig.1.1. Tersus INS-B and INS-P**



**Fig.1.2. Tersus INS-D**

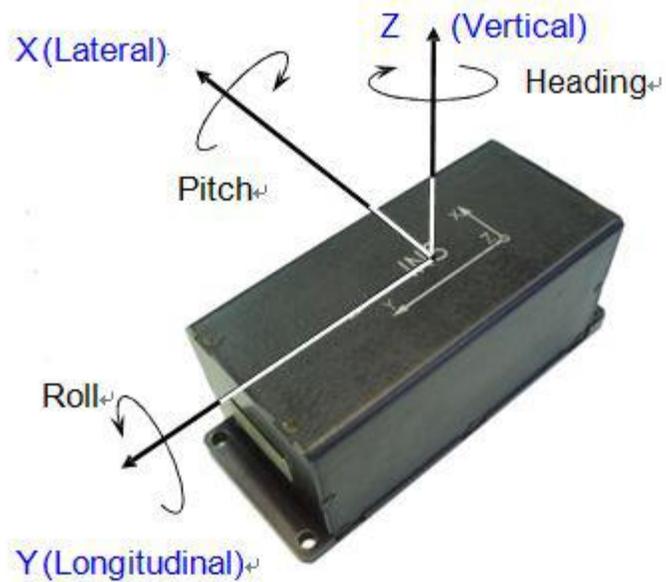
Fig.1.3 shows the INS own coordinate system  $Ox_0y_0z_0$ . This coordinate system is body-fixed and defined as the calibrated sensors coordinate system. Non-orthogonality between axes of the body-fixed coordinate system  $Ox_0y_0z_0$  is an order of  $0.01^\circ$ .

Measured angles are the standard Euler angles of rotation from the Earth-level frame (East-North-Up) to the body frame, heading first, then pitch, and then roll.

Orientation angles, measured by the Tersus INS, are not limited and are within common ranges:

- Heading  $0...360^\circ$ ;
- Pitch  $\pm 90^\circ$ ;
- Roll  $\pm 180^\circ$ .

Also the Tersus INS provides orientation calculation in quaternion form. See "APPENDIX D. Forms of the Tersus INS orientation presentation".



**Fig.1.3. Coordinate system of the Tersus INS**

At its operation the Tersus INS calculates position and linear velocity using its gyros and accelerometers data with correction from the onboard GNSS receiver. For altitude calculation the INS also uses correction from the onboard pressure sensor.

The Tersus INS calculates position for the center of the INS unit.

## 1.2. Principles of the Tersus INS Operation

Fig.2.1 shows the operational diagram of the Tersus INS. The INS uses gyros to measure absolute angular rate of the carrier object, accelerometers to measure the specific force (apparent acceleration of the object), magnetometers to measure components of the Earth magnetic field.

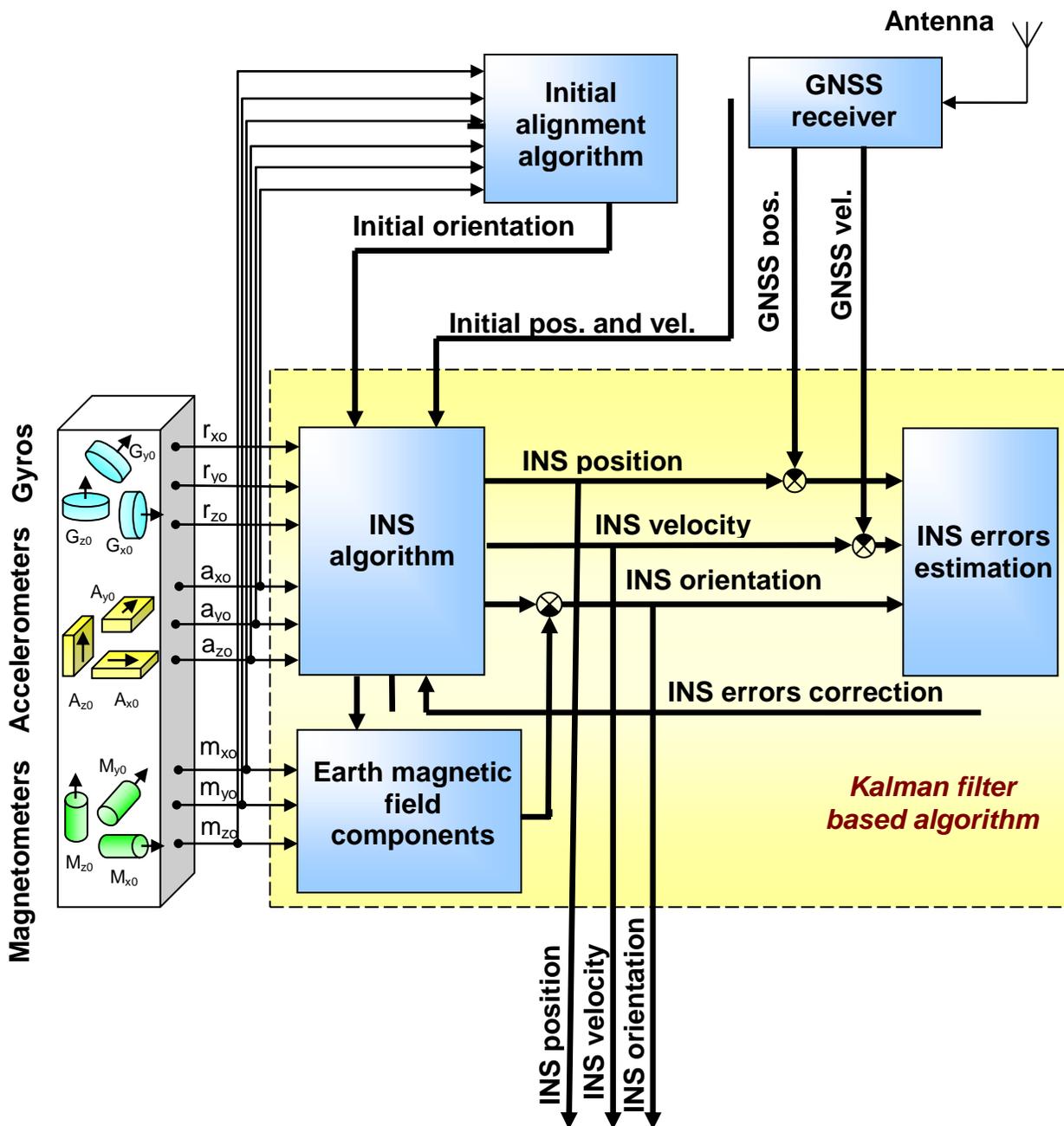


Fig.2.1. Operational Diagram of the Tersus INS

Orientation angles (heading, pitch and roll) are obtained by using special integration of gyros outputs with correction from GNSS position and velocity data.. INS-D also utilises gyros correction by heading calculated as direction between two GNSS antennas.

Position (latitude, longitude and altitude) are calculated using special integration of accelerometers and known orientation. To avoid accumulation of the INS error they are estimated and compensated using Global Navigation Satellite System (GNSS) data provided by onboard receiver and pressure sensor data.

Also accelerometers are used to determine initial attitude of the INS, and magnetometers are used to determine initial heading. In INS-D unit initial heading is calculated as direction between two antennas if GNSS data are available and RTK solution for heading is made by on-board GNSS receiver.

The base of the INS algorithm is robust Kalman filter which is used for estimation of the INS errors in orientation, position, velocity calculation and also gyros and accelerometers biases. For this purpose the Kalman filter uses aiding information from GNSS about position and velocity, and also barometric altitude calculated from pressure sensor data.

As result of integration of all above data, the INS provides accurate calculation of stabilized heading, pitch and roll angles, latitude, longitude and altitude, east, north and vertical velocity. The Kalman filter automatically adjusts for changing of dynamic conditions.

Note the initial position and velocity are provided by the GNSS receiver if it has solution. If GNSS data are not available then the initial position are taken from the INS nonvolatile memory. There the initial position can be changed using the LoadINSpar command (see Table 6.22, bytes #8-19) or using the INS Demo Program (that is more easy)

After the Tersus INS power on an initialisation of the o-nboard GNSS receiver starts that takes about 25 seconds. Then the INS is ready to receive commands from the host computer and to start required operation.

After start the Tersus INS it requires about 30 seconds for initial alignment process. At this initial orientation angles are determined as initial conditions for integration of gyros outputs. Also gyros bias is estimated using Kalman

filter for next compensation. Therefore don't move the INS during initial alignment process. If this requirement is not met then large errors may be occurred in orientation angles calculation.

Features of INS algorithm and possibilities of their adjustment are described in the INS Demo User's Manual, Rev.2.0 and higher, section "4.3.1. "Settings" tab of «Correction options...» window".

### **1.3. True and magnetic heading**

As the Tersus INS uses magnetic sensors for heading reference, then it directly determines just magnetic heading. Then INS calculates true North heading using the current magnetic declination. Declination, also called magnetic variation, is the difference between true and magnetic North, relative to a point on the Earth. Declination angle vary throughout the world, and changes slowly over time. Magnetic declination angle can be entered directly to the Tersus INS memory using special command (see Table 6.22, bytes #4-7) or the Tersus INS Demo Program. Also, the magnetic declination can be calculated by INS itself based on calculated latitude, longitude, altitude and date.

Both INS unit onboard and INS Demo Program calculate the magnetic declination using the World Magnetic Model WMM2015 produced by the U.S. National Geophysical Data Center and the British Geological Survey, <http://www.ngdc.noaa.gov/geomag/WMM/DoDWMM.shtml>

The World Magnetic Model is the standard model of the US Department of Defense, the UK Ministry of Defense, the North Atlantic Treaty Organization (NATO), and the World Hydrographic Office (WHO) navigation and attitude/heading referencing systems.

Since INS firmware version 2.2.0.2 the INS unit can calculate the magnetic declination continuously onboard if "Auto" checkbox is checked in the "IMU" tab of the «Devices Options» window in the INS Demo Program. INS outputs current magnetic declination in "INS Full Output Data" format (see Table 6.10).

Note using magnetometers for INS heading correction requires necessity of magnetometers calibration after INS unit installed on carrier object to compensate hard and soft iron effects of the carrier object on the INS

heading determination accuracy (see section “6.7. Calibration of the Tersus INS on hard and soft iron” for details).

#### **1.4. Ground track angle vs heading**

Ground track angle or the course over ground azimuth is determined using the position delta between two position computed. Track angle shows direction of vehicle motion in horizon plane.

For some carrier objects it is possible to use GNSS track angle instead of magnetic heading for INS correction. In such case magnetometers can be switched off, and INS does not require any calibration of magnetometers.

Ground track angle can be used as heading for ground vehicles where the direction of travel is coincident with the forward axis of the vehicle and the roll of the vehicle is close to zero. But replacement of heading by the ground track angle may not be suitable for some marine or airborne applications, where the direction of travel may be different from the forward axis of the vehicle because of factors like a crab angle.

Also the ground track angle has no sense when the vehicle is stationary. But integration of INS with GNSS data allows to use GNSS track angle instead of magnetic heading for INS correction even at vehicle stops. Only initial vehicle movement is required to perform calculation of initial heading in INS.

#### **1.5. Using GNSS heading in INS-D**

More accurate INS heading correction than use of magnetometers or GNSS track angle can be provided in INS-D with two antennas installed along forward axis of carrier object. In INS-D magnetometers also can be switched off, and INS does not require any calibration of magnetometers in such case.

In contrast to using GNSS track angle, heading calculated on base of two antennas position does not require vehicle movement strictly in direction of the forward axis of the vehicle, moreover, vehicle can be stationary.

## **2. SCOPE AND APPLICABILITY**

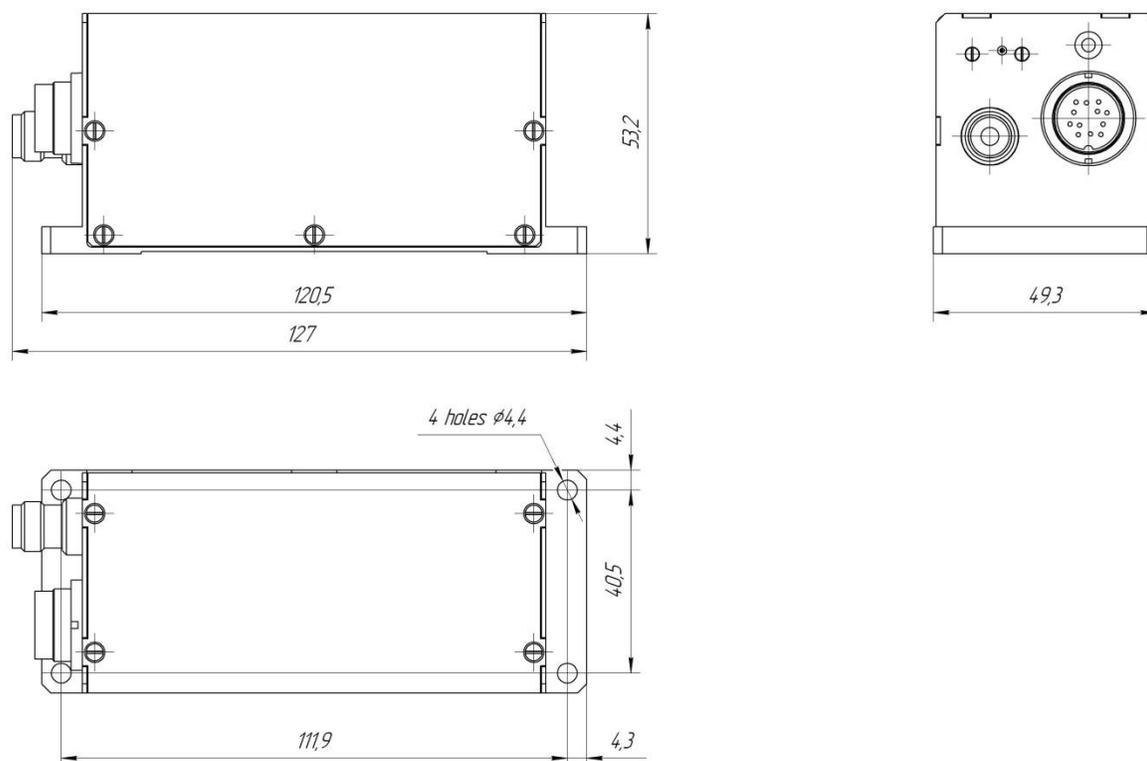
This Interface Control Document (ICD) provides details on mechanically mounting, the electrical connections, powering and software interface between the Tersus INS and host computer. This document is intended for all parties requiring such information, including engineers and researchers responsible for implementing the interface.

### 3. SPECIFICATIONS

See separate document, Tersus INS Datasheet.

### 4. MECHANICAL INTERFACE

Fig.4.1 shows the outline drawings of the Tersus INS. All dimensions are in millimetres.

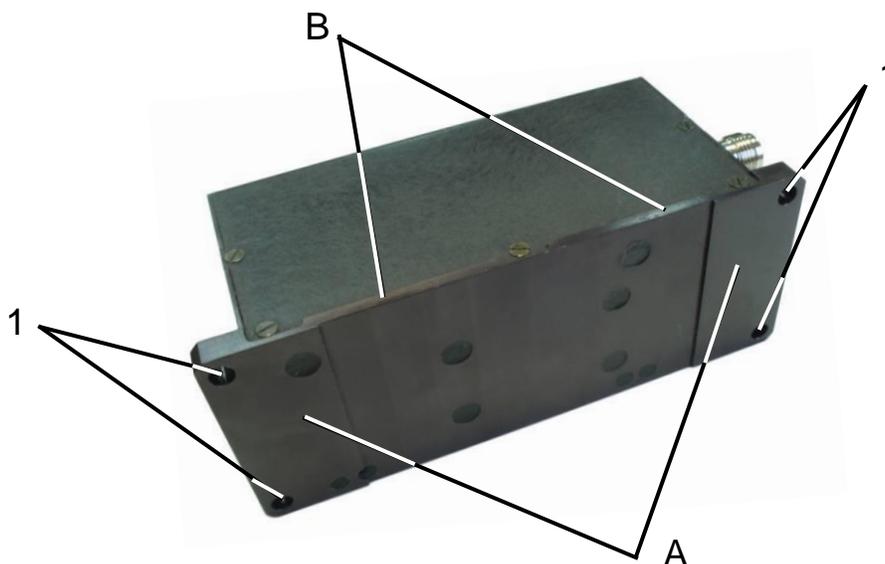


**Fig.4.1. The Tersus INS outline drawing  
(all dimensions are in millimetres)**

## 4.1. Mechanically mounting the Tersus INS

The Tersus INS housing has two base surfaces A and B (see Fig.4.2) that are designed for the INS mounting during its run and testing.

Salient bottom base surface A has 4 holes  $\varnothing 4.2$  mm (see Fig.4.2, positions 1) which are designed for the INS mounting. Lateral base surface B is designed for the INS alignment during mounting.



**Fig.4.2. INS mounting surfaces A, B and mounting holes 1, 2**

The Tersus INS is factory calibrated with respect to the base surfaces A and B, thus it must be aligned within the host system (carrier object) with respect to these mounting surface, not the device edges.

When mounting Tersus INS on your system, please pay attention to orientation of input axes "X", "Y", "Z" marked on the cover of the INS (see Fig.1.3). During the ordinary operation on the carrier object the INS is set on the surface A with the axis Y directed to the nose of the object.

Also the Tersus INS can be mounted on the object in any known position (up to upside-down, upright etc.) relative to the object axes. Such mounting doesn't change right determination of the object orientation if angles of the INS mounting are correctly stored in the INS nonvolatile memory. See Appendix B. Variants of the Tersus INS mounting relative to carrier object axes.

To obtain accurate attitude and heading, please remember that mounting is very important and mounting error can cause attitude and heading errors. When Tersus INS mounting please align it on two base surfaces A, B relative your system axes.

The Tersus INS is mounting on your system by using 4 holes  $\varnothing 4.2$  mm (see Fig.4.2, positions 1).

Requirements to the mounting surface of the carrier object: flatness tolerance is 0.03 mm; undulation is  $Ra=1.25$ .

## 4.2. Installation of single GNSS antenna

Usually the INS unit and GNSS antenna are installed in different places of the carrier object. Moreover, placement of the antenna close to the INS unit is undesirable because of the antenna impact on the INS magnetometers.

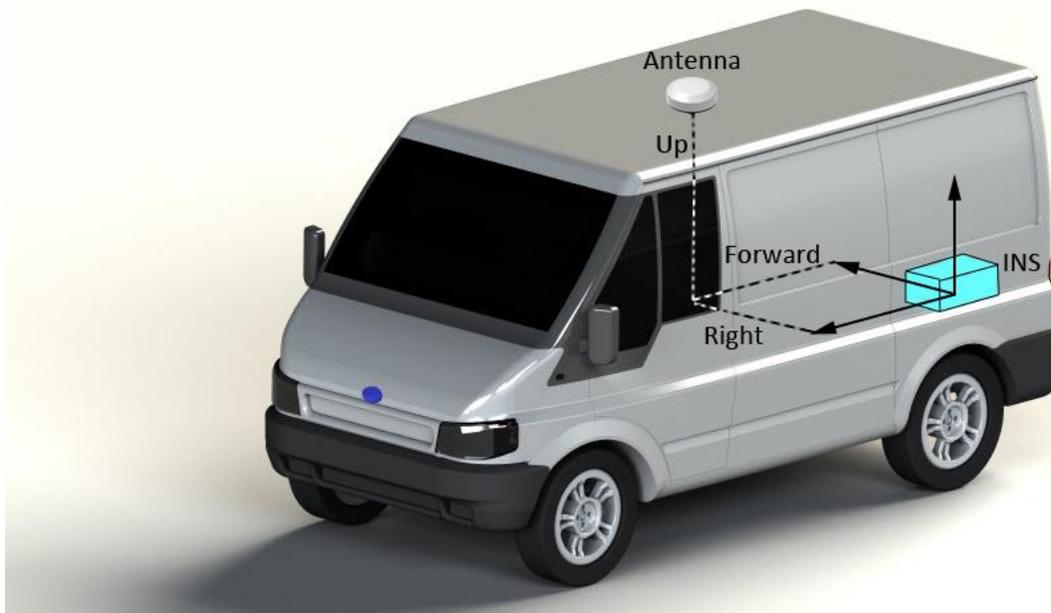
While the best place for the INS unit is center of gravity of the carrier object, the GNSS antenna must of course be placed with a clear view of the sky with a sufficient ground plane.

After the INS unit and GNSS antenna installation on the carrier object it is necessary to measure the antenna position relative to the INS unit, in the object axes – on the right, forward and up. Then it is necessary to store these coordinates to the INS nonvolatile memory using the LoadINSPar command (see Table 6.22, bytes #29-34) or using the INS Demo Program (that is more easy).

Fig.4.3 shows positive right, forward and up directions of the antenna position relative to the INS unit.

### **Important notes:**

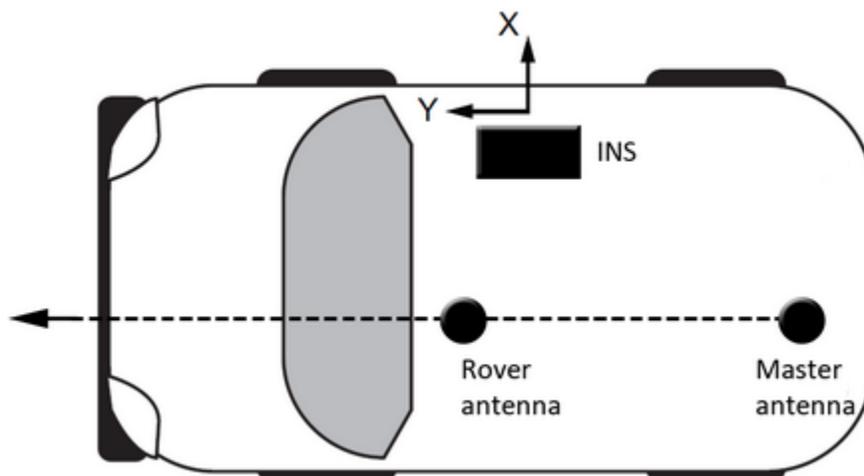
1. If after the INS mounting its axes (see Fig.1.3) are parallel to the carrier object axes, then the antenna coordinates should be measured in the directions of X, Y and Z axes.
2. On the other hand, the INS unit can be mounted on the object in any known position (up to upside-down, upright etc., see Appendix B. Variants of the Tersus INS mounting relative to the object axes). In that case please set the GNSS antenna coordinates measures just in the object axes (on the right, forward and up directions), but not in the INS axes.



**Fig.4.3. Determination of the GNSS antenna position relative to the INS unit (positive directions)**

### **4.3. Installation of two GNSS antennas for INS-D operation**

The Tersus INS-D uses heading calculated by dual-antenna GNSS receiver for the INS correction. Two antennas must be installed in parallel to the longitudinal axis of the carrier object to allow GNSS receiver to measure object heading accurately. At this the rover antenna is installed ahead the master antenna, so direction from the master to the rover antenna is forward for the carrier object, see Fig.4.4.



**Fig.4.4. Installation of the master and rover GNSS antennas on carrier object**

At this requirements for the master antenna installation are the same as described in section “4.2. Installation of single GNSS antenna”. Position of the master antenna relative to the center of the INS unit must be measured and stored to the INS nonvolatile memory.

#### **4.4. Where to install the Tersus INS and its antenna for tests**

The Tersus INS has magnetometers with wide dynamic range and its sophisticated calibration algorithms allow it to operate in many environments. For optimal performance however, you should mount the Tersus INS with the following considerations in mind.

- ***Locate the Tersus INS away from local sources of magnetic fields***

The place for testing must not have ferromagnetic (magneto-susceptible) materials and the lab room itself must have the level of intrinsic magnetic and electro-magnetic fields suitable for the magnetic heading system testing:

- inside and near the lab room there must be no powerful source of magnetic, electrical and electro-magnetic fields. The magnetic field intensity must not be different from the Earth magnetic field intensity at the test site more than 0.01%;
- small ferromagnetic objects must be as far as 3 meters from the test table. Large size ferromagnetic objects such as cars and trucks must be as far as 15 m from the table;
- it is necessary to conduct a regular check-up of the magnetic field uniformity inside the lab room.

It is highly recommended to degauss the INS before heading test to remove permanent magnetization of some components in the INS (if you accidentally expose the unit to a large magnetic field). You can use a hand-held degausser (tape eraser) to demagnetize the INS. Most audio and video degaussing units can be used. Follow the instructions for your demagnetizer.

If heading accuracy is not checked and only pitch and roll accuracy are tested then there are no requirements to magnetic fields and ferromagnetic materials near place of the Tersus INS mounting,

- ***The Tersus INS should be mounted in a physically stable location***

Choose a location that is isolated from excessive shock, oscillation, and vibration. Special rotary table must be used for the Tersus INS accuracy testing, that mounted on a special testing basement which is free from the laboratory oscillations and vibrations.

Tests on vibrations and shocks are fulfilled separately from the main accuracy tests.

- ***Install the Tersus INS and GNSS antenna on the same base***

For test of the INS position and linear velocity calculation, it is necessary to connect the active GNSS antenna(s) to the INS. Both INS unit and the antenna(s) should be installed immovable each to other. Position of the antenna(s) relative to the INS unit should be measured and stored to the INS nonvolatile memory (see sections “4.2. Installation of single GNSS antenna” and “4.3. Installation of two GNSS antennas for INS-D operation”, for details).

#### **4.5. Where to install the Tersus INS on the object**

It is necessary to follow the recommendations listed in the section 4.3 whenever it is possible, when installing the Tersus INS on an carrier object.

- ***Tersus INS should be installed on an object as far as possible from large ferromagnetic masses of the object and powerful sources of magnetic, electrical and electro-magnetic fields***

Tersus INS software allows compensation of hard and soft iron effects of the carrier object on the heading measurement accuracy. For this purpose, field calibration of the INS magnetometers is provided. This calibration does not require any additional equipment, but it requires turns of the carrier object, on which the INS is mounted.

Note that the above field calibration is correct until the residual magnetic field of the object surrounding the INS is changed. If this field is changed due to displacement of ferromagnetic masses of the object or magnetic field sources, the INS should be re-calibrated.

Field calibration procedure of the Tersus INS can be performed by two means:

- by INS itself using special commands described in the section 6.7;
- using the Tersus INS Demo Program.

The INS Demo Program provides more variants of the field calibration and is more convenient for use, but it requires connection of the INS to PC. Calibration of the INS itself is performed without its disconnection from the host system on the carrier object.

More detailed description of the field calibration procedure is given in the section “6.7. Calibration of the Tersus INS on hard and soft iron”.

- ***It is preferable to locate the Tersus INS as close to the center of gravity of the object as possible***

With such location, effects of linear accelerations during oscillations on the INS accelerometers are reduced, and therefore, orientation angle determination errors are also reduced.

## 5. ELECTRICAL INTERFACE

All connectors and LED indicator are placed on the back side of the Tersus INS, see Fig.5.1 and Fig.5.2.



**Fig.5.1. Back side of the Tersus INS-B and INS-P**

- 1 – interface connector;
- 2 – GNSS antenna TNC connector;
- 4 – LED indicator; 5 – pressure sensor



**Fig.5.2. Back side of the Tersus INS-D**

- 1 – interface connector;
- 2 – master GNSS antenna TNC connector;
- 3 – rover GNSS antenna TNC connector;
- 4 – LED indicator; 5 – pressure sensor

The Tersus INS has TNC female connectors for the GNSS antenna connection.

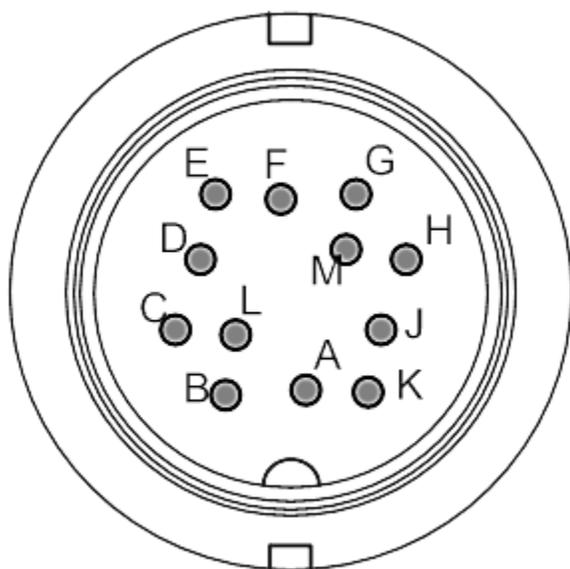
Also the Tersus INS has the Binder male connector for electrical connection to the host system. This connector is different for the INS with RS-232 and RS-422 interface:

- The Tersus INS with RS-232 interface has the Binder Series 723 male 12 pin connector, part # 09 0131 80 12, see <https://www.binder-usa.com/products/partsdetail/86929>
- The Tersus INS with RS-422 interface has the Binder Series 723 male 19 pin connector, part # 09 0463 80 19, see <https://www.binder-usa.com/products/partsdetail/86957>

The host system should have a cable with appropriate mating connector:

- For INS with RS-232 interface: the Binder Series 423, 425 or 723 female 12 pin connector (or cordset), part # 09 0130 70 12, # 99 5130 40 12, or # 79 6130 20 12.
- For INS with RS-422 interface: the Binder Series 423 or 723 female 19 pin connector (or cordset), part # 99 5662 00 19, # 99 5662 75 19 or # 09 0462 70 19, # 99 0462 75 19.

Fig.5.3 shows connector pinout of the Tersus INS with **RS-232** interface. Table 5.1 contains pin diagram of this connector and appropriate color of wires in cable with mating Binder Series 425 Female plug, part # 79 6130 20 12.



**Fig.5.3. The Tersus INS RS-232 connector pinout (mating side of the connector)**

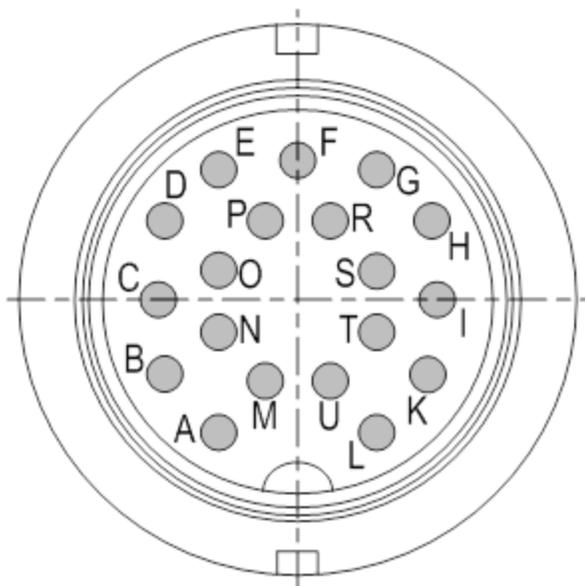
**Table 5.1. Pin diagram of the Tersus INS RS-232 connector**

Pin	Wire color	Signal
A	White	RS232 – RX2
B	Brown	RS232 – TX2
C	Green	RS232 – RX3
D	Yellow	RS232 – TX3
E	Grey	Power
F	Pink	Ground
G	Blue	RS232 – RX1
H	Red	RS232 – TX1
J	Black	PPS
K	Violet	GPIO
L	Grey/pink	Do not connect
M	Red/blue	Do not connect

**Note:** Do not connect anything to pins #L or #M that are connected to INS PCB for firmware updates.

Fig.5.4 shows connector pinout of the Tersus INS with **RS-422** interface. Table 5.2 contains pin diagram of this connector and appropriate color of wires in Alpha Wire cable part number 5478C with 16 conductors.

**Table 5.2. Pin diagram of the Tersus INS RS-422 connector**



**Fig.5.4. The Tersus INS RS-422 connector pinout (mating side of the connector)**

Pin	Pairs color	Wire color	Signal
G	Yellow	Yellow	RS422-A
R	+ Black	Black	RS422-B
F	Orange	Orange	RS422-X
E	+ Black	Black	RS422-Z
P			Reserve1
D	Red	Red	POWER
O	+ Black	Black	GND
C	Blue+	Blue	RS232-RX2
B	Black, Brown+	Brown	RS232-TX2
N	Brown+ Black	2xBlack	GND2
I	Green+	Green	RS232-RX3
K	Black, White+	White	RS232-TX3
T	White+ Black	2xBlack	GND3
L	Red	Red	PPS
U	+White	White	GPIO
A			Do not connect
M			Do not connect
H			Reserve2
S			Reserve3

**Note:** Do not connect anything to pins #A and #M that are connected to INS PCB for firmware updates.

Since the serial number F1560007 the Tersus INS has three COM-ports with RS-232 interface on default:

- COM1 is the main. It is used for commands and data transfer between the Tersus INS and the host computer.
- COM2 is used for output of the raw GNSS receiver data (see section 6.10. Post processing of the INS data) or NMEA data set.
- COM3 has two functions:
  - to receive data for differential corrections of GNSS (DGPS mode);
  - or to output \$GPRMC messages (since INS firmware version 2.2.0.3)

**Table 5.3. Electrical specifications**

Parameter	Conditions	Min	Typical	Max	Units
Input Supply		+9	+12V	+36V	Volts DC
INS-B Current	$V_{DD} = +12V$	200	220	250	mA
INS-P Current	$V_{DD} = +12V$	225	245	275	mA
INS-D Current	$V_{DD} = +12V$	325	345	355	mA

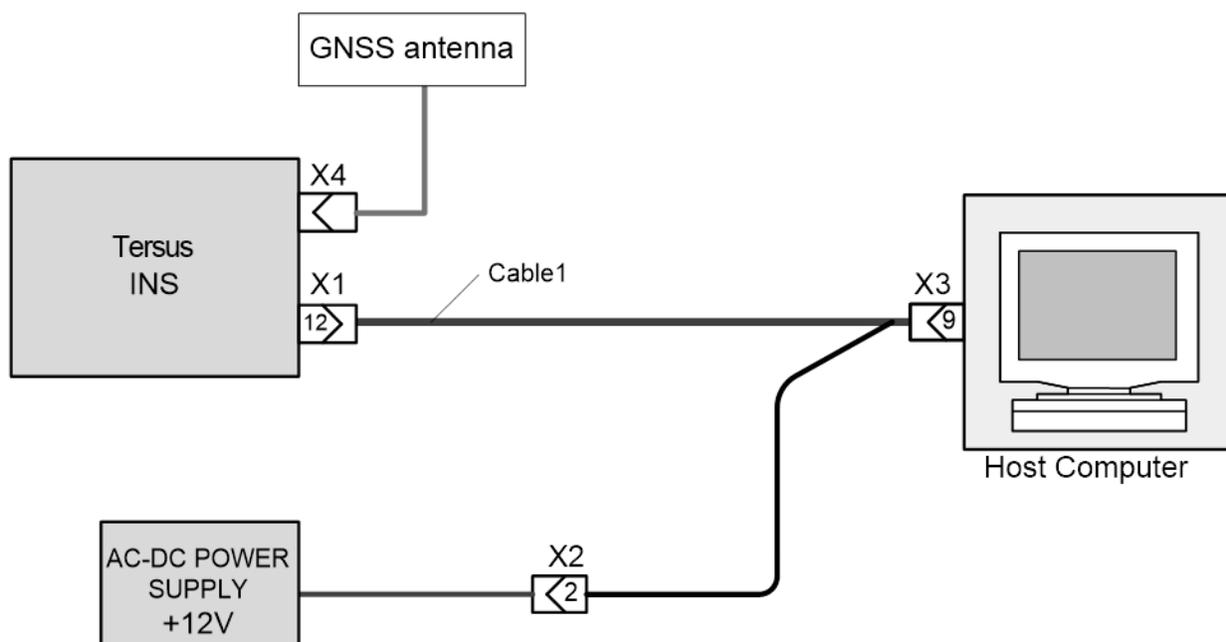
At the Tersus INS operations, it should be connected to the host system that provides command interface described in the section 6 and the INS powering.

### 5.1. Connection of the Tersus INS with RS-232 interface to the host computer for tests

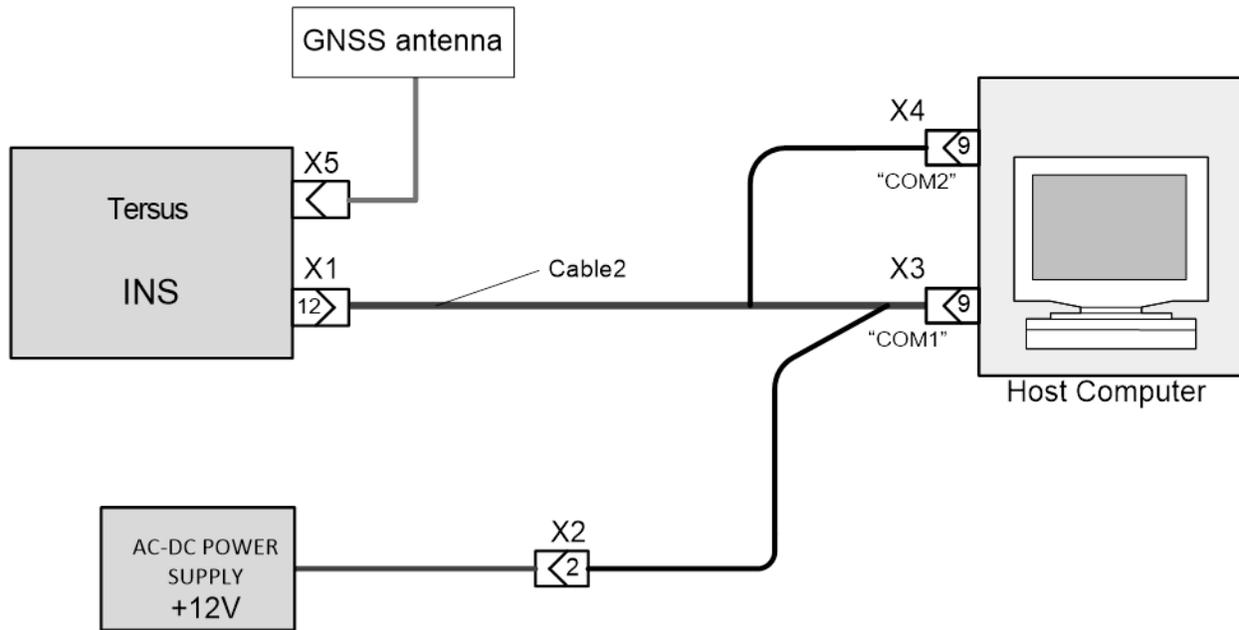
For tests the Tersus INS with RS-232 interface can be connected to PC by cables as Fig.5.5 -- Fig.5.7 show. For usual operations the COM1 port of INS should be connected to PC using cable 1 (see Fig.5.5). To use the raw GNSS data and NMEA messages the cable 2 or cable 3 should be used (see Fig.5.6). To provide the INS operation with DGPS mode the Cable 3 should be used (see Fig.5.7).

As default, the Tersus provides cable 1 for the INS evaluation.

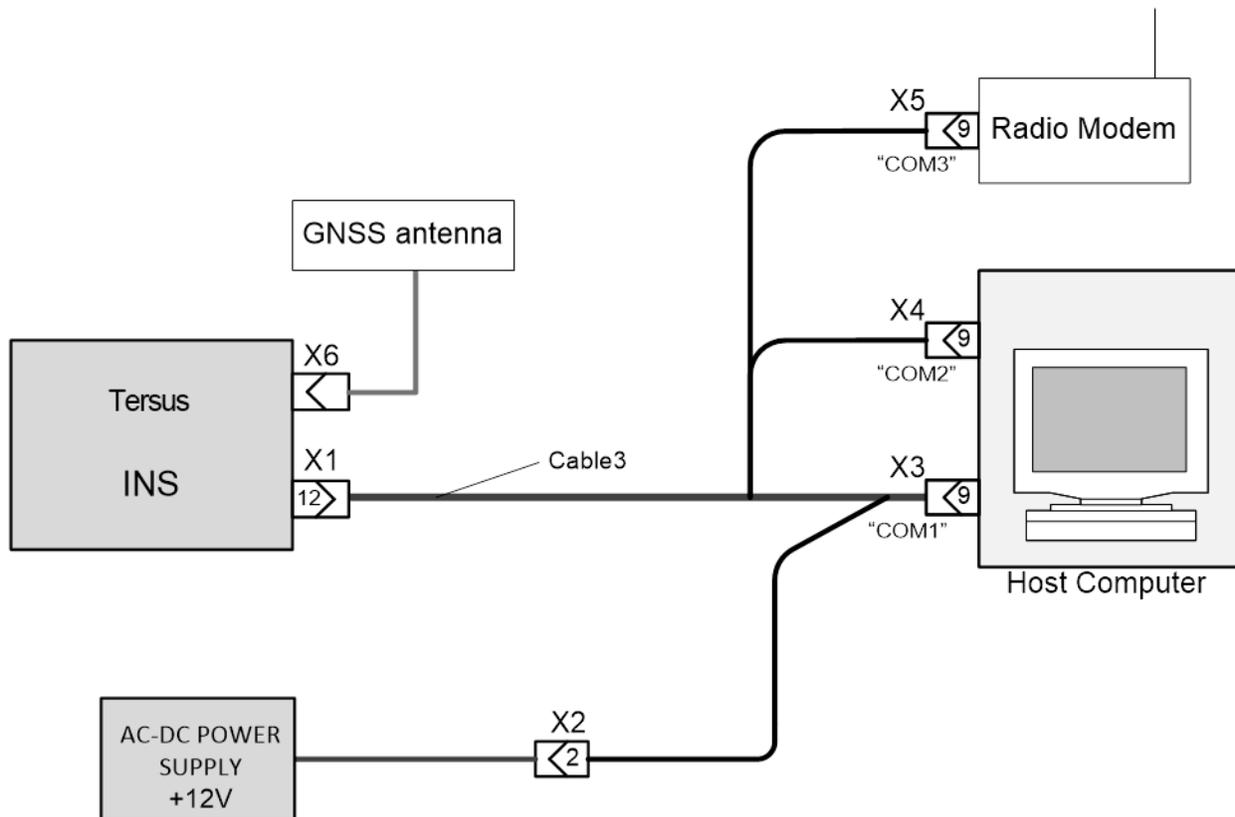
For the Tersus INS powering the AC/DC adapter can be used which receives the power from the 100...240V 50...60Hz AC power source. This AC/DC adapter is provided by the Tersus and is included in the delivery set.



**Fig.5.5. The diagram of electric connection of the Tersus INS to host computer (PC) for tests**



**Fig.5.6. The diagram of electric connection of the Tersus INS to PC with output of the raw GNSS data or NMEA data set**



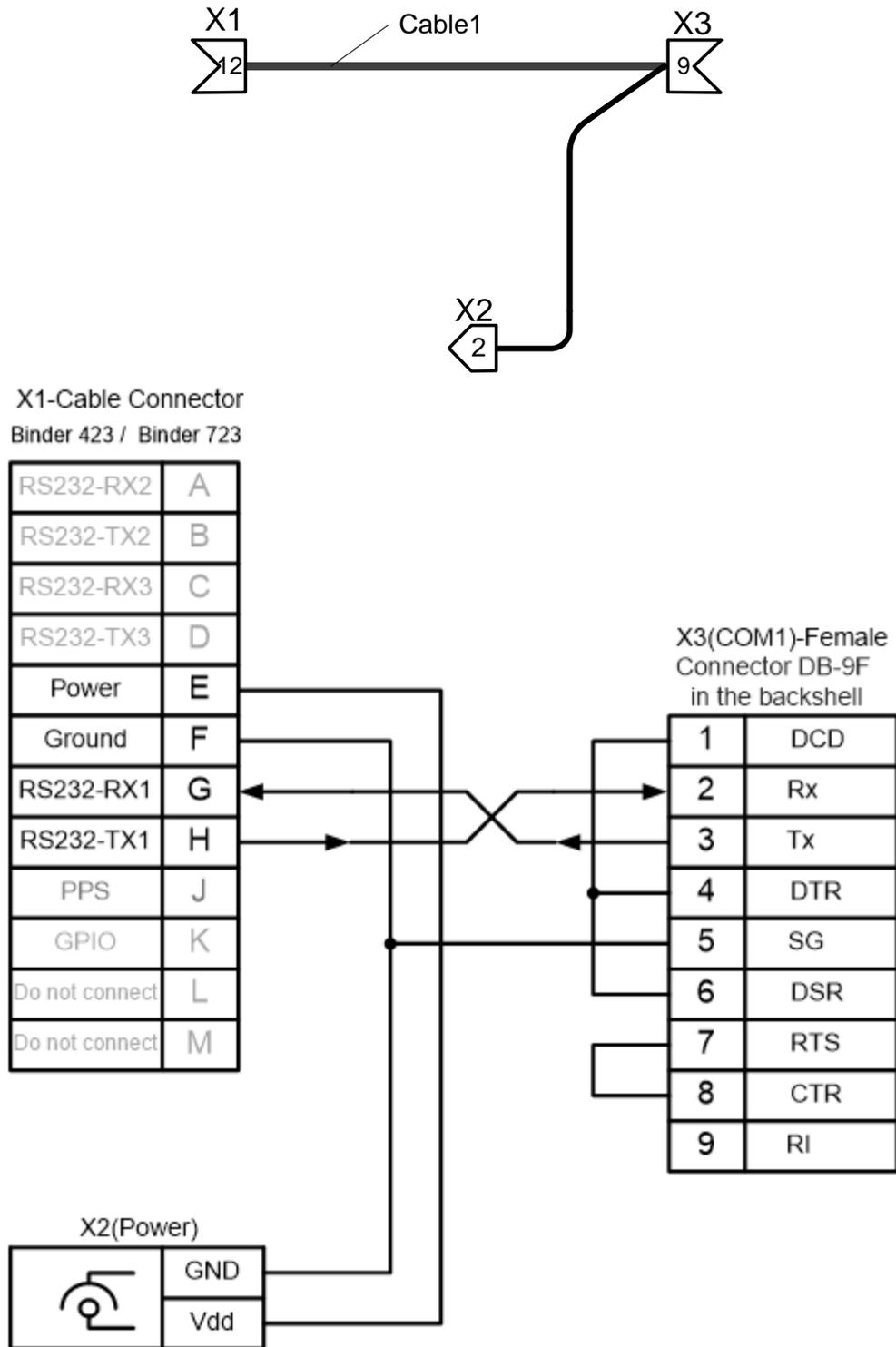
**Fig.5.7. The diagram of electric connection of the Tersus INS with DGPS mode to PC for tests**

The delivery set for the INS with RS-232 interface electrical connection to PC is provided by the Tersus and includes:

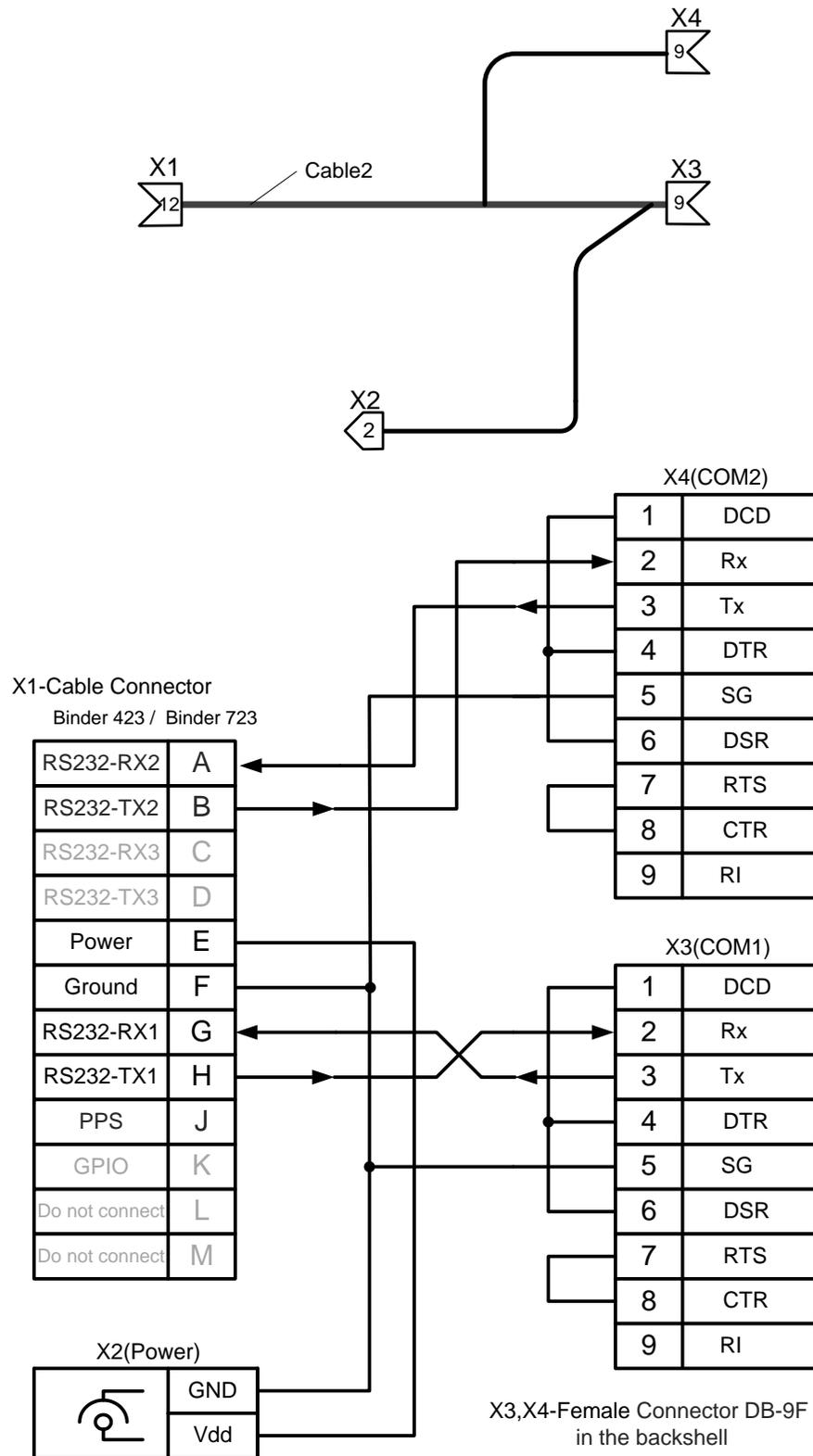
- interface cable 1 for the Tersus INS COM1 port connection to the COM-port of PC or another device, with branch wires for the Tersus INS DC powering;
- COM-to-USB converter for connection of the INS to PC through the USB port;
- AC/DC adapter.

Also Tersus INS Demo software is included in the delivery set for quick evaluation of the Tersus INS.

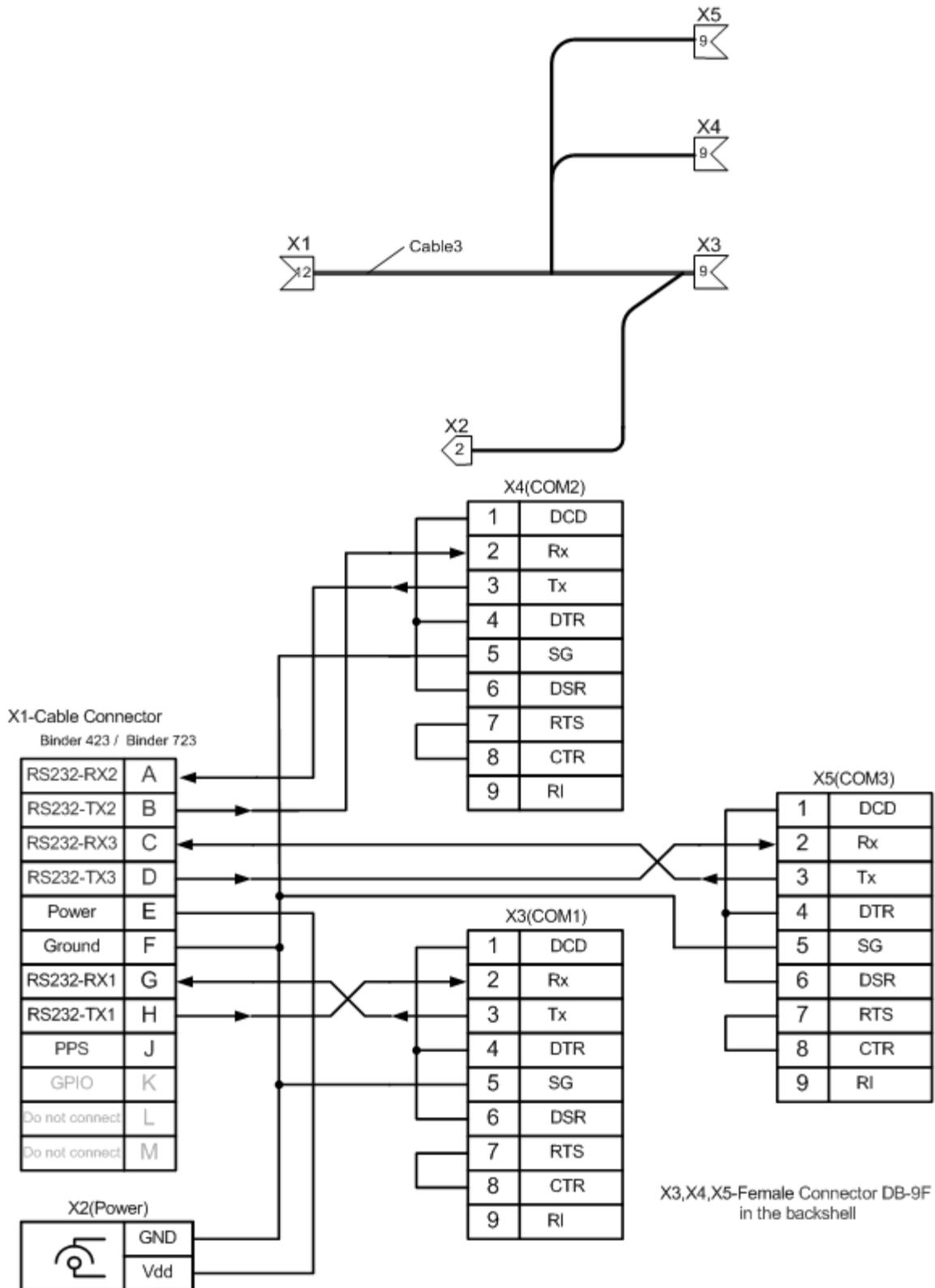
Fig.5.8 – Fig.5.10 show the diagram of the interface cables 1, 2, 3 for the Tersus INS connections to the COM-ports of host computer and to the DC power source.



**Fig.5.8. The diagram of the interface cable 1 for the Tersus INS connection to the COM-port of the host computer and to the AC/DC adapter**



**Fig.5.9. The diagram of the interface cable 2 for the Tersus INS connections to two COM-ports of the host computer and to the AC/DC adapter**



**Fig.5.10. The diagram of the interface cable 3 for the Tersus INS connections to two COM-ports of the host computer, to radio modem and to the AC/DC adapter**

## **5.2. Connection of the Tersus INS with RS-422 interface to the host computer for tests**

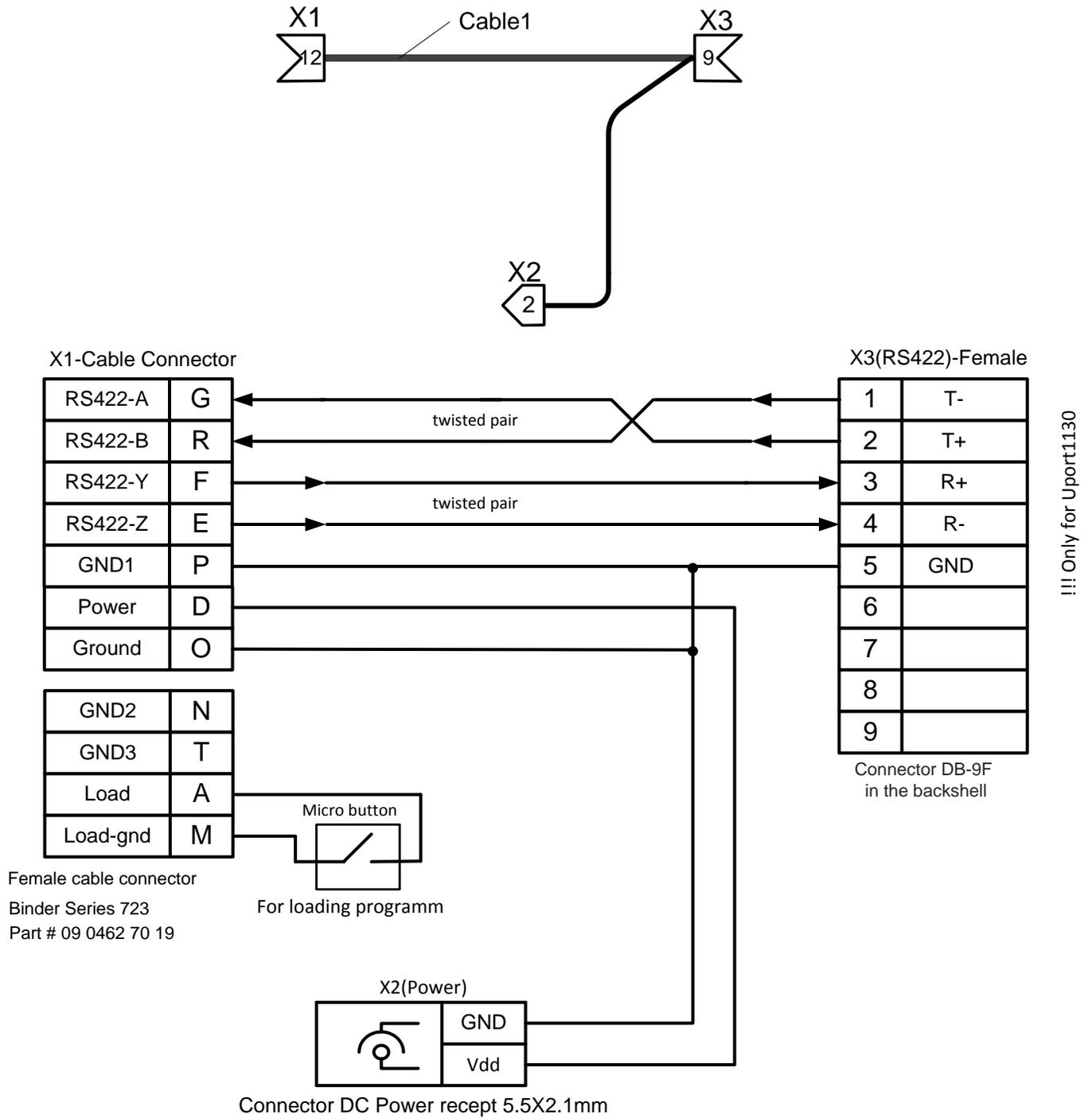
Usual PC has no possibility of devices connection through RS-422 interface directly. Therefore for the Tersus INS with RS-422 interface connection to PC it is necessary to use some converter, for example Serial-to-USB MOXA 1130 converter, which is supplied with INS unit by the Tersus. In other parts above diagrams Fig.5.5 -- Fig.5.7 are still valid.

Fig.5.11, Fig.5.12 show the diagram of the interface cables 1, 3 for the Tersus INS with RS-422 interface connections to the COM-ports of host computer and to the DC power source.

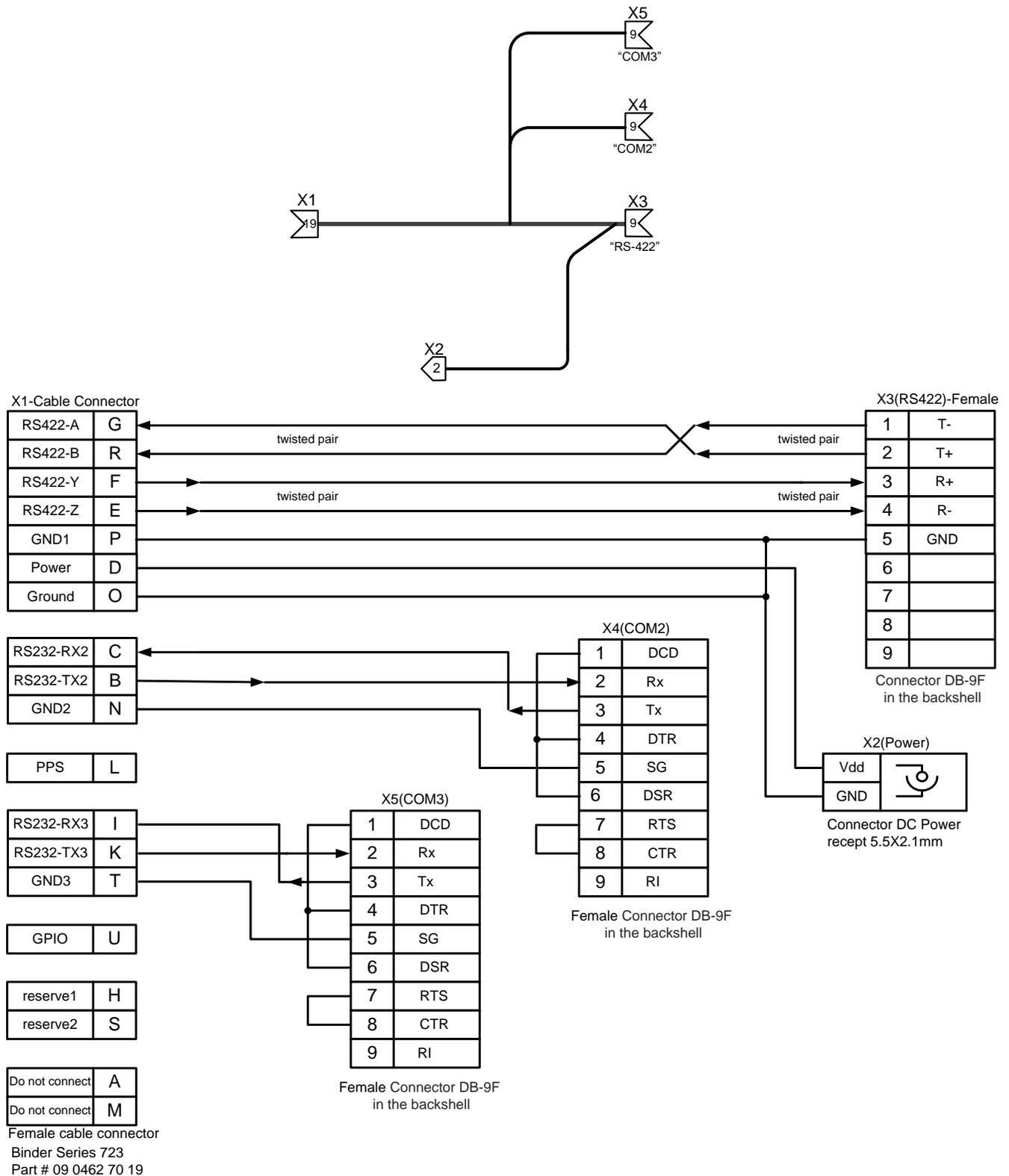
The delivery set for the INS with RS-422 interface electrical connection to PC is provided by the Tersus and includes:

- interface cable 1 for the Tersus INS COM1 port connection to the COM-port MOXA converter, with branch wires for the Tersus INS DC powering;
- USB-to-Serial MOXA converter for connection of the INS to PC through the USB port;
- AC/DC adapter.

Also Tersus INS Demo software is included in the delivery set for quick evaluation of the Tersus INS.



**Fig.5.11. The diagram of the interface cable 1 for the Tersus INS RS-422 connection to the host computer and to the AC/DC adapter**



**Fig.5.12. The diagram of the interface cable 3 for the Tersus INS RS-422 connections to two COM-ports of the host computer, to radio modem and to the AC/DC adapter**

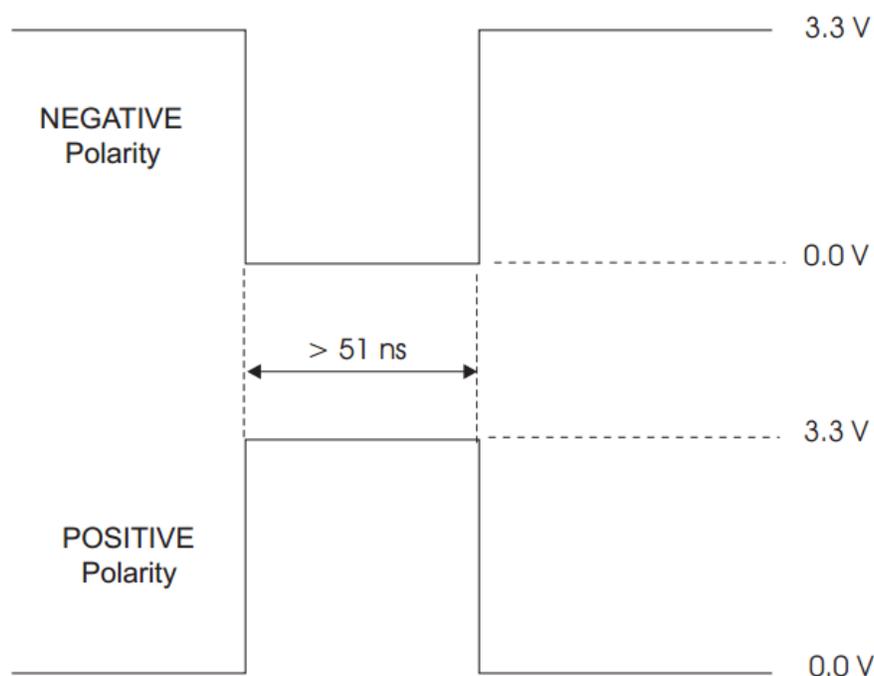
### 5.3. PPS description

The Tersus INS outputs the pulse per second (PPS) signal generated by GNSS receiver. Appropriate pin of the INS main connector provides the PPS signal (see Table 5.1 and Table 5.2).

The leading edge of the PPS pulse is always the trigger / reference:

- Negative – generates a normally high, active low pulse with the falling edge as the reference;
- Positive – generates a normally low, active high pulse with the rising edge as the reference.

PPS pulse is shown on the Fig.5.13.



**Fig.5.13. PPS pulse**

Since the INS firmware version 2.2.0.3 the pulse polarity, period and pulse width are user-adjustable and can be set using the Tersus INS Demo Program since version 2.0.22.84 from 04/22/2016 (see INS Demo User’s Manual, Rev.1.0, section “13.1.Control of PPS output signal”). By default GNSS receiver generates a normally high, active low (negative polarity) pulse with the falling edge as the reference. Default PPS period is 1 second, pulse width is 1000 microseconds.

**Note:** Cable set provided with the Tersus INS is designed for INS connection to PC and therefore it does not transfer PPS signal. To receive PPS signal it is necessary to make another cable with PPS wire. Please contact Tersus to purchase cable with PPS signal transferring.

#### **5.4. GPIO description**

The Tersus INS provides general-purpose input/output (GPIO) pin in the main connector (see pin diagram of the Tersus INS connector in Table 5.1 and Table 5.2).

Since the INS firmware version 2.2.0.3 the GPIO can be used for mark inputs to trigger specific GNSS raw receiver data. TTL mark pulse configuration is the same as Fig.5.13 shows. Adjustment of the mark input signal processing is provided by the Tersus INS Demo Program since version 2.0.22.84 from 04/22/2016 (see INS Demo User's Manual, Rev.1.0, section "13.2.Processing of mark input signal"): processing of the mark input signal can be enabled or disabled, polarity can be changed and a time offset and guard against extraneous pulses can be added.

To allow mark inputs the MARK\_switch should be set to 1 (see section 6.4.1).

When a pulse is detected at GPIO mark input then the GNSS receiver generates asynchronous MARK2POS and MARK2TIME logs which are added to the raw GNSS data.

## 6. SOFTWARE INTERFACE

After the Tersus INS power on an initialisation of the on-board GNSS receiver starts that takes about 25 seconds. During this initialization the INS' LED indicator (see Fig.5.1) lights yellow. After the initialization completed, the INS' indicator lights red, and the INS works in the mode of commands waiting.

If the auto start option is enabled the INS starts operation automatically after power on (see section 6.8 for more details). The INS indicator lights green.

The commands are transmitted through the COM1 serial port according to the protocol RS232 with baud rate 115200 bps (default settings).

**Table 6.1. COM-port parameters**

COM-port parameters	
Baud rate	115200
Data bits	8
Parity	none
Stop bits	1

### Notes

1. Other baud rate than 115200 bps can be set for INS with firmware version since 2.2.0.0. See section "6.12. Change of the main COM port baud rate" for details.
2. The Tersus INS with RS-422, RS-485, CAN 2.0 interfaces are also available.

All commands and messages to / from the Tersus INS have the byte structure shown in the Table 6.2. Exception is done for the INS output in the NMEA format (see section 6.2).

**Table 6.2. Byte structure for all commands and messages to / from the INS**

Byte number	0	1	2	3	4, 5	6 .. (n-1)	n, (n+1)
Parameter	Header 0	Header 1	Message type	INS data identifier	Message length	Payload	Check sum
Length	1 byte	1 byte	1 byte	1 byte	1 word	Variable	1 word
Note	0xAA	0x55		In INS messages	Equal to n		

In the Table 6.2 and in all other tables there is denoted:

**word** = unsigned 2 byte integer;

**sword** = signed 2 byte integer.

Message type is equal to:

- 0 – for commands;
- 1 – for transferred data.

All the INS outputs are data, therefore they have Message type = 1.

INS data identifier is used in INS output data only. This byte is equal to code of the command from the host system which requested this INS message. See all commands code in “APPENDIX C. Full list of the Tersus INS commands”.

Note byte #3 in the block of the initial alignment data is equal to set output data rate (see Table 6.20). In all other messages and commands byte #3 in the Table 6.2 is zero.

**Note:** in INS with firmware version before 2.1.2.0 this byte #3 is zero in all messages.

The Message length is the number of bytes in the message without header.

The Check sum is the arithmetical sum of bytes 2...(n-1) (all bytes without header). In the check sum the low byte is transmitted first (see Table 6.3).

**Table 6.3. Format of the check sum transmitting**

byte0	byte1
low byte	high byte

**Important note**

The low byte is transmitted by first in all data denoted as word, sword, float.

## 6.1. Operational modes of the Tersus INS

The Tersus INS can operate in the four modes:

1. **Idle** mode. All sensors and electronics are powered. The INS microprocessor waits any command from the host computer to start operate in one of the next modes. In the idle mode the indicator of INS lights red.
2. **Continuous** operating mode. In this mode the INS operates in the endless loop, providing the continuous output of calculated position, orientation and other data according to chosen output data format (see section 6.2). Data rate is set by user from 1 Hz to 200 Hz. In the Continuous operating mode indicator of the INS lights green.
3. **“On Request”** operating mode. It is close to the Continuous operating mode, but the INS sends only one data block after each Request command issued from host computer. In this mode indicator of the INS lights green.
4. **Calibration** operating mode. In this mode the embedded calibration procedure is performed for compensation of hard and soft iron effects of the carrier object. See section 6.7 for more details.

## 6.2. Output Data Formats of the Tersus INS in the Operating Modes

The next output data formats are available in the “Continuous” and “On Request” operating modes:

- INS OPVT;
- INS QPVT;
- INS OPVT2A;
- INS OPVT2AW;
- INS OPVT2Ahr;
- INS Full Output Data;
- INS Sensors Data;
- INS Minimal Data;
- INS NMEA Output;
- INS Sensors NMEA Output;

Note output data formats INS OPVT2A, INS OPVT2AW, INS OPVT2Ahr are created for INS-D to output orientation data calculated by dual antenna

GNSS receiver. But all listed above data formats can be used for any INS model – INS-B, INS-P, INS-D, absent data will be replaced by zeros.

### 6.2.1. The “INS OPVT” (Orientation, Position, Velocity, Time) data format

This is default data format. It provides the INS output in the form of:

- 3 orientation angles (heading, pitch and roll);
- calibrated outputs of the 9 sensors (gyros, accelerometers, magnetometers) that give information about current angular rate, linear acceleration of the INS and components of outer magnetic field;
- AHRS (IMU) service data;
- position – latitude, longitude, altitude above mean sea level (or heave);
- east, north and vertical velocity;
- GNSS position and velocity data;
- GPS reference time;
- GPS service data;
- calibrated data from the pressure sensor – pressure and barometric altitude.

More correctly gyros, accelerometers, magnetometers output are integrated angular rate, linear acceleration (specific force), magnetic field increments. In the INS output these increments are divided by time step of data output so they may be interpreted as average angular rates, linear acceleration and magnetic field for cycle of data output. On the other hand, incremental sensor data are good for the INS using as IMU (inertial measurement unit) – they are delta Theta and Delta Velocity divided by time step of data output.

Structure of the INS data blocks at the “INS OPVT” data format corresponds to the Table 6.2 with payload shown in the Table 6.4.

**Note:** before INS firmware version 2.2.1.0 other GNSS information (TS\_gps, GNSS\_info) were shown in bytes #80, 81. This information can be returned if uncheck “Extended info” checkbox in INS Demo Program in “GNSS receiver” tab of “Devices options” menu item.

Maximum data rate for the INS output at the “INS OPVT” data format is limited to 100 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

**Table 6.4. The INS message payload at the “INS OPVT” data format**

Byte number	0 – 1	2 – 3	4 – 5	6 – 11	12 – 17	18 – 23	24 – 25	26 – 27	28 – 29
Parameter	Heading	Pitch	Roll	GyroX,	AccX,	MagX,	USW	Vinp	Temper

				GyroY, GyroZ	AccY, AccZ	MagY, MagZ			
Length	2 byte word	2 byte sword	2 byte sword	3× 2 byte sword	3× 2 byte sword	3× 2 byte sword	2 byte word	2 byte word	2 byte sword
Note	Orientation angles, deg*100			Angular rates, deg/s *KG	Accele- rations g*KA	Magne- tic fields, nT/10		Supply voltage, VDC* 100	Temper- ature, C*10

**Table 6.4 (continued)**

Byte number	30 – 33	34 – 37	38 – 41	42 – 45	46 – 49	50 – 53
Parameter	Latitude	Longitude	Altitude or Heave	East speed	North speed	Vertical speed
Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	4 byte integer	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	m/s*100	m/s*100

**Table 6.4 (continued)**

Byte number	54 – 57	58 – 61	62 – 65	66 – 69	70 – 71	72 – 75
Parameter	Latitude GNSS	Longitude GNSS	Altitude GNSS	Horizont al speed	Track over ground	Vertical speed
Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	2 byte word	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	deg*100	m/s*100

**Table 6.4 (continued)**

Byte number	76-79	80	81	82	83-84	85-86	87-90	91
Parameter	ms_gps	GNSS_ info1	GNSS_ info2	#solnSVs	V_latency	P_bar	H_bar	New GPS
Length	4 byte	1 byte	1 byte	1 byte	2 byte	2 byte word	4 byte integer	1 byte
Note	ms				s*1000	Pa/2	m*100	

**Notes:**

1. Values of KG, KA are scale factors depending on gyro and accelerometer range:

Gyro range, deg/sec	250 or 300	450 or 500	1000	2000
KG	100	50	20	10

Accelerometer range, g	2	6	8
KA	10000	5000	4000

2. Angular rates, linear accelerations and magnetic fields are in the carrier object axes (X is lateral axis, Y is longitudinal axis, Z is vertical axis). The INS orientation relative to the carrier object axes is set by alignment angles (see Appendix B. Variants of the Tersus INS mounting relative to the object axes).
3. USW is unit status word (see section 6.9 for details).
4. Vinp is input voltage of the INS.
5. Temper is averaged temperature in 3 gyros.
6. ms\_gps are milliseconds from the beginning of the GPS reference week;
7. GNSS\_info1, GNSS\_info2 contain information about GNSS data (see Table 6.5, Table 6.6);
8. #SolnSVs is number of satellites used in navigation solution;
9. V\_latency is latency in the velocity time tag in milliseconds;
10. Choice of altitude or heave and appropriate rate for output is supported in INS-D units and depends on switch h\_output (see section 6.5 for details).
11. P\_bar, H\_bar – pressure and barometric height.
12. New\_GPS is indicator of new update of GPS data;
13. The low byte is transmitted by first.

**Table 6.5. GNSS\_info1 – information about GNSS data**

Bit	Value and Description
0 – 3	<u>Position type:</u> 0 – Single point position; 1 – DGPS (pseudorange differential solution); 2 – Solution calculated using corrections from SBAS; 3 – PPP solution; 4 – RTK (other) solution; 5 – RTK (narrow-int) solution; 6 – Other.
4 – 7	<u>Pseudorange iono correction:</u> 0 – unknown or default Klobuchar model; 1 – Klobuchar Broadcast; 2 – SBAS Broadcast; 3 – Multi-frequency Computed; 4 – DGPS (pseudorange differential correction); 5 – Blended Iono Value.

**Table 6.6. GNSS\_info2 – information about GNSS data**

Bit	Value and Description
0 – 1	<u>Solution status:</u> 0 – GNSS solution is computed; 1 – insufficient observations;

	2 – not yet converged from cold start; 3 – other reason of absent solution.
2 – 3	<u>GPS reference time status:</u> 0 – time validity is unknown; 1 – time is coarse set and is being steered; 2 – position is lost and the range bias cannot be calculated; 3 – time is fine set and is being steered.
4	1 – GPS GNSS signal is used
5	1 – GLONASS GNSS signal is used
6	1 – Galileo GNSS signal is used
7	1 – Beidou GNSS signal is used

### 6.2.2. The “INS QPVT” (Quaternion of orientation, Position, Velocity, Time) data format

This data format is near the same as the “INS OPVT” format but provides the quaternion of orientation instead of orientation angles. See “APPENDIX D. Forms of the Tersus INS orientation presentation” for correct relationship between orientation angles and quaternion.

The “INS QPVT” format provides output in the form of:

- Quaternion of orientation;
- calibrated outputs of the 9 sensors (gyros, accelerometers, magnetometers) that give information about current angular rate, linear acceleration of the INS and components of outer magnetic field;
- AHRS (IMU) service data;
- position – latitude, longitude, altitude above mean sea level (or heave);
- east, north and vertical velocity;
- GNSS position and velocity data;
- GPS reference time;
- GPS service data;
- calibrated data from the pressure sensor – pressure and barometric altitude.

More correctly gyros, accelerometers, magnetometers output are integrated angular rate, linear acceleration (specific force), magnetic field increments. In the INS output these increments are divided by time step of data output so they may be interpreted as average angular rates, linear acceleration and magnetic field for cycle of data output. On the other hand, incremental sensor data are good for the INS using as IMU (inertial measurement unit) – they are delta Theta and Delta Velocity divided by time step of data output.

Structure of the INS data blocks at the “INS QPVT” data format corresponds to the Table 6.2 with payload shown in the Table 6.7.

**Note:** before INS firmware version 2.2.1.0 other GNSS information (TS\_gps, GNSS\_info) were shown in bytes #82, 83. This information can be returned if uncheck “Extended info” checkbox in INS Demo Program in “GNSS receiver” tab of “Devices options” menu item.

Maximum data rate for the INS output at the “INS QPVT” data format is limited to 100 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

**Table 6.7. The INS message payload at the “INS QPVT” data format**

Byte number	0-7	8 – 13	14 – 19	20 – 25	26 – 27	28 – 29	30-31
Parameter	Lk0, Lk1, Lk2, Lk3	GyroX, GyroY, GyroZ	AccX, AccY, AccZ	MagX, MagY, MagZ	USW	Vinp	Temper
Length	4× 2 byte sword	3× 2 byte sword	3× 2 byte sword	3× 2 byte sword	2 byte word	2 byte word	2 byte sword
Note	Quaternion of orientation *10000	Angular rates, deg/s *KG	Accelerations g*KA	Magnetic fields, nT/10		Supply voltage, VDC* 100	Temperature, °C*10

**Table 6.7 (continued)**

Byte number	32 – 35	36 – 39	40 – 43	44 – 47	48 – 51	52 – 55
Parameter	Latitude	Longitude	Altitude or Heave	East speed	North speed	Vertical speed
Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	4 byte integer	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	m/s*100	m/s*100

**Table 6.7 (continued)**

Byte number	56 – 59	60 – 63	64 – 67	68 – 71	72 – 73	74 – 77
Parameter	Latitude GNSS	Longitude GNSS	Altitude GNSS	Horizontal speed	Track over ground	Vertical speed

Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	2 byte word	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	deg*100	m/s*100

**Table 6.7 (continued)**

Byte number	78-81	82	83	84	85-86	87-88	89-92	93
Parameter	ms_gps	GNSS_info1	GNSS_info2	#SolnSVs	V_latency	P_bar	H_bar	New GPS
Length	4 byte	1 byte	1 byte	1 byte	2 byte	2 byte word	4 byte integer	1 byte
Note	ms				s*1000	Pa/2	m*100	

**Notes:**

1. The “INS QPVT” data format is implemented in INS with firmware since version 2.1.2.0.
2. Values of KG, KA are scale factors depending on gyro and accelerometer range:

Gyro range, deg/sec	250 or 300	450 or 500	1000	2000
KG	100	50	20	10

Accelerometer range, g	2	6	8
KA	10000	5000	4000

3. Angular rates, linear accelerations and magnetic fields are in the carrier object axes (X is lateral axis, Y is longitudinal axis, Z is vertical axis). The INS orientation relative to the carrier object axes is set by alignment angles (see Appendix B. Variants of the Tersus INS mounting relative to the object axes).
4. USW is unit status word (see section 6.9 for details).
5. Vinp is input voltage of the INS.
6. Temper is averaged temperature in 3 gyros.
7. ms\_gps are milliseconds from the beginning of the GPS reference week;
8. GNSS\_info1, GNSS\_info2 contain information about GNSS data (see Table 6.5, Table 6.6);
9. #SolnSVs is number of satellites used in navigation solution;
10. V\_latency is latency in the velocity time tag in milliseconds;
11. Choice of altitude or heave and appropriate rate for output is supported in INS-D units and depends on switch h\_output (see section 6.5 for details).
12. P\_bar, H\_bar – pressure and barometric height.
13. New\_GPS is indicator of new update of GPS data;
14. The low byte is transmitted by first.

### 6.2.3. The “INS OPVT2A” (Orientation, Position, Velocity, Time, Dual-antenna receiver data) format

The “INS OPVT2A” data format is implemented in INS with firmware since version 2.2.1.7. This data format is based on the “INS OPVT” format but provides additional data calculated by dual antenna GNSS receiver:

- 3 orientation angles (heading, pitch and roll) calculated by INS;
- calibrated outputs of the 9 sensors (gyros, accelerometers, magnetometers) that give information about current angular rate, linear acceleration of the INS and components of outer magnetic field;
- AHRS (IMU) service data;
- position – latitude, longitude, altitude above mean sea level (or heave);
- east, north and vertical velocity;
- GNSS position and velocity data;
- GPS reference time;
- GPS orientation data;
- GPS service data;
- calibrated data from the pressure sensor – pressure and barometric altitude.

Structure of the INS data blocks at the “INS OPVT2A” data format corresponds to the Table 6.2 with payload shown in the Table 6.8.

Maximum data rate for the INS output at the “INS OPVT2A” data format is limited to 90 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

**Table 6.8. The INS message payload at the “INS OPVT2A” data format**

Byte number	0 – 1	2 – 3	4 – 5	6 – 11	12 – 17	18 – 23	24 – 25	26 – 27	28 – 29
Parameter	Heading	Pitch	Roll	GyroX, GyroY, GyroZ	AccX, AccY, AccZ	MagX, MagY, MagZ	USW	Vinp	Temper
Length	2 byte word	2 byte sword	2 byte sword	3× 2 byte sword	3× 2 byte sword	3× 2 byte sword	2 byte word	2 byte word	2 byte sword
Note	Orientation angles, deg*100			Angular rates, deg/s *KG	Accelerations g*KA	Magnetic fields, nT/10		Supply voltage, VDC* 100	Temperature, °C*10

**Table 6.8 (continued)**

Byte number	30 – 33	34 – 37	38 – 41	42 – 45	46 – 49	50 – 53
Parameter	Latitude	Longitude	Altitude or Heave	East speed	North speed	Vertical speed
Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	4 byte integer	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	m/s*100	m/s*100

**Table 6.8 (continued)**

Byte number	54 – 57	58 – 61	62 – 65	66 – 69	70 – 71	72 – 75
Parameter	Latitude GNSS	Longitude GNSS	Altitude GNSS	Horizontal speed	Track over ground	Vertical speed
Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	2 byte word	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	deg*100	m/s*100

**Table 6.8 (continued)**

Byte number	76-79	80	81	82	83-84	85	86-87	88-89
Parameter	ms_gps	GNSS_info1	GNSS_info2	#solnSVs	V_latency	Angles position type	Heading GNSS	Pitch GNSS
Length	4 byte	1 byte	1 byte	1 byte	2 byte	1 byte	2 byte word	2 byte sword
Note	ms				s*1000		Orientation angles, deg*100	

**Table 6.8 (continued)**

Byte number	90-91	92-93	94-95	96-99	100
Parameter	Heading STD GNSS	Pitch STD GNSS	P_bar	H_bar	New GPS
Length	2 byte word	2 byte word	2 byte word	4 byte integer	1 byte
Note	STD, deg*100		Pa/2	m*100	

**Notes:**

1. Values of KG, KA are scale factors depending on gyro and accelerometer range:

Gyro range, deg/sec	250 or 300	450 or 500	1000	2000
KG	100	50	20	10

Accelerometer range, g	2	6	8
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KA	10000	5000	4000
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2. Angular rates, linear accelerations and magnetic fields are in the carrier object axes (X is lateral axis, Y is longitudinal axis, Z is vertical axis). The INS orientation relative to the carrier object axes is set by alignment angles (see Appendix B. Variants of the Tersus INS mounting relative to the object axes).
3. USW is unit status word (see section 6.9 for details).
4. Vinp is input voltage of the INS.
5. Temper is averaged temperature in 3 gyros.
6. ms\_gps are milliseconds from the beginning of the GPS reference week;
7. GNSS\_info1, GNSS\_info2 contain information about GNSS data (see Table 6.5, Table 6.6);
8. #SolnSVs is number of satellites used in navigation solution;
9. V\_latency is latency in the velocity time tag in milliseconds;
10. Angles position type is GNSS position type at orientation calculation (see Table 6.14);
11. Choice of altitude or heave and appropriate rate for output is supported in INS-D units and depends on switch h\_output (see section 6.5 for details).
12. P\_bar, H\_bar – pressure and barometric height.
13. New\_GPS is indicator of new update of GPS data;
14. The low byte is transmitted by first.

#### 6.2.4. The “INS OPVT2AW” (Orientation, Position, Velocity, Time, Dual-antenna receiver data, GPS Week) format

The “INS OPVT2AW” data format is implemented in INS with firmware since version 2.5.0.5. This data format is based on the “INS OPVT2A” format but also provides the GPS Week number.

Structure of the INS data blocks at the “INS OPVT2AW” data format corresponds to the Table 6.2 with payload shown in the Table 6.9.

Maximum data rate for the INS output at the “INS OPVT2AW” data format is limited to 90 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

**Table 6.9. The INS message payload at the “INS OPVT2AW” data format**

Byte number	0 – 1	2 – 3	4 – 5	6 – 11	12 – 17	18 – 23	24 – 25	26 – 27	28 – 29
Parameter	Heading	Pitch	Roll	GyroX, GyroY, GyroZ	AccX, AccY, AccZ	MagX, MagY, MagZ	USW	Vinp	Temper
Length	2 byte word	2 byte sword	2 byte sword	3× 2 byte sword	3× 2 byte sword	3× 2 byte sword	2 byte word	2 byte word	2 byte sword
Note	Orientation angles,			Angular	Accele-	Magne-		Supply	Temper

	deg*100	rates, deg/s *KG	rations g*KA	tic fields, nT/10		voltage, VDC* 100	ature, C*10
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**Table 6.9 (continued)**

Byte number	30 – 33	34 – 37	38 – 41	42 – 45	46 – 49	50 – 53
Parameter	Latitude	Longitude	Altitude or Heave	East speed	North speed	Vertical speed
Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	4 byte integer	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	m/s*100	m/s*100

**Table 6.9 (continued)**

Byte number	54 – 57	58 – 61	62 – 65	66 – 69	70 – 71	72 – 75
Parameter	Latitude GNSS	Longitude GNSS	Altitude GNSS	Horizont al speed	Track over ground	Vertical speed
Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	2 byte word	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	deg*100	m/s*100

**Table 6.9 (continued)**

Byte number	76-79	80-81	82	83	84	85-86	87
Parameter	ms_gps	GPS week	GNSS_ info1	GNSS_ info2	#solnSVs	V_latency	Angles position type
Length	4 byte	2 byte word	1 byte	1 byte	1 byte	2 byte	1 byte
Note	ms					s*1000	

**Table 6.9 (continued)**

Byte number	88-89	90-91	92-93	94-95	96-97	98-101	102
Parameter	Heading GNSS	Pitch GNSS	Heading STD GNSS	Pitch STD GNSS	P_bar	H_bar	New GPS

Length	2 byte word	2 byte sword	2 byte word	2 byte word	2 byte word	4 byte integer	1 byte
Note	Orientation angles, deg*100		STD, deg*100		Pa/2	m*100	

**Notes:**

1. Values of KG, KA are scale factors depending on gyro and accelerometer range:

Gyro range, deg/sec	250 or 300	450 or 500	1000	2000
KG	100	50	20	10

Accelerometer range, g	2	6	8
KA	10000	5000	4000

2. Angular rates, linear accelerations and magnetic fields are in the carrier object axes (X is lateral axis, Y is longitudinal axis, Z is vertical axis). The INS orientation relative to the carrier object axes is set by alignment angles (see Appendix B. Variants of the Tersus INS mounting relative to the object axes).
3. USW is unit status word (see section 6.9 for details).
4. Vinp is input voltage of the INS.
5. Temper is averaged temperature in 3 gyros.
6. ms\_gps are milliseconds from the beginning of the GPS reference week;
7. GNSS\_info1, GNSS\_info2 contain information about GNSS data (see Table 6.5, Table 6.6);
8. #SolnSVs is number of satellites used in navigation solution;
9. V\_latency is latency in the velocity time tag in milliseconds;
10. Angles position type is GNSS position type at orientation calculation (see Table 6.14);
11. Choice of altitude or heave and appropriate rate for output is supported in INS-D units and depends on switch h\_output (see section 6.5 for details).
12. P\_bar, H\_bar – pressure and barometric height.
13. New\_GPS is indicator of new update of GPS data;
14. The low byte is transmitted by first.

### 6.2.5. The “INS OPVT2Ahr” (Orientation, Position, Velocity, Time, Dual-antenna receiver data, with high resolution) format

The “INS OPVT2Ahr” data format is implemented in INS with firmware since version 2.3.0.5. This data format provides the same data as the “INS OPVT2A” format, but sensors and position data are presented with higher resolution:

- 3 orientation angles (heading, pitch and roll) calculated by INS;
- calibrated outputs of 3 gyros and 3 accelerometers with high resolution;
- calibrated outputs of 3 magnetometers;
- AHRS (IMU) service data;
- position – latitude, longitude, altitude above mean sea level (or heave), with high resolution;
- east, north and vertical velocity;

- GNSS position (with high resolution) and velocity data;
- GPS reference time;
- GPS orientation data;
- GPS service data;
- calibrated data from the pressure sensor – pressure and barometric altitude.

Structure of the INS data blocks at the “INS OPVT2Ahr” data format corresponds to the Table 6.2 with payload shown in the Table 6.10.

Maximum data rate for the INS output at the “INS OPVT2Ahr” data format is limited to 70 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

**Table 6.10. The INS message payload at the “INS OPVT2Ahr” data format**

Byte number	0 – 1	2 – 3	4 – 5	6 – 17	18 – 29	30 – 35	37 – 37	38 – 39	40 – 41
Parameter	Heading	Pitch	Roll	GyroX, GyroY, GyroZ	AccX, AccY, AccZ	MagX, MagY, MagZ	USW	Vinp	Temper
Length	2 byte word	2 byte sword	2 byte sword	3× 4 byte integer	3× 4 byte integer	3× 2 byte sword	2 byte word	2 byte word	2 byte sword
Note	Orientation angles, deg*100			Angular rates, deg/s *1.0e5	Accelerations, g*1.0e6	Magnetic fields, nT/10		Supply voltage, VDC* 100	Temperature, °C*10

**Table 6.10 (continued)**

Byte number	42 – 49	50 – 57	58 – 61	62 – 65	66 – 69	70 – 73
Parameter	Latitude	Longitude	Altitude or Heave	East speed	North speed	Vertical speed
Length	8 byte integer	8 byte integer	4 byte integer	4 byte integer	4 byte integer	4 byte integer
Note	deg*1.0e9	deg*1.0e9	m*1000	m/s*100	m/s*100	m/s*100

**Table 6.10 (continued)**

Byte number	74 – 81	82 – 89	90 – 93	94 – 97	98 – 99	100 – 103
Parameter	Latitude GNSS	Longitude GNSS	Altitude GNSS	Horizontal speed	Track over ground	Vertical speed

Length	8 byte integer	8 byte integer	4 byte integer	4 byte integer	2 byte word	4 byte integer
Note	deg*1.0e9	deg*1.0e9	m*1000	m/s*100	deg*100	m/s*100

**Table 6.10 (continued)**

Byte number	104-107	108	109	110	111-112	113	114-115	116-117
Parameter	ms_gps	GNSS_info1	GNSS_info2	#solnSVs	V_latency	Angles position type	Heading GNSS	Pitch GNSS
Length	4 byte	1 byte	1 byte	1 byte	2 byte	1 byte	2 byte word	2 byte sword
Note	ms				s*1000		Orientation angles, deg*100	

**Table 6.10 (continued)**

Byte number	118-119	120-121	122-123	124-127	128
Parameter	Heading STD GNSS	Pitch STD GNSS	P_bar	H_bar	New GPS
Length	2 byte word	2 byte word	2 byte word	4 byte integer	1 byte
Note	STD, deg*100		Pa/2	m*100	

**Notes:**

1. Angular rates, linear accelerations and magnetic fields are in the carrier object axes (X is lateral axis, Y is longitudinal axis, Z is vertical axis). The INS orientation relative to the carrier object axes is set by alignment angles (see Appendix B. Variants of the Tersus INS mounting relative to the object axes).
2. USW is unit status word (see section 6.9 for details).
3. Vinp is input voltage of the INS.
4. Temper is averaged temperature in 3 gyros.
5. ms\_gps are milliseconds from the beginning of the GPS reference week;
6. GNSS\_info1, GNSS\_info2 contain information about GNSS data (see Table 6.5, Table 6.6);
7. #SolnSVs is number of satellites used in navigation solution;
8. V\_latency is latency in the velocity time tag in milliseconds;
9. Angles position type is GNSS position type at orientation calculation (see Table 6.14);
10. Choice of altitude or heave and appropriate rate for output is supported in INS-D units and depends on switch h\_output (see section 6.5 for details).
11. P\_bar, H\_bar – pressure and barometric height.
12. New\_GPS is indicator of new update of GPS data;

13. The low byte is transmitted by first.

### 6.2.6. The “INS Full Output Data” format

This data format is near the same as the “INS OPVT” format but all sensors data are in original ADC codes (raw data). Usually the “INS Full Output Data” format is used by the INS developers for full control of calculations in the INS microprocessor. Also this format can be used by user at any troubles to get full data from the INS for next sending them to developers.

Structure of the INS data blocks at the “INS Full Output Data” format corresponds to the Table 6.2 with payload shown in the Table 6.11.

**Note:** before INS firmware version 2.2.1.0 other GNSS information (TS\_gps, GNSS\_info) were shown in bytes #84, 85. This information can be returned if uncheck “Extended info” checkbox in INS Demo Program in “GNSS receiver” tab of “Devices options” menu item.

Maximum data rate for the INS output at the “INS Full Output Data” format is limited to 100 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

**Table 6.11. The message payload at the “INS Full Output Data” format**

Byte number	0 – 1	2 – 3	4 – 5	6 – 23	24 – 25	26 – 27	28 – 29	30 – 31	32 – 33
Parameter	Heading	Pitch	Roll	Ugyro, Uacc, Umag	Reser- ved	Mdec	USW	Vdd	Utermo
Length	2 byte word	2 byte sword	2 byte sword	9×2 byte sword	2 byte sword	2 byte sword	2 byte word	2 byte word	2 byte sword
Note	Orientation angles, deg*100			Raw sensor data (gyros, accelerometers, magnetometers)		deg*100		Combi- ned voltage	Temper ature in each sensor

**Table 6.11 (continued)**

Byte number	34 – 37	38 – 41	42 – 45	46 – 49	50 – 53	54 – 57
Parameter	Latitude	Longitude	Altitude	East	North	Vertical

			or Heave	speed	speed	speed
Length	4 byte integer					
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	m/s*100	m/s*100

**Table 6.11 (continued)**

Byte number	58 – 61	62 – 65	66 – 69	70 – 73	74 – 75	76 – 79
Parameter	Latitude GNSS	Longitude GNSS	Altitude GNSS	Horizontal speed	Track over ground	Vertical speed
Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	2 byte word	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m/s*100	deg*100	m/s*100

**Table 6.11 (continued)**

Byte number	80 – 83	84	85	86	87-88	89-90	91-92	93
Parameter	ms_gps	GNSS _info1	GNSS _info2	#SolnSVs	V_latency	UP	UT	New GPS
Length	4 byte integer	1 byte	1 byte	1 byte	2 byte	2 byte word	2 byte word	1 byte
Note	ms				s*1000			

**Notes**

1. Mdec is magnetic declination (see section 1.3 for details), since INS firmware version 2.2.0.2.
2. USW is unit status word (see section 6.9 for details).
3. The following data are recorded in the field «Vdd» sequentially:
  - the INS input voltage, Vinp, VDC\*100;
  - stabilized voltage supplied to the INS sensors, Vdd, VDC\*1000;
4. In the «Utermo» field ADC codes are recorded sequentially from 7 temperature sensors inside gyros, accelerometers and magnetometers.
5. ms\_gps are milliseconds from the beginning of the GPS reference week;
6. TS\_gps is time status which indicates the quality of the GPS reference time (see Table 6.5);
7. GNSS\_info contains information about GNSS data (see Table 6.6);
8. #SolnSVs is number of satellites used in navigation solution;
9. V\_latency is latency in the velocity time tag in milliseconds;
10. Choice of altitude or heave and appropriate rate for output is supported in INS-D units and depends on switch h\_output (see section 6.5 for details).
11. UP and UT are raw data from the pressure sensor – pressure and temperature.
12. New\_GPS is indicator of new update of GPS data;

13. The low byte is transmitted by first.

### 6.2.7. The “INS Sensors Data” format

This data format contains data from the devices inside INS:

AHRS (IMU) data:

- 3 orientation angles (heading, pitch and roll);
- raw data from the 9 sensors (gyros, accelerometers, magnetometers) in original ADC codes;
- AHRS service data;

GNSS receiver data:

- position – latitude, longitude, height above mean sea level;
- standard deviations of latitude, longitude and height;
- horizontal and vertical speed;
- direction of motion (track over ground);
- GPS reference time;
- GPS service data;

Pressure sensor data:

- temperature and pressure raw data in ADC codes.

Structure of the INS data blocks at the “INS Sensors Data” format corresponds to the Table 6.2 with payload shown in the Table 6.12.

Maximum data rate for the INS output at the “INS Sensors Data” format is limited to 100 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

**Table 6.12. The message payload at the “INS Sensors Data” format**

Byte number	0 – 1	2 – 3	4 – 5	6 – 23	24 – 25	26 – 27	28 – 29	30 – 31	32 – 33
Parameter	Heading (AHRS)	Pitch (AHRS)	Roll (AHRS)	Ugyro, Uacc, Umag	Reser-ved	Reser-ved	USW	Vdd	Utermo
Length	2 byte word	2 byte sword	2 byte sword	9×2 byte sword	2 byte sword	2 byte sword	2 byte word	2 byte word	2 byte sword
Note	Orientation angles, deg*100			Raw sensor data (gyros, accelerometers, magnetometers)				Combi- ned voltage	Temper- ature in each sensor

**Table 6.12 (continued)**

Byte number	34 – 37	38 – 41	42 – 45	46-47	48 – 49	50 – 51	52-55	56-57	58-61
Parameter	Latitude GNSS	Longitude GNSS	Altitude GNSS	Latitude STD	Longitude STD	Altitude STD	Horizontal speed	Track over ground	Vertical speed
Length	4 byte integer	4 byte integer	4 byte integer	2 byte word	2 byte word	2 byte word	4 byte integer	2 byte word	4 byte integer
Note	deg *1.0e7	deg *1.0e7	m*100	m*1000	m*1000	m*1000	m/s*100	deg*100	m/s*100

**Table 6.12 (continued)**

Byte number	62 – 65	66	67	68	69	70	71	72
Parameter	ms_gps	TS_gps	sol_stat	pos_type	#SVs	#SolnSVs	#SolnL1SVs	#SolnMultiSVs
Length	4 byte	1 byte	1 byte	1 byte	1 byte	1 byte	1 byte	1 byte
Note	ms							

**Table 6.12 (continued)**

Byte number	73	74	75	76-77	78-79	80-81	82	83
Parameter	ext_sol_stat	Galileo and BeiDou	GPS and GLONASS	V_latency	UP	UT	New GPS	Reserv
Length	1 byte	1 byte	1 byte	2 byte	2 byte word	2 byte word	1 byte	1 byte
Note				s*1000				

### **Notes**

1. USW is unit status word (see section 6.9 for details).
2. The following data are recorded in the field «Vdd» sequentially:
  - the INS input voltage,  $V_{inp}$ ,  $VDC*100$ ;
  - stabilized voltage supplied to the INS sensors,  $V_{dd}$ ,  $VDC*1000$ ;
3. In the «Utermo» field ADC codes are recorded sequentially from 7 temperature sensors inside gyros, accelerometers and magnetometers.
4. ms\_gps are milliseconds from the beginning of the GPS reference week;
5. TS\_gps is time status which indicates the quality of the GPS reference time (see Table 6.5);
6. sol\_stat is GNSS solution status (see Table 6.13);
7. pos\_type is GNSS position type (see Table 6.14);
8. #SVs is number of satellites tracked;
9. #SolnSVs is number of satellites used in navigation solution;
10. #SolnL1SVs is number of satellites with L1/E1/B1 signals used in solution;
11. #SolnMultiSVs is number of satellites with multi-frequency signals used in solution;
12. ext\_sol\_stat is GNSS extended solution status (see Table 6.15);
13. GPS and GLONASS is GPS and GLONASS signal-used mask (see Table 6.16);
14. Galileo and BeiDou is Galileo and BeiDou signal-used mask (see Table 6.17);
15. V\_latency is latency in the velocity time tag in milliseconds;

- 16. Choice of altitude or heave and appropriate rate for output is supported in INS-D units and depends on switch h\_output (see section 6.5 for details).
- 17. UP and UT are raw data from the pressure sensor – pressure and temperature.
- 18. New\_GPS is indicator of new update of GPS data;
- 19. The low byte is transmitted by first.

**Table 6.13. sol\_stat – GNSS solution status**

Value	Description
0	Solution computed
1	Insufficient observations
2	No convergence
3	Singularity at parameters matrix
4	Covariance trace exceeds maximum (trace > 1000 m)
5	Test distance exceeded (maximum of 3 rejections if distance >10 km)
6	Not yet converged from cold start
7	Height or velocity limits exceeded (in accordance with export licensing restrictions)
8	Variance exceeds limits
9	Residuals are too large
13	Large residuals make position unreliable
18	When a FIX POSITION command is entered, the receiver computes its own position and determines if the fixed position is valid
19	The fixed position, entered using the FIX POSITION command, is not valid
20	Position type is unauthorized - HP or XP on a receiver not authorized

**Table 6.14. pos\_type – GNSS position or velocity type**

Value	Description
0	No solution
8	Velocity computed using instantaneous Doppler
16	Single point position
17	Pseudorange differential solution
18	Solution calculated using corrections from an WAAS
19	Propagated by a Kalman filter without new observations
20	OmniSTAR VBS position <sup>(1)</sup>
32	Floating L1 ambiguity solution
33	Floating ionospheric-free ambiguity solution
34	Floating narrow-lane ambiguity solution
48	Integer L1 ambiguity solution
50	Integer narrow-lane ambiguity solution
64	OmniSTAR HP position <sup>(1)</sup>
65	OmniSTAR XP or G2 position <sup>(1)</sup>
68	Converging PPP TerraStar-C solution <sup>(2)</sup>
69	Converged PPP TerraStar-C solution <sup>(2)</sup>
77	Converging PPP TerraStar-L solution <sup>(2)</sup>
78	Converged PPP TerraStar-L solution <sup>(2)</sup>

**Notes**

- (1) A subscription for OmniSTAR or use of a DGPS service is required. It is not realized in the Tersus INS firmware yet.
- (2) PPP solution requires access to a suitable correction stream, delivered either through L-Band or the internet. For L-Band delivered TerraStar or Veripos service, appropriate receiver software model is required, along with a subscription to the desired service. It is not realized in the Tersus INS firmware yet.

**Table 6.15. ext\_sol\_stat – GNSS extended solution status**

Bit	Mask	Description
0	0x01	If an RTK solution: Fixed solution has been verified If a PDP solution: solution is GLIDE Otherwise: Reserved
1-3	0x0E	Pseudorange Iono Correction 0 = Unknown or default Klobuchar model 1 = Klobuchar Broadcast 2 = SBAS Broadcast 3 = Multi-frequency Computed 4 = PSRDiff Correction 5 = Blended Iono Value
4	0x10	Reserved
5	0x20	0 = No antenna warning 1 = Antenna information is missing
6-7	0xC0	Reserved

**Table 6.16. GPS and GLONASS signal-used mask**

Bit	Mask	Description
0	0x01	GPS L1 used in solution
1	0x02	GPS L2 used in solution
2	0x04	GPS L5 used in solution
3	0x08	Reserved
4	0x10	GLONASS L1 used in solution
5	0x20	GLONASS L2 used in solution
6-7	0x40-0x80	Reserved

**Table 6.17. Galileo and BeiDou signal-used mask**

Bit	Mask	Description
0	0x01	Galileo E1 used in solution
1-3	0x02-0x08	Reserved
4	0x10	BeiDou B1 used in solution
5	0x20	BeiDou B2 used in solution
6-7	0x40-0x80	Reserved

### 6.2.8. The “INS Minimal Data” format

This data format specifies the minimum of the INS data that can be transferred with larger data rate as 150 Hz.

- 3 orientation angles (heading, pitch and roll);
- AHRS (IMU) service data;
- position – latitude, longitude, altitude above mean sea level (or heave);
- east, north and vertical velocity;
- GPS reference time;
- GPS service data.

Structure of the INS data blocks at the “INS Minimal Data” format corresponds to the Table 6.2 with payload shown in the Table 6.18.

**Note:** before INS firmware version 2.2.1.0 other GNSS information were shown in byte #40 – TS\_gps. This information can be returned if uncheck “Extended info” checkbox in INS Demo Program in “GNSS receiver” tab of “Devices options” menu item.

Maximum data rate for the INS output at the “INS Minimal Data” format is 200 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

**Table 6.18. The message payload at the “INS Minimal Data” format**

Byte number	0 – 1	2 – 3	4 – 5	6 – 7	8 – 9	10 – 11	12 – 15	16 – 19	20 – 23
Parameter	Heading	Pitch	Roll	USW	Vinp	Temper	Latitude	Longitude	Altitude or Heave
Length	2 byte word	2 byte sword	2 byte sword	2 byte word	2 byte word	2 byte sword	4 byte integer	4 byte integer	4 byte integer
Note	Orientation angles, deg*100				Supply voltage, VDC*100	Temperature, °C*10	deg *1.0e7	deg *1.0e7	m*100

**Table 6.18 (continued)**

Byte number	24 – 27	28 – 31	32 – 35	36-39	40	41
Parameter	East speed	North speed	Vertical speed	ms_gps	GNSS_info1	#SolnSVs
Length	4 byte integer	4 byte integer	4 byte integer	4 byte integer	1 byte	1 byte
Note	m/s*100	m/s*100	m/s*100			

**Notes:**

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1. USW is unit status word (see section 6.9 for details).
2. Vinp is input voltage of the INS.
3. Temper is averaged temperature in 3 gyros.
4. ms\_gps are milliseconds from the beginning of the GPS reference week;
5. GNSS\_info1 contains information about GNSS data (see Table 6.5);
6. #SolnSVs is number of satellites used in navigation solution.
7. The low byte is transmitted by first.

### 6.2.9. The “INS NMEA Output” data format

At the “INS NMEA Output” the INS data are transmitted in the form of sentences with printable ASCII characters like the NMEA 0183 format. Each sentence starts with a "\$" sign and ends with <CR><LF> (carriage return 0xD and line feed 0xA symbols). All data fields are separated by commas. The general form of the “INS NMEA Output” sentence is the next

**\$PAPR,LLmm.mmmm,n,YYYmm.mmmm,x,AAAA.aa,B,RRRR.rr,PPP.pp,HHH.hh,tttttttt,TTT.t,VV.v,SSSS\*CC<CR><LF>**

where PAPR is identifier and other fields are listed below:

- **LLmm.mmmm** is unsigned latitude, where LL are degrees, mm.mmmm are minutes;
- **n** is N or S (North or South);
- **YYYmm.mmmm** is unsigned longitude, where YYY are degrees, mm.mmmm are minutes;
- **x** is E or W (East or West);
- **AAAA.aa** is altitude or heave in meters;
- **B** denotes kind of height data that is defined by switch h\_output (see section 6.5 for details):  
 'a' – altitude;  
 'h' – heave.
- **RRRR.rr** is roll in degrees;
- **PPP.pp** is pitch in degrees;
- **HHH.hh** is heading in degrees;
- **tttttttt** is timestamp (milliseconds from the beginning of the GPS reference week);
- **TTT.t** is temperature inside INS (averaged value for 3 gyros);
- **VV.v** is input voltage of the INS;
- **SSSS** is unit status word, USW (see section 6.9 for details). It is hex written with ASCII;
- **CC** is check sum that consists of a "\*" and two hex digits representing XOR of all characters between, but not including "\$" and "\*" .

Maximum data rate for the INS output at the “INS NMEA Output” data format is limited to 100 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

### 6.2.10. The “INS Sensors NMEA Output” data format

The “INS Sensors NMEA output” data have structure close to the “INS NMEA”, with addition of gyros and accelerometers data. So, at the “INS Sensors NMEA output” the INS data are transmitted in the form of sentences with printable ASCII characters like the NMEA 0183 format. Each sentence starts with a "\$" sign and ends with <CR><LF> (carriage return 0xD and line feed 0xA symbols). All data fields are separated by commas. The general form of the “INS Sensors NMEA output” sentence is the next

**\$PAPS,LLmm.mmmm,n,YYYmm.mmmm,x,AAAA.aa,B,RRRR.rr,PPP.pp,HHH.hh,GGGG.xx,GGGG.yy,GGGG.zz,AA.xxxx,AA.yyyy,AA.zzzz,tttttttt,TTT.t,VV.v,SSSS\*CC<CR><LF>**

where PAPS is identifier and other fields are listed below:

- **LLmm.mmmm** is unsigned latitude, where LL are degrees, mm.mmmm are minutes;
- **n** is N or S (North or South);
- **YYYmm.mmmm** is unsigned longitude, where YYY are degrees, mm.mmmm are minutes;
- **x** is E or W (East or West);
- **AAAA.aa** is altitude or heave in meters;
- **B** denotes kind of height data that is defined by switch h\_output (see section 6.5 for details):  
‘a’ – altitude;  
‘h’ – heave.
- **RRRR.rr** is roll in degrees;
- **PPP.pp** is pitch in degrees;
- **HHH.hh** is heading in degrees;
- **GGGG.xx** is gyro X data in degrees/s;
- **GGGG.yy** is gyro Y data in degrees/s;
- **GGGG.zz** is gyro Z data in degrees/s;
- **AA.xxxx** is accelerometer X data in g;
- **AA.yyyy** is accelerometer Y data in g;
- **AA.zzzz** is accelerometer Z data in g;
- **tttttttt** is timestamp (milliseconds from the beginning of the GPS reference week);
- **TTT.t** is temperature inside INS in °C (averaged value for 3 gyros);
- **VV.v** is input voltage of the INS, in Volts;
- **SSSS** is unit status word, USW (see Appendix C for details). It is hex written with ASCII;
- **CC** is check sum that consists of a "\*" and two hex digits representing XOR of all characters between, but not including "\$" and "\*" .

Maximum data rate for the INS output at the “INS Sensors NMEA Output” data format is limited to 80 Hz at standard COM-port baud rate 115200 bps. See Table 6.55 for maximum data rate at other baud rates.

### 6.2.11. The GNSS receiver NMEA data format (through COM2 port)

The Tersus INS can use the second COM2 port for output the set of GNSS receiver data in NMEA format. The INS starts output of these data after power on and completing of the receiver initialization (when the INS LED indicator switches from yellow to red).

NMEA data set is variable and can be changed by user using INS Demo Program. NMEA data set can include next synchronous logs:

- GPGGA,
- GPGSA,
- GPRMC,
- GPVTG,
- GPZDA.

The data for synchronous logs are generated with set frequency (see section 6.4. Control of the GNSS receiver).

Data are transmitted in the form of sentences with printable ASCII characters like the NMEA 0183 format. Each sentence starts with a "\$" sign and ends with <CR><LF> (carriage return 0xD and line feed 0xA symbols). All data fields are separated by commas.

GPGGA log contains time, position and fix related data of the GNSS receiver. The structure of the GPGGA log is next:

**Table 6.20 The GPGAA log structure**

Message component	Description
<b>\$GPGGA</b>	Log header
<b>utc</b>	UTC time status of position (hours/minutes/seconds/decimal seconds)
<b>lat</b>	Latitude (DDmm.mm)
<b>lat dir</b>	Latitude direction (N = North, S = South)
<b>lon</b>	Longitude (DDDmm.mm)
<b>lon dir</b>	Longitude direction (E = East, W = West)
<b>quality</b>	GPS Quality Indicators (see Table 6.21)

<b># sats</b>	Number of satellites in use. May be different to the number in view
<b>hdop</b>	Horizontal dilution of precision
<b>alt</b>	Antenna altitude above/below mean sea level
<b>a-units</b>	Units of antenna altitude (M = meters)
<b>undulation</b>	Undulation - the relationship between the geoid and the WGS84 ellipsoid
<b>u-units</b>	Units of undulation (M = meters)
<b>age</b>	Age of correction data (in seconds)
<b>stn ID</b>	Differential base station ID
<b>*xx</b>	Checksum
<b>[CR][LF]</b>	Sentence terminator

**Table 6.21 GPS Quality Indicators**

Indicator	Description
0	Fix not available or invalid
1	Single point
2	Pseudorange differential
	Unconverged OmniSTAR
	HP/XP/G2/VBS converging PPP
4	RTK fixed ambiguity solution (RT2)
	Operational
5	RTK floating ambiguity solution (RT20)
	Converged OmniSTAR HP/XP/G2
	Converged PPP
6	Dead reckoning mode
7	Manual input mode (fixed position)
8	Simulator mode
9	WAAS (SBAS)

GPGSA log contains GNSS receiver operating mode, satellites used for navigation and DOP values. The structure of the GPVTG log is next:

**Table 6.22 The GPGSA log structure**

Message component	Description
<b>\$ GPGSA</b>	Log header
<b>mode MA</b>	A = Automatic 2D/3D M = Manual, forced to operate in 2D or 3D
<b>mode 123</b>	Mode: 1 = Fix not available; 2 = 2D; 3 = 3D
<b>prn</b>	PRN numbers of satellites used in solution (null for

<b>(fields 4-15)</b>	unused fields), total of 12 fields GPS = 1 to 32 SBAS = 33 to 64 (add 87 for PRN number) GLO = 65 to 96
<b>pdop</b>	Position dilution of precision
<b>hdop</b>	Horizontal dilution of precision
<b>vdop</b>	Vertical dilution of precision
<b>*xx</b>	Checksum
<b>[CR][LF]</b>	Sentence terminator

GPRMC log contains time, position and fix related data of the GNSS receiver. The structure of the GPRMC log is next:

**Table 6.23 The GPRMC log structure**

Message component	Description
<b>\$ GPRMC</b>	Log header
<b>utc</b>	UTC time status of position (hours/minutes/seconds/decimal seconds)
<b>pos status</b>	Position status: A = data valid, V = data invalid
<b>lat</b>	Latitude (DDmm.mm)
<b>lat dir</b>	Latitude direction (N = North, S = South)
<b>lon</b>	Longitude (DDDmm.mm)
<b>lon dir</b>	Longitude direction (E = East, W = West)
<b>speed Kn</b>	Speed over ground, knots
<b>track true</b>	Track made good, degrees True
<b>date</b>	Date: dd/mm/yy
<b>mag var</b>	Magnetic variation direction E/W
<b>mode ind</b>	Positioning system mode indicator (see Table 6.25)
<b>*xx</b>	Checksum
<b>[CR][LF]</b>	Sentence terminator

GPVTG log contains the track made good and speed relative to the ground. The structure of the GPVTG log is next:

**Table 6.24 The GPVTG log structure**

Message component	Description
<b>\$ GPVTG</b>	Log header
<b>track true</b>	Track made good, degrees True
<b>T</b>	True track indicator

<b>track mag</b>	Track made good, degrees Magnetic; Track mag = Track true + (MAGVAR correction)
<b>M</b>	Magnetic track indicator
<b>speed Kn</b>	Speed over ground, knots
<b>N</b>	Nautical speed indicator (N = Knots)
<b>speed Km</b>	Speed, kilometers/hour
<b>K</b>	Speed indicator (K = km/hr)
<b>mode ind</b>	Positioning system mode indicator (see Table 6.25)
<b>*xx</b>	Checksum
<b>[CR][LF]</b>	Sentence terminator

**Table 6.25 NMEA Positioning System Mode Indicator**

Mode	Indicator
<b>A</b>	Autonomous
<b>D</b>	Differential
<b>E</b>	Estimated (dead reckoning) mode
<b>M</b>	Manual input
<b>N</b>	Data not valid

GPZDA log outputs the UTC date and time. The structure of the GPZDA log is next:

**Table 6.26 The GPZDA log structure**

Message component	Description
<b>\$ GPZDA</b>	Log header
<b>utc</b>	UTC time status
<b>day</b>	Day, 01 to 31
<b>month</b>	Month, 01 to 12
<b>year</b>	Year
<b>null</b>	Local zone description—not available
<b>7null</b>	Local zone minutes description—not available
<b>*xx</b>	Checksum
<b>[CR][LF]</b>	Sentence terminator

### 6.2.12. The GNSS receiver GPRMC data format (through COM3 port)

The Tersus INS can use the third COM3 port for output the GNSS receiver log GPRMC. To set GPRMC message for output through COM3 port please use the INS Demo Program (see INS Demo User's Manual section "4.2.2 GNSS receiver tab of "Device options... " window").

The INS starts output of these data after power on and completing of the receiver initialization (when the INS LED indicator switches from yellow to red). The data for synchronous logs are generated with set frequency (see section 6.4. Control of the GNSS receiver).

Data are transmitted in the form of sentences with printable ASCII characters like the NMEA 0183 format. Each sentence starts with a "\$" sign and ends with <CR><LF> (carriage return 0xD and line feed 0xA symbols). All data fields are separated by commas.

GPRMC log contains time, position and fix related data of the GNSS receiver. See the structure of the GPRMC log in the Table 6.23.

### 6.3. Control of the Tersus INS

After power connection an initialisation of the onboard GNSS receiver starts that takes about 15 seconds. During this initialization the INS' LED indicator (see Fig.5.1) lights yellow. After the initialization completed the LED indicator switches to red, and the INS' goes to the idle mode in which it is ready to receive commands from the host computer.

When the INS switches from idle to any operation mode, the light indicator changes its color from red to green.

The next commands are used to control the INS:

- INS\_OPVTdata;
- INS\_QPVTdata;
- INS\_OPVT2Adata;
- INS\_OPVT2Ahrdata;
- INS\_OPVT2AWhrdata;
- INS\_FullData;
- INS\_SensorsData;
- INS\_minData;
- INS\_NMEA;
- INS\_Sensors\_NMEA;
- SetOnRequestMode;
- Stop;
- ReadINSpar;
- LoadINSpar;
- GetDevInfo;
- GetBIT.

All these commands have the byte structure shown in the Table 6.2. Payload for all commands has length 1 byte and contains code of the command. See Appendix C for exact structure of these commands.

**6.3.1. INS\_OPVTdata, INS\_QPVTdata, INS\_OPVT2Adata,  
INS\_OPVT2AWdata, INS\_OPVT2Ahrdata, INS\_FullData,  
INS\_SensorsData, INS\_minData, INS\_NMEA, INS\_Sensors\_NMEA**

Commands INS\_OPVTdata, INS\_QPVTdata, INS\_OPVT2Adata, INS\_OPVT2AWdata, INS\_OPVT2Ahrdata, INS\_FullData, INS\_SensorsData, INS\_minData, INS\_NMEA, INS\_Sensors\_NMEA are used to start the Tersus INS in the “Continuous” operating mode with appropriate variant of output data format as Table 6.27 shows.

**Table 6.27. INS control command and appropriate output data format**

Command	Code	Output data format
INS_SensorsData	0x50	INS Sensors Data
INS_FullData	0x51	INS Full Output Data
INS_OPVTdata	0x52	INS OPVT
INS_QPVTdata	0x56	INS QPVT
INS_OPVT2Adata	0x57	INS OPVT2A
INS_OPVT2AWdata	0x59	INS OPVT2AW
INS_OPVT2Ahrdata	0x58	INS OPVT2Ahr
INS_minData	0x53	INS Minimal Data
INS_NMEA	0x54	INS NMEA Output
INS_Sensors_NMEA	0x55	INS and Sensors NMEA Output

All these commands have the byte structure shown in the Table 6.2. Payload for all commands has length 1 byte and contains code of the command listed in the Table 6.27.

In order to identify to the host system that INS received one of these commands, the INS answers back immediately on this command prior to completion of the initial alignment process. The INS calculates the check sum of the message (without its header and check sum) and returns it for a checking. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word). This check sum should be equal to the check sum in the message that was sent to the INS.

After receiving of any from these commands the INS starts process of initial alignment that takes usually 30 seconds. This process includes the INS gyros bias estimation, therefore don't move the INS during its initial alignment. If

this requirement is not met then large errors may be occurred in orientation and position calculation.

**Note:** Default time 30 seconds of the initial alignment can be changed (see section 6.3.4. LoadINSpar command) but only in agreement with developers of the Tersus INS.

After completing of the initial alignment the INS gives out message with block of the initial alignment data (see Table 6.28, Table 6.29) and goes to the “Continuous” operating mode.

**Table 6.28. Byte structure of the block of initial alignment data**

Byte number	0	1	2	3	4, 5	6..55	56, 57
Parameter	Header 0	Header 1	Message type	Output data rate (Hz)	Message length	Payload	Check sum
Length	1 byte	1 byte	1 byte	1 byte	1 word	50 bytes	1 word
Note	0xAA	0x55	0x01	hexadecimal value	0x38 0x00	see Table 6.21	

**Table 6.29. Structure of the payload of the block of initial alignment data**

Byte	Parameter	Format	Length	Note
0-11	Gyros bias	float	3*4	3 numbers in ADC codes
12-23	Average acceleration	float	3*4	3 numbers in ADC codes
24-35	Average magn. field	float	3*4	3 numbers in ADC codes
36-39	Initial Heading	float	4	degrees
40-43	Initial Roll	float	4	degrees
44-47	Initial Pitch	float	4	degrees
48-49	USW (see section 6.9)	word	2	0 – successful initial alignment; ≠0 – unsuccessful

In the “Continuous” operating mode set by any of above commands INS\_OPVTdata, INS\_QPVTdata, INS\_OPVT2Adata, INS\_OPVT2AWdata, INS\_OPVT2Ahrdata,, INS\_FullData, INS\_SensorsData, INS\_minData, INS\_NMEA, INS\_Sensors\_NMEA, the program in the INS microprocessor operates in the endless loop, providing the process of data reading from ADC and calculation of position and orientation.

At the **INS\_OPVTdata, INS\_QPVTdata, INS\_OPVT2Adata, INS\_OPVT2AWdata, INS\_OPVT2Ahrdata, INS\_FullData, INS\_SensorsData, INS\_minData** commands output data blocks have binary

structure described in the Table 6.2 with payload depending on chosen variant of output data format (see matching Table 6.27 and more detailed Tables 6.4, 6.7, 6.8, 6.9, 6.10, 6.11, 6.12 and 6.18).

**Note:** For better identification of data format of the INS output blocks, since the INS firmware version 2.1.2.0 the INS data identifier is present in the data block structure (see Table 6.2, byte #3) which is equal to appropriate command code and corresponds to data format according to the Table 6.27.

At the **INS\_NMEA**, **INS\_Sensors\_NMEA** commands output data blocks are transmitted in the form of sentences with printable ASCII characters as sections 6.2.9 – 6.2.10 describe.

The update rate of data blocks is set by the user in range (1...200) Hz, but maximum data rate depends on chosen output data format and COM port baud rate (see Table 6.55).

### **6.3.2. SetOnRequestMode command – getting INS data on request (on demand)**

The command SetOnRequestMode is used to start the Tersus INS operation in the “On Request” (on demand) operating mode. This command has the byte structure shown in the Table 6.2 where payload is one byte equal to 0xC1.

In order to identify to the host system that INS received this command, the INS answers back immediately on this command prior to completion of the initial alignment process. The INS calculates the check sum of the message (without its header and check sum) and returns it for a checking. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word). This check sum should be equal to the check sum in the message that was sent to the INS.

After receiving of the SetOnRequestMode command the INS starts process of initial alignment that takes usually 30 seconds. This process includes the INS gyros bias estimation, therefore don't move the INS during its initial alignment. If this requirement is not met then large errors may be occurred in orientation angles calculation.

**Note:** Default time 30 seconds of the initial alignment can be changed (see section 6.3.4. LoadINSpar command) but only in agreement with developers of the Tersus INS.

After completing of the initial alignment the INS gives out message with block of the initial data (payload is 50 bytes of the data – see the Table 6.28, Table 6.29) and goes to the “On Request” operating mode.

In the “On Request” operating mode the INS sends only one data block after each request. To get this data block send one of above described commands INS\_OPVTdata, INS\_QPVTdata, INS\_OPVT2Adata, INS\_OPVT2AWdata, INS\_OPVT2Ahrdata,, INS\_FullData, INS\_minData, INS\_NMEA, INS\_Sensors\_NMEA (see section 6.3.1). Note INS\_SensorsData command is not supported in the “On Request” operating mode since the INS firmware version 2.1.1.0.

If one of the **INS\_OPVTdata, INS\_QPVTdata, INS\_OPVT2Adata, INS\_OPVT2AWdata, INS\_OPVT2Ahrdata, INS\_FullData, INS\_minData** commands is used for request then output data block has binary structure described in the Table 6.2 with payload depending on chosen variant of output data format (see matching Table 6.19 and more detailed Tables 6.4, 6.7, 6.8, 6.9, 6.10, 6.11, 6.12 and 6.18).

**Note:** For better identification of data format of the INS output blocks, since the INS firmware 2.1.2.0 the INS data identifier is present in the data block structure (see Table 6.2, byte #3) which is equal to appropriate command code and corresponds to data format according to the Table 6.20.

If one of the **INS\_NMEA, INS\_Sensors\_NMEA** commands is used for request then output data block contains printable ASCII characters as sections 6.2.9 – 6.2.10 describe.

### 6.3.3. Stop command

At receiving the Stop command (code 0xFE in the “Payload” field) the INS stops work in an operating mode and goes to the idle mode. At that the INS LED indicator changes its color to red. The INS is ready to receive any command from the host computer.

**Important Note:** Before using all other commands please send the **Stop** command to the INS to switch device into the idle mode. Be sure that the INS’s light indicator is red before sending of any other commands.

### 6.3.4. LoadINSpar command

The LoadINSpar command (code 0x40 in the “Payload” field) is used to load the block of the INS parameters (which are available for changing by user) into the INS nonvolatile memory. After sending the LoadINSpar command, the block of the INS parameters must be send to the INS in the message shown in the Table 6.2 with payload shown in the Table 6.30. This message should be sent without pause after sending the LoadINSpar command.

**Table 6.30. Payload of the message following after the LoadINSpar command (block of parameters for loading to the INS)**

Byte	Parameter	Format	Length	Note
0-1	Data rate	word	2	Hz
2-3	Initial alignment time	word	2	seconds
4-7	Magnetic declination, Mdec	longint	4	degrees*100, if Mdec > 360 then INS calculates it
8-11	Latitude	longint	4	degrees*1e7
12-15	Longitude	longint	4	degrees*1e7
16-19	Altitude	longint	4	meters*100
20	Date (Year from 2000)	byte	1	0 to 255
21	Date (Month)	byte	1	1 to 12
22	Date (Day)	byte	1	1 to 31
23-24	Alignment angle A1	sword	2	Angles of INS mounting on the carrier object, degrees*100 (see Appendix B)
25-26	Alignment angle A2	sword	2	
27-28	Alignment angle A3	sword	2	
29-30	INS mount, right	sword	2	INS mounting lever relative to the object center of gravity, m*100 (see section 6.6)
31-32	INS mount, forward	sword	2	
33-34	INS mount, up	sword	2	
35-36	Antenna pos., right	sword	2	GNSS antenna mounting lever relative to the INS, meters*100
37-38	Antenna pos., forward	sword	2	
39-40	Antenna pos., up	sword	2	
41	Altitude or Heave output, h_output	byte	1	1 = Altitude 2 = Heave (see section 6.5)
42	Cutoff frequency for Heave HP filter	byte	1	Hz*100 (see section 6.5.1)
43	Cutoff frequency for Heave LP filter	byte	1	Hz*10, must be not less than cutoff frequency for Heave HP filter, or zero
44-45	Target position, right	sword	2	Target position relative to the INS for Heave calculation, lever, m*100
46-47	Target position, forward	sword	2	
48-49	Target position, up	sword	2	
50-57	INS device name	char	8	<b>only read</b> , change is ignored
58	Baro_enabled	byte	1	0 = disabled; 1 = enabled
59	Reserved	byte	1	

The INS calculates the check sum of received parameters and returns it for a checking. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (2 bytes).

**Notes:**

1. The most easy and sure way to change above parameters is using the Tersus INS Demo Program.
2. Before using **LoadINSpar** command it is necessary to use **ReadINSpar** command (see below) to read parameters from the INS at first. After that user can change some parameters listed in the Table 6.30, and to send back all block of parameters to the Tersus INS.
3. Default time 30 seconds of the initial alignment can be changed but only in agreement with developers of the Tersus INS.
4. It is necessary to set current latitude, longitude and altitude for setting the initial position in case of the GNSS data may be not available at the INS start.
5. It is necessary to set current latitude, longitude, altitude, year, month, day before hard/soft iron calibration of the INS magnetometers (see section 6.7).
6. Baro\_enabled switch enables or disables using of the pressure sensor data for the INS altitude correction. On default it is enabled. See section 6.5 for details.

**6.3.5. ReadINSpar command**

The ReadINSpar command (code 0x41 in the “Payload” field, see the Table 6.2) is used to read block of the Tersus INS parameters (60 bytes) from the INS nonvolatile memory.

After receiving ReadINSpar command, the INS sends out the message with structure according to Table 6.2 and payload shown in the Table 6.31.

**Table 6.31. Payload of the INS answer on the ReadINSpar command (block of parameters read from the INS)**

Byte	Parameter	Format	Length	Note
0-1	Data rate	word	2	Hz
2-3	Initial alignment time	word	2	seconds
4-7	Magnetic declination, Mdec	longint	4	degrees*100
8-11	Latitude	longint	4	degrees*1e7
12-15	Longitude	longint	4	degrees*1e7
16-19	Altitude	longint	4	meters*100
20	Date (Year from 2000)	byte	1	0 to 255
21	Date (Month)	byte	1	1 to 12
22	Date (Day)	byte	1	1 to 31
23-24	Alignment angle A1	sword	2	Angles of INS mounting on the

25-26	Alignment angle A2	sword	2	carrier object, degrees*100 (see Appendix B)
27-28	Alignment angle A3	sword	2	
29-30	INS mount, right	sword	2	INS mounting lever relative to the object center of gravity, m*100 (see section 6.6)
31-32	INS mount, forward	sword	2	
33-34	INS mount, up	sword	2	
35-36	Antenna pos., right	sword	2	GNSS antenna mounting lever relative to the INS, meters*100
37-38	Antenna pos., forward	sword	2	
39-40	Antenna pos., up	sword	2	
41	Altitude or Heave output, h_output	byte	1	1 = Altitude 2 = Heave (see section 6.5)
42	Cutoff frequency for Heave HP filter	byte	1	Hz*100 (see section 6.5.1)
43	Cutoff frequency for Heave LP filter	byte	1	Hz*10, must be not less than cutoff frequency for Heave HP filter, or zero
44-45	Target position, right	sword	2	Target position relative to the INS for Heave calculation, lever, m*100
46-47	Target position, forward	sword	2	
48-49	Target position, up	sword	2	
50-57	INS device name	char	8	
58	Baro_enabled	byte	1	0 = disabled; 1 = enabled
59	Reserved	byte	1	

See Notes to the section 6.3.4. LoadINSpar command.

### 6.3.6. GetDevInfo command

The GetDevInfo command (code 0x12 in the “Payload” field) is used to get detailed information about devices installed in the INS:

- 1) INS processor;
- 2) IMU (AHRS);
- 3) GNSS receiver;
- 4) Pressure sensor.

As answer the INS sends out the message with structure according to the Table 6.2 and payload shown in the Table 6.32.

**Table 6.32. Payload of the INS answer on the GetDevInfo command**

Byte	Parameter	Format	Length	Note
0-7	ID_sn	char	8	Integrated device (INS) s/n
8-47	ID_fw	char	40	INS firmware version
48	Press_Sens	byte	1	Pressure sensor: 0 = absent, 1= Type1, 2= Type2
49	IMU_type	byte	1	IMU type (1=AHRS)

<b>50-57</b>	IMU_sn	<b>char</b>	<b>8</b>	IMU (AHRS) s/n
<b>58-97</b>	IMU_fw	<b>char</b>	<b>40</b>	IMU (AHRS) firmware version
<b>98-113</b>	GNSS_model	<b>char</b>	<b>16</b>	GNSS receiver model
<b>114-129</b>	GNSS_sn	<b>char</b>	<b>16</b>	GNSS receiver product s/n
<b>130-145</b>	GNSS_hw	<b>char</b>	<b>16</b>	GNSS receiver hardware version
<b>146-161</b>	GNSS_fw	<b>char</b>	<b>16</b>	GNSS receiver firmware version
<b>162-163</b>	GPS_week	<b>word</b>	<b>2</b>	GPS reference week number
<b>164</b>	GNSS_data_rate	<b>byte</b>	<b>1</b>	GNSS receiver max data rate, Hz
<b>165</b>	Reserved	<b>byte</b>	<b>1</b>	Reserved

### 6.3.7. GetBIT command

The Tersus INS has continuous built-in monitoring of its health. In both “Continuous” and “On Request” operation modes the INS sends out the Unit Status Word (USW) in each data block (see Table 6.4, 6.7, 6.8, 6.9, 6.10, 6.11, 6.12 and 6.18). The USW is described in the section 6.9.

The USW can be got in any time if the INS is in Idle or “On Request” operation mode (after SetOnRequestMode command). For this the **GetBIT** command (code 0x1A in the “Payload” field) is used. In answer the INS sends out the message with data according to the Table 6.33.

**Table 6.33. Payload of the INS answer on the GetBIT command**

Byte number	0 – 1	2 – 3
Parameter	Utermo100	USW
Length	2 byte word	2 byte word

In the Table 6.33 Utermo100 is the INS temperature in 1/100 °C increments.

## 6.4. Control of the GNSS receiver

### 6.4.1. GNSS receiver parameters

User can get information about the GNSS receiver model, serial number, firmware version and data rate using GetDevInfo command (see section 6.3.6).

Setting of the GNSS receiver parameters is available for INS firmware version since 2.0.1.2 and is performed by the Tersus INS Demo Program – see User’s Manual, section “10.2. Control of the GNSS receiver” for details. There are the next parameters that can be changed:

- **COM2\_data** – allows to choose GNSS data set for output through COM port 2 (see Table 6.34)

**Table 6.34 COM2\_data values**

COM2_data value	Data set
0	No data
1	Raw GNSS
2	NMEA GGA, VTG, ZDA

- **NMEA\_set** – allows to set needed NMEA messages for output through COM port 2 (see Table 6.35):

**Table 6.35 NMEA\_set value**

Bit	Parameter	Description
0	GPGGA	0 – unset 1 – set
1	GPGSA	0 – unset 1 – set
2	GPRMC	0 – unset 1 – set
3	GPVTG	0 – unset 1 – set
4	GPZDA	0 – unset 1 – set
5	Reserved	–
6	Reserved	–
7	Reserved	–

By default INS outputs GPGLA, GPVTG and GPZDA messages if COM2\_data value is set to 2 (see Table 6.34).

- **GNSS\_raw\_data\_frq** – allows to output GNSS data with specified frequency (see Table 6.36).

**Table 6.36. GNSS\_raw\_data\_frq values**

GNSS_raw_data_frq value	Frequency, Hz
0	No raw data
1	1
2	2
3	4
4	5
5	10
6	20

- **GNSS\_com2\_bps** – sets baud rate of COM2 which outputs GNSS data (see Table 6.37).

**Table 6.37. GNSS\_com2\_bps values**

GNSS_com2_bps value	Baud rate, bps
0	115200
1	230400
2	460800
3	921600

- **GNSS\_corr\_type** – specifies type of GNSS correction which should be used. (see Table 6.38):
  - **No correction** – no GNSS corrections will be used;
  - **AUTO** – both SBAS and DGPS correction data will be used;
  - **SBAS** – correction data from Satellite Based Augmentation Systems (SBAS) will be used;
  - **DGPS** – transmitted from a base station Differential GPS (DGPS) correction data will be used.

Default value is “AUTO” (GNSS\_corr\_type=1).

**Table 6.38. GNSS\_corr\_type values**

GNSS_corr_type value	Type of correction
0	No correction
1	AUTO
2	SBAS
3	DGPS

- **SBAScontrol** – specifies type of SBAS correction (see Table 6.39). Default value is “Auto SBAS” (SBAScontrol=1);

**Table 6.39. SBAScontrol values**

SBAScontrol value	Type of SBAS correction
0	No SBAS
1	AUTO
2	ANY
3	WAAS
4	EGNOS
5	MSAS
6	GAGAN
7	QZSS

- **GNSS\_corr\_format** – specifies format of differential correction data (see Table 6.40). Default value is “Auto” (GNSS\_corr\_format=0);

**Table 6.40. GNSS\_corr\_format values**

GNSS_corr_format value	Type of format
0	AUTO
1	RTCM
2	RTCMV3

- **GNSS\_com3\_bps** – sets baud rate of COM3 which provides input of the GNSS corrections (see Table 6.41).

**Table 6.41. GNSS\_com3\_bps values**

GNSS_com3_bps value	Baud rate, bps
0	9600
1	14400
2	19200
3	38400
4	57600
5	115200

**Note:** COM3 port can be used for input of the GNSS corrections only if GPRMC parameter is set to zero (see below).

- **GPRMC** – allows to output \$GPRMC log with the recommended minimum navigation data provided by the GNSS receiver through COM3 port with specified frequency (see Table 6.42). Default value is “No” (GPRMC =0).

**Table 6.42. GPRMC values**

GPRMC value	Frequency, Hz
0	No GPRMC data
1	1
2	2
3	4
4	5
5	10
6	20

**Note:** If GPRMC parameter is set to nonzero value then COM3 port can't be used for input of the GNSS corrections.

- **PPS\_switch** – allows to output PPS signal (see Table 6.43). Default value is “Enabled” (PPS\_switch =0).

**Table 6.43 PPS\_switch values**

PPS_switch value	Enabled or disabled
0	Enabled
1	Disabled

- **PPS\_polarity** – specifies polarity of the PPS pulse (see section “5.3. PPS description”). Table 6.44 shows available values of the PPS\_polarity parameter. Default value is “Negative” (PPS\_polarity =0).

**Table 6.44. PPS\_polarity values**

PPS_polarity value	Polarity
0	Negative
1	Positive

- **PPS\_period** – sets period of the pulse in seconds (see Table 6.45). Default value is “1.0” (PPS\_period =6).

**Table 6.45. PPS\_period values**

PPS_period value	Period, sec
0	1.0
1	0.05
2	0.1
3	0.2
4	0.25
5	0.5
6	1.0
7	2.0
8	3.0
9	4.0
10	5.0
11	6.0
12	7.0
13	8.0
14	9.0
15	10.0
16	11.0
17	12.0
18	13.0
19	14.0
20	15.0
21	16.0
22	17.0
23	18.0
24	19.0
25	20.0

- **PPS\_pulse\_width** – sets pulse width of the PPS signal in microseconds. Default value is **PPS\_pulse\_width =1000**.
- **MARK\_switch** – allows to control the processing of the mark input signal through GPIO pin of the main INS connector (see section “5.4. GPIO description”). Table 6.46 shows the MARK\_switch values. Default value is “Disabled” (MARK\_switch =0);

**Table 6.46. MARK\_switch values**

MARK_switch value	Mark signal processing
0	Disabled
1	Enabled

- **MARK\_polarity** – specifies polarity of the pulse at a mark input (see Table 6.47). Default value is “Negative” (**MARK\_polarity =0**);

**Table 6.47. MARK\_polarity values**

MARK_polarity value	Polarity
0	Negative
1	Positive

- **MARK\_timebias** – sets an offset, in nanoseconds, to be applied to the time the mark input pulse occurs. Default value is MARK\_timebias =0;
- **MARK\_timeguard** – sets a time period, in milliseconds, during which subsequent pulses after an initial pulse are ignored. Default value is MARK\_timeguard =4, minimum value is MARK\_timeguard =2.

***Important note:*** It is necessary to power off / on the INS after changing any of GNSS receiver parameters to restart the GNSS receiver with new settings.

## 6.5. Altitude and Heave calculation

At its operation the Tersus INS calculates position using its sensors data with correction from the onboard GNSS receiver. Also, for altitude calculation the INS can use correction from the onboard pressure sensor.

In practice the GNSS altitude data are much less accurate than the horizontal position (because of high vertical dilution of precision). Using a static pressure sensor (barometer), as an aiding sensor for the altitude, increases the vertical accuracy. Though the relation between altitude and pressure is dependent on many factors, the most important is the “weather”.

The Tersus INS allows two variants of the altitude correction that depends on the Baro\_enabled switch:

- a) correction by altitude and vertical velocity provided by GNSS data (Baro\_enabled=0);
- b) correction by barometric altitude calculated using pressure sensor data and vertical velocity provided by GNSS data (Baro\_enabled=1).

The default value is Baro\_enabled=1. User can change this value using the LoadINSpar command (see Table 6.30, byte #58) or using the INS Demo Program (that is more easy).

***Important note:*** To measure barometric altitude the pressure sensor in the INS must have access to the ambient external pressure. Also the pressure sensor must not be exposed to high speed air streams. So if the INS is installed inside a pressurized cabin or outside the high-speed object, please set Baro\_enabled=0 to switch to the GNSS altitude for INS correction.

Note in both variants of the INS altitude correction, the initial altitude is equal to altitude provided by the GNSS receiver if it has solution. If GNSS data are not available then the initial altitude is equal to its value stored in the INS nonvolatile memory. There initial altitude can be changed using the LoadINSpar command (see Table 6.30, bytes #16-19) or using the INS Demo Program (that is more easy)

Also the INS-D can calculate heave for marine applications. Heave is a ship motion along the vertical axis.

The **h\_output** switch set what INS-D data are output:

- 1 – altitude;
- 2 – heave.

Value of the h\_output switch can be stored using the LoadINSpar command (see Table 6.30, byte #41) or using the INS Demo Program (that is more easy).

**Notes:**

1. Tersus INS-B and INS-P units do not calculate heave, so setting the h\_output=2 switch will cause zero output.
2. Heave calculation also can use data from the pressure sensor (at Baro\_enabled=1). In that case the pressure sensor in the INS must have access to the ambient external pressure, and the pressure sensor must not be exposed to high speed air streams.

### **6.5.1. Adjustment of the algorithm of heave calculation in INS-D**

To calculate the heave as the INS-D vertical position with respect to its equilibrium position, the vertical acceleration is doubly integrated. However, because signals from accelerometers always contain a DC component as well as spurious low frequency components, after integration the heave error is accumulated and increases with time significantly. To avoid such error, integrated signals are filtered by High-Pass (HP) filter. Also, to decrease noise the Low-Pass (LP) filter can be applied.

One of the main adjustment parameters is cutoff frequency for heave HP filter, fh\_HP. It must be much less than the main frequency of a ship vertical motion. But very low value of the fh\_HP allow accelerometers' bias instability to affect the heave accuracy. The default value is fh\_HP = 0.02 Hz that should be enough for intensive vertical motion of a ship.

Values of HP and LP cutoff frequencies for the heave filter can be set using the LoadINSpar command (see Table 6.30, bytes #42 and 43) or using the INS Demo Program (that is more easy).

Power\_fft\_min – the threshold of fast Fourier transform (FFT) spectrum power at which the lead-lag filter parameters are recalculated. F\_fft parameter sets the frequency of the FFT usage for lead-lag filter parameters recalculation. The default values are Power\_fft\_min = 40 and F\_fft = 0.04.

Values of Power\_fft\_min and F\_fft for the heave filter can be set using the INS Demo Program – see INS Demo Program User's Manual, section "10.3.1. Adjustment of the algorithm of heave calculation".

Note. initialization of the adaptive algorithm of heave calculation takes approximately 100 seconds. During this initialization heave is calculated roughly.

### **6.5.2. Heave calculation for chosen point of the carrier object**

Usually heave is calculated for place of the INS mounting on the carrier object. But it is possible to set desirable point on the carrier object for heave calculation. For this purpose please set coordinates of this point relative to the INS-D position, in the object axes – on the right, forward and up. For this please use the LoadINSpar command (see Table 6.30, bytes #44-49) or the INS Demo Program (that is more easy).

### **6.6. Acceleration compensation at object swaying**

It is possible to increase the INS orientation accuracy at the carrier object swaying if to compensate linear acceleration at place of the INS mounting. For this purpose please set coordinates of the INS mounting relative to the center of the object swaying (usually this is object center of gravity).

These coordinates are set in meters in such sequence of the object directions: right, forward, up. For this please use the LoadINSpar command (see Table 6.30, bytes #29-34) or the INS Demo Program (that is more easy).

### **6.7. Calibration of the Tersus INS on hard and soft iron**

The Tersus INS software allows compensation of hard and soft iron effects of the carrier object on the heading determination accuracy. For this purpose, field calibration of the INS magnetometers is provided (see Appendix A, The INS calibration). Tersus utilizes several types of field calibration depending on the carrier object type.

**Note INS does not require calibration of its magnetometers on hard/soft iron if “Use\_mags” switch is disabled in the “Settings” tab of «Correction options...» window of the INS Demo Program.**

The next types of the calibration are realized in the Tersus INS firmware:

- 3D calibration;
- 2D-2T calibration;
- 2D calibration;
- VG3D calibration (since firmware version 2.6.2.2);
- on-the-fly VG3D calibration (since firmware version 2.6.2.2).

The next commands are used for the INS calibration:

Start3DClb;	StartClbRun;	ClearClb;
StartVG3DClb;	StopClbRun;	ExitClb;
Start2D2TClb;	FinishClb;	GetClbRes;
Start2DClb;	AcceptClb;	StartVG3Dclb_flight;
		StopVG3Dclb_flight.

All these commands have the byte structure shown in the Table 6.2. Payload for all commands has length 1 byte and contains code of the command. See Appendix C for examples of these commands.

### 6.7.1. Start3DClb command for INS 3D calibration

The **3D calibration** is designed for carrier objects that can operate in full heading, pitch and roll ranges. At this calibration the carrier object should be rotated in all these ranges.

To start the 3D calibration the host computer sends to the INS the Start3DClb command (code 0x23 in the “Payload” field) followed by message with block of parameters listed in the Table 6.48. This message have the byte structure shown in the Table 6.2, and should be sent without pause after sending the Start3DClb command.

**Table 6.48. Payload of the message following after the Start3DClb, StartVG3DClb, Start2D2TClb and Start2DClb commands (the block of parameters loaded to the INS)**

Byte	Parameter	Format	Length	Note
0-3	Reserved	byte	4	
4-5	Time of data accumulation in one run	word	2	Seconds
6-9	Latitude	float	4	Degrees
10-13	Longitude	float	4	Degrees
14-17	Altitude	float	4	Meters
18-21	Date (Year, Month, Day)	float	4	Year + (Month -1)/12 + Day/365

The INS calculates the check sum of received parameters and returns it for a checking. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word).

Then the INS starts process of initial alignment. This process includes the INS gyros bias estimation, therefore don't move the INS during its initial

alignment. Default time of the initial alignment is 30 seconds and can be changed (see section 6.3.4. LoadINSpar command) but only in agreement with developers of the Tersus INS.

After completing of the initial alignment the INS gives out the block of the initial alignment data (see the Table 6.28, Table 6.29) and starts data accumulation during time specified in message sent after the Start3DClb command (see the Table 6.48).

During the INS data accumulation the object should be rotated in full azimuth, pitch and roll ranges. For example the object is rotated in the horizon plane (the Z-axis is up) with periodical stops about each 90 degrees for tilting in pitch and roll. After full 360° rotation the object with the INS is turned over (the Z-axis is down) and the procedure described above should be repeated. During this calibration the range of pitch and roll angles changing must be as much as possible.

**Note:** there is estimation of 3D calibration quality in terms of possible INS heading accuracy. To allow this possibility it is necessary to include additional rotation of the INS with the carrier object in the horizon plane on about 360 degrees or more with pitch and roll near the level. Acceptable pitch and roll change can be set using INS Demo Software by the “Pitch/Roll threshold” parameter in the “Device Options”.

After set accumulation time is reached or StopClbRun command is sent to the INS (see section 6.7.2 for details) the INS finishes data accumulation and calculates the calibration parameters.

After calculation of the calibration parameters that takes <0.5 seconds, the INS gives out message with the calibration results (see the Table 6.49) and it waits one of the next commands:

- the AcceptClb command (see section 6.7.3) to accept and save the calibration parameters (usually if the “Calibration success” byte in the INS message is nonzero and corresponds to satisfactory INS heading accuracy (see the Table 6.49 and Note below it));
- or the ExitClb command (see section 6.7.4 to exit from calibration procedure without accepting and saving its results (usually if the “Calibration success” byte in the INS message is equal to 0 or corresponds to not satisfactory INS heading accuracy (see the Table 6.49 and Note below it)).

The INS answers on these commands with checksum and goes to idle mode.

**Table 6.49. Payload of the INS message after calibration completed**

Byte	Parameter	Format	Length	Note
0	Type of calibration	byte	1	1 for 2D calibration; 2 for 2D-2T calibration; 3 for 3D calibration; 5 for VG3D calibration
1	Number of used calibration runs	byte	1	
2	Percent of used data points	byte	1	for 2D and 3D calibrations only
3	Calibration success	byte	1	0 – calibration is not successful >0 – calibration is successful (see Note below)
4-39	Matrix for soft iron correction	float	9*4	Matrix Tm_c (3×3) by rows
39-51	Matrix for hard iron correction	float	3*4	Matrix Hm_0 (3×1)

**Note:** there is estimation of the calibration quality as predicted INS heading accuracy. So nonzero value of byte #3 “Calibration success” is predicted maximum (3 sigma) heading error of the INS after calibration, in degrees\*10. For example, byte #3 equal to 5 corresponds to the INS accuracy  $\pm 0.5$  deg. If calibration is successful but INS cannot estimate predicted accuracy it returns byte #3 equal to 255.

### 6.7.2. StopClbRun command

After receiving the StopClbRun command (code 0x20 in the “Payload” field) the INS early stops data accumulation in the calibration run before set accumulation time is reached.

Then the calibration procedure continues in the same way as after set accumulation time was reached.

### 6.7.3. AcceptClb command

The AcceptClb command (code 0x2E in the “Payload” field) is applied to accept the calibration parameters and to save them to the INS nonvolatile memory. This command can be used in the end of the calibration procedure.

The INS answers on this command. The INS calculates the check sum of the message (without its header and check sum) and returns it for a checking.

Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word).

#### 6.7.4. ExitClb command

The ExitClb command (code 0xFE in the “Payload” field) is used to exit from the calibration without any calculations in the INS and without saving any calibration parameters. The INS stops work in operating mode and goes into the idle mode.

The INS answers on this command. The INS calculates the check sum of the message (without its header and check sum) and returns it for a checking. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word).

#### 6.7.5. StartVG3DClb command for INS VG3D calibration

Since firmware version 2.6.2.2 the INS provides **VG3D calibration**. The **VG3D calibration** is designed for carrier objects that can operate in full heading, pitch and roll ranges. VG3D calibration is similar to 3D calibration but allows performing simpler rotation than is necessary for 3D calibration.

**Note:** VG3D calibration is at the testing stage. Please contact Tersus about the possibility of using the VG3D calibration.

To start the VG3D calibration the host computer sends to the INS the StartVG3DClb command (code 0x25 in the “Payload” field) followed by message with block of parameters listed in the Table 6.48. This message have the byte structure shown in the Table 6.2, and should be sent without pause after sending the StartVG3DClb command.

The INS calculates the check sum of received parameters and returns it for a checking. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word).

Then the INS starts process of initial alignment. This process includes the INS gyros bias estimation, therefore don't move the INS during its initial alignment. Default time of the initial alignment is 30 seconds and can be changed (see section 6.3.4. LoadINSpar command) but only in agreement with developers of the Tersus INS.

After completing of the initial alignment the INS gives out the block of the initial alignment data (see the Table 6.28, Table 6.29) and starts data accumulation during time specified in message sent after the StartVG3DCIb command (see the Table 6.48).

During the INS data accumulation the object should be rotated in full azimuth range and maximum possible pitch and roll ranges. Allowed object motion should be agreed with Tersus.

After set accumulation time is reached or StopClbRun command is sent to the INS (see section 6.7.2 for details) the INS finishes data accumulation and calculates the calibration parameters.

After calculation of the calibration parameters that takes <0.5 seconds, the INS gives out message with the calibration results (see the Table 6.49) and it waits one of the next commands:

- the AcceptClb command (see section 6.7.3) to accept and save the calibration parameters (usually if the “Calibration success” byte in the INS message is nonzero and corresponds to satisfactory INS heading accuracy (see the Table 6.49 and Note below it));
- or the ExitClb command (see section 6.7.4) to exit from calibration procedure without accepting and saving its results (usually if the “Calibration success” byte in the INS message is equal to 0 or corresponds to not satisfactory INS heading accuracy (see the Table 6.49 and Note below it)).

The INS answers on these commands with checksum and goes to idle mode.

#### **6.7.6. Start2D2TCIb command for INS 2D-2T calibration**

The **2D-2T calibration** is designed for objects that operate in full azimuth range but with limited range of pitch and roll angles. This calibration procedure involves a few full 360° rotations of the object in azimuth with different pitch angles.

To start the 2D-2T calibration the host computer sends to the INS the Start2D2TCIb command (code 0x22 in the “Payload” field) followed by message with block of parameters listed in the Table 6.48. This message have the byte structure shown in the Table 6.2, and should be sent without pause after sending the Start2D2TCIb command.

The INS calculates the check sum of received parameters and returns it for a checking. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word).

The 2D-2T calibration procedure involves a few runs with full 360° rotations of the object with installed INS in heading with different pitch angles.

Set the object to the first pitch angle (usually the minimum pitch angle is set first). Then send the StartClbRun command followed by message (see section 6.7.6) to start the first run of the calibration.

After receiving the StartClbRun command with its message, the INS calculates the check sum of received block of parameters and returns it for checking. This check sum should be equal to the check sum in the StartClbRun command message that was sent to the INS. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word).

Then the INS starts process of initial alignment. This process includes the INS gyros bias estimation, therefore don't move the INS during its initial alignment. Default time of the initial alignment is 30 seconds and can be changed (see section 6.3.4. LoadINSPar command) but only in agreement with developers of the Tersus INS.

After completing of the initial alignment the INS gives out the block of the initial alignment data (see the Table 6.28, Table 6.29) and starts data accumulation during time specified in message sent after the Start2D2TClb command (see the Table 6.48). Rotate object in azimuth with approximately constant pitch and roll. This rotation must include one or more full 360 deg turns. Please, correct the time required for such rotation in the «Time of data accumulation» field of the message (Table 6.48) to provide necessary rotation.

After set accumulation time is reached or StopClbRun command is sent to the INS (see section 6.7.2 for details) the INS gives out message with result of the calibration run (see the Table 6.50).

**Table 6.50. Payload of the INS message after each calibration run of the 2D-2T calibration**

Byte	Parameter	Format	Length	Note
0	Type of calibration	byte	1	2 for 2D-2T calibration
1	Calibration run	byte	1	1, 2, ...
2	Percent of used data points	byte	1	
3	Calibration success	byte	1	0 – unsuccessful; >0 – successful (see Note below)
4-7	Reserved	float	4	
8-11	Average pitch, deg	float	4	
12-15	Average roll, deg	float	4	
16-27	Reserved	float	3*4	
28-29	USW	word	2	See section 6.9

If the “Calibration success” byte is zero (calibration run is not successful) in the INS answer Table 6.50 then this run will be excluded from calculations in the 2D-2T calibration procedure. To complete this procedure, it is necessary to perform at least two successful runs with essentially different pitch angles.

**Note:** there is estimation of the calibration quality as predicted INS heading accuracy. So nonzero value of byte #3 “Calibration success” is predicted maximum (3 sigma) heading error of the INS after calibration, in degrees\*10. For example, byte #3 equal to 5 corresponds to the INS accuracy  $\pm 0.5$  deg. If calibration is successful but INS cannot estimate predicted accuracy it returns byte #3 equal to 255.

After each calibration run completed the INS sends message with payload shown in the Table 6.50, and it waits one of the next three commands from the host computer:

1. StartClbRun command followed by its message (see section 6.7.7) to start new calibration run. Before send this command the object should be turned to the next pitch angle. After sending this command the above described procedure of the calibration run with object rotation in heading should be performed.
2. FinishClb command (see section 6.7.8 for details) to finish the calibration procedure and to calculate calibration parameters. After that the INS gives out message with the calibration results (see the Table 6.48) and waits one of the two commands:
  - a. the AcceptClb command (see section 6.7.3) to accept and save the calibration parameters (usually if the “Calibration success” byte in

- the INS message is nonzero and corresponds to satisfactory INS heading accuracy (see the Table 6.49 and Note below it));
- b. or the ExitClb command (see section 6.7.4) to exit from calibration procedure without accepting and saving its results (usually if the “Calibration success” byte in the INS message is equal to 0 or corresponds to not satisfactory INS heading accuracy (see the Table 6.49 and Note below it)).

The INS answers on these commands with checksum and goes to idle mode.

3. ExitClb command (see section 6.7.4) In this case the calibration finishes without any calculations in the INS and without saving any calibration parameters. The INS answers on this command with checksum and goes into the idle mode.

**Notes:**

1. Rotation of the object with the INS in heading must include one or more full 360° turns. Please, correct the time required for saving data in the «**Accumulation time**» window to attain necessary rotations.
2. During calibration run pitch and roll angles should be approximately constant.
3. If place of the INS mounting on the object is changed, or if the object is changed, then the INS should be re-calibrated on the hard and soft iron of this object.

**6.7.7. StartClbRun command**

If calibration procedure includes more than one run (like 2D-2T calibration) then the StartClbRun command (code 0x2B in the “Payload” field) is used to start each run.

For unification with the StartClbRun command for some other calibration types, this command must be followed by message with block of parameters listed in the Table 6.51. But for the 2D-2T calibration the values of those 6 bytes don’t influence, so these 6 bytes may be any, for example zeros. Only requirement is that this message should have the byte structure shown in the Table 6.2, and should be sent without pause after sending the StartClbRun command.

**Table 6.51. Payload of the message following after the StartClbRun command (block of parameters loaded to the INS)**

Byte	Parameter	Format	Length	Note
------	-----------	--------	--------	------

<b>0-3</b>	Reserved	<b>float</b>	<b>4</b>	
<b>4-5</b>	Reserved	<b>word</b>	<b>2</b>	

After receiving the StartClbRun command the INS calculates the check sum of received parameters and returns it for a checking. This check sum should be equal to the check sum in the StartClbRun command message that was sent to the INS. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word).

### 6.7.8. FinishClb command for INS 2D-2T calibration

After receiving the FinishClb command (code 0x2C in the “Payload” field) the INS finishes the calibration procedure with multiple runs (like 2D-2T) and calculates the calibration parameters. After that the INS gives out message with the calibration results (see the Table 6.49).

Then the INS waits one of the next commands:

- the AcceptClb command (see section 6.7.3) to accept and save the calibration parameters;
- or the ExitClb command (see section 6.7.4) to exit from calibration procedure without accepting and saving its results.

### 6.7.9. Start2DClb command for INS 2D calibration

The **2D calibration** is designed for carrier objects that operate in full azimuth range but with small pitch and roll angles (not more than a few degrees). This calibration procedure involves full 360° rotation of the carrier object in azimuth. During this rotation pitch and roll angles must be as close to zero as possible.

To start the 2D calibration the host computer sends to the INS the Start2DClb command (code 0x21 in the “Payload” field) followed by message with block of parameters listed in the Table 6.48. This message have the byte structure shown in the Table 6.2, and should be sent without pause after sending the Start2DClb command. Note that first 4 bytes in the payload (Reference azimuth) do not influence on the 2D calibration as it is noted in the Table 6.48.

The INS calculates the check sum of received parameters and returns it for a checking. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word).

Then the INS starts process of initial alignment. This process includes the INS gyros bias estimation, therefore don't move the INS during its initial alignment. Default time of the initial alignment is 30 seconds and can be changed (see section 6.3.4. LoadINSPar command) but only in agreement with developers of the Tersus INS.

After completing of the initial alignment the INS gives out the block of the initial alignment data (see the Table 6.28, Table 6.29) and starts data accumulation during time specified in message sent after the Start2DCIb command (see the Table 6.48). Rotate carrier object in azimuth with pitch and roll angles close to zero as possible. This rotation must include one or more full 360 deg turns. Please, correct the time required for such rotation in the «Time of data accumulation» field of the message (Table 6.48) to provide necessary rotation.

After set accumulation time is reached or StopClbRun command is sent to the INS (see section 6.7.2 for details) the INS finishes data accumulation and calculates the calibration parameters.

After calculation of the calibration parameters that takes <0.5 seconds, the INS gives out message with the calibration results (see the Table 6.49) and it waits one of the next commands:

- the AcceptClb command (see section 6.7.3) to accept and save the calibration parameters (usually if the “Calibration success” byte in the INS message is nonzero and corresponds to satisfactory INS heading accuracy (see the Table 6.49 and Note below it));
- or the ExitClb command (see section 6.7.4) to exit from calibration procedure without accepting and saving its results (usually if the “Calibration success” byte in the INS message is equal to 0 or corresponds to not satisfactory INS heading accuracy (see the Table 6.49 and Note below it)).

The INS answers on these commands with checksum and goes to idle mode.

### **6.7.10. ClearClb command**

The ClearClb command (code 0x2F in the “Payload” field) is used to clear parameters of the hard and soft iron calibration from the INS nonvolatile memory.

The INS answers on this command. The INS calculates the check sum of the message (without its header and check sum) and returns it for a checking. Byte structure of this message is shown in the Table 6.2 where payload is the calculated check sum (1 word).

You should clear parameters of the soft and hard iron calibration if you uninstall the INS from object to avoid incorrect azimuth determination with standalone INS.

### 6.7.11. GetClbRes command

The GetClbRes command (code 0x2A in the “Payload” field) can be send from the host computer to check the last calibration results of the INS. As answer on this command the INS sends out the message with the data block near the same as after completing calibration, see the Table 6.52.

**Table 6.52. Payload of the INS answer on request GetClbRes about calibration results**

Byte	Parameter	Format	Length	Note
0	Type of calibration performed	byte	1	0 – INS is not calibrated; 1 – 2D calibration; 2 – 2D-2T calibration; 3 – 3D calibration; 5 – VG3D calibration; >0x80 – INS is calibrated by loading calibration parameters from other software (e.g. Demo software).
1	Number of used calibration runs	byte	1	
2	Reserved	byte	1	
3	Calibration success	byte	1	0 – not successful calibration >0 – successful calibration (see Note below)
4-39	Matrix for soft iron correction	float	9*4	Matrix Tm_c (3×3) by rows
39-51	Matrix for hard iron correction	float	3*4	Matrix Hm_0 (3×1)

**Note:** There is estimation of the calibration quality as predicted INS heading accuracy. So nonzero value of byte #3 “Calibration success” is predicted maximum (3 sigma) heading error of the INS after calibration, in degrees\*10. For example, byte #3 equal to 5 corresponds to the INS accuracy  $\pm 0.5$  deg. If calibration is successful but INS cannot estimate predicted accuracy it returns byte #3 equal to 255.

### 6.7.12. StartVG3Dclb\_flight and StopVG3Dclb\_flight commands for start and finish INS on-the-fly VG3D calibration

Since firmware version 2.6.2.2 the INS provides **on-the-fly VG3D calibration**. It allows to calibrate INS unit during INS ordinary operation without interruption of INS navigation data calculation and output.

To start the on-the-fly VG3D calibration the host computer sends to the INS the StartVG3Dclb\_flight command (code 0x26 in the “Payload” field), i.e.

```
AA 55 00 00 07 00 26 2D 00
```

**Note** these are hexadecimal numbers but not ASCII text symbols.

After receiving of this command INS starts accumulation of magnetometers data for VG3D calibration. At this the bit #7 is set to 1 in INS status word USW for indication of data accumulation process (see Fig.6.1 and section 6.9).

The carrier object with INS unit should be rotated in full azimuth, pitch and roll ranges. For example, airplane should perform at least two full 360° coordinated turns (on right and on left) with maximum roll angles.

After finishing of calibration rotation of the carrier object it is necessary to send the StopVG3Dclb\_flight command (code 0x27 in the “Payload” field) to the INS unit, i.e.

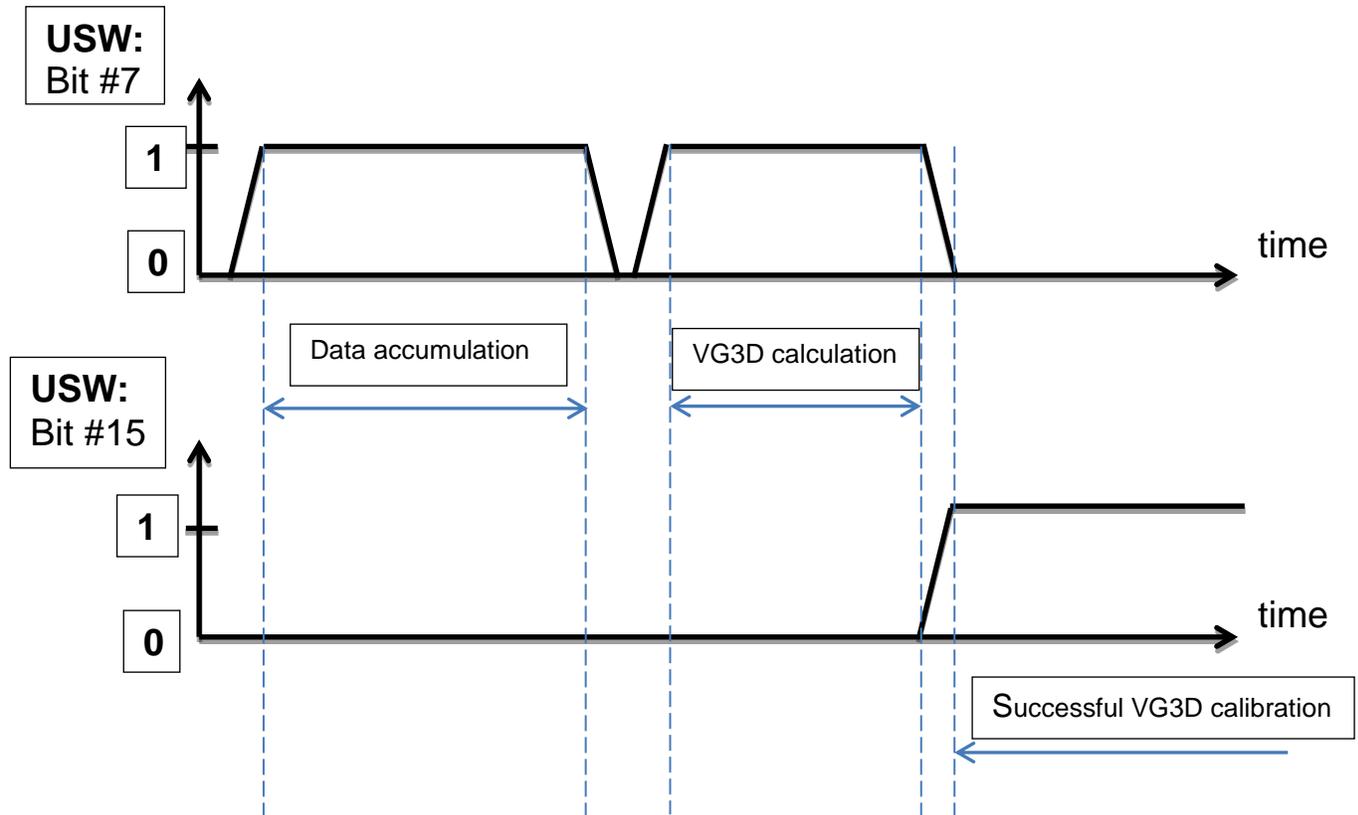
```
AA 55 00 00 07 00 27 2E 00
```

**Note** these are hexadecimal numbers but not ASCII text symbols.

After receiving of this command INS stops data accumulation for VG3D calibration and sets the USW bit #7 to 0 (see Fig.6.1).

Then INS starts calculations for VG3D calibration and sets USW bit #7 to 1 again. In the end of these calculations, if calibration is successful, INS calculates calibration parameters for compensation of hard and soft iron, and stores them to INS nonvolatile memory. Also INS sets the USW bit #15 to 1 to inform the host system that on-the-fly VG3D calibration is performed and successful (see Fig.6.1).

Calculated calibration parameters are applied immediately to INS magnetometers data for compensation of hard and soft iron of the carrier object.



**Fig.6.1. The diagram of indication of on-the-fly VG3D calibration procedure in the USW (Unit Status Word, see section 6.9)**

Note during all steps of on-the-fly VG3D calibration the INS unit continues calculation of navigation data and their output.

Because these calibration parameters are stored to INS nonvolatile memory then they will be applied at all the next INS operations until new calibration is performed or parameters are cleared using the ClearClb command (see section 6.7.10).

On the other hand, if INS unit is uninstalled from the carrier object then it is necessary to clear parameters of the soft and hard iron calibration using the ClearClb command (see section 6.7.10).

Parameters of the on-the-fly VG3D calibration can be checked after INS stop using the GetClbRes command (see section 6.7.11).

## 6.8. INS automatic start

Since firmware version 1.0.2.0 the Tersus INS auto start is implemented that allows start of its operation and data output after power on without any command from the host computer. There is possible to choose desirable output data format for auto start (see section 6.2).

The auto start option can be enabled or disabled using the INS Demo Program, in the “Options / Device options” menu. There is drop-down list “Auto start” where auto start with desirable output data format can be chosen. See INS Demo Program User’s Manual, section “10.5. INS automatic start” for details.

If the auto start option is enabled then after the INS power on the next operations take place:

- Initialization of the onboard GNSS receiver that takes not more than 15 seconds. The INS LED indicator lights yellow.
- Then the INS automatically starts operation from sending out the message AA 55 01 00 08 00 00 00 09 00 (in hexadecimal format) that indicates INS started without any external command. The INS LED indicator changes color to green.
- After that the initial alignment procedure starts when initial orientation angles are calculated and gyros bias is estimated for its next compensation. Therefore don’t move the INS during initial alignment process. If this requirement is not met then large errors may be occurred in orientation angles calculation.

**Note:** Default time of the initial alignment is 30 seconds. It can be changed (see section 6.3.4) but only in agreement with developers of the Tersus INS.

- After completing of the initial alignment the INS gives out message with block of the initial alignment data (see Table 6.27) and starts data output according to the chosen data format. The INS LED indicator lights green.

**Note:** To identify the INS output data format at auto start mode use the INS data identifier in the data block structure (see Table 6.2, byte #3), which is equal to the command code and corresponds to data format according to the Table 6.20. This is implemented in the INS firmware since version 2.1.2.0.

To stop the INS please send the Stop command (see section 6.3.3). After receiving the Stop command the INS stops data calculation and goes to the idle mode. The INS LED indicator changes its color to red. The INS is ready to receive any command from the host computer.

## 6.9. The Unit Status Word definition

The Unit Status Word (USW) provides the INS state information. The low byte (bits 0-7) of USW indicates failure of the INS. If this byte is 0, the INS operates correctly, if it is not 0, see the Table 6.53 for type of failure. The high byte (bits 8-15) contains a warning or is informative for the user. Status of each bit of the USW warning byte is specified in the Table 6.53.

**Table 6.53. The Unit Status Word description**

	Bit	Parameter	Description
Low (failure) byte	0	Initial Alignment	0 – Successful initial alignment 1 – Unsuccessful initial alignment due to INS moving or large changing of outer magnetic field
	1	INS Parameters	0 – Parameters are correct 1 – Parameters are incorrect
	2	Gyroscope Unit	0 – No failure 1 – Failure detected
	3	Accelerometer Unit	0 – No failure 1 – Failure detected
	4	Magnetometer Unit	0 – No failure 1 – Failure detected
	5	Electronics	0 – No failure 1 – Failure detected
	6	GNSS receiver	0 – No failure 1 – Failure detected
	7	On-the-fly VG3D calibration	1 – during data accumulation and calculation 0 -- otherwise
High (warning) byte	8	Incorrect Power Supply	0 – Supply voltage is not less than minimum level 1 – Low supply voltage detected
	9		0 – Supply voltage is not greater than max level 1 – High supply voltage detected
	10	Angular Rate Exceeding Detect	0 – X-angular rate is within the range 1 – X-angular rate is outrange
	11		0 – Y-angular rate is within the range 1 – Y-angular rate is outrange
	12		0 – Z-angular rate is within the range 1 – Z-angular rate is outrange
	13	Large Magnetic Field Detect	0 – Total magnetic field is within the normal range 1 – Total magnetic field limit is exceeded
	14	Environmental Temperature	0 – Temperature is within the operating range 1 – Temperature is out of the operating range
	15	On-the-fly VG3D calibration	0 – No on-the-fly calibration 1 – Successfully calibrated during current run

## 6.10. Post-processing of the INS and GNSS data

For applications requiring highly accurate post-mission position, velocity and orientation, the INS and GNSS data post-processing can be used. Contact Tersus support for more detail about post-processing software.

For such post-processing the raw GNSS and raw IMU data should be used.

The Tersus INS uses the second COM port (COM2) for output the raw GNSS receiver data (see section 6.10.1). Starting from the INS s/n F1560005 presence of the COM2 is default option. For raw GPS data recording from receiver an external program **GNSS\_Reader** can be used. The GNSS\_Reader is supplied with the Tersus INS Demo software.

File with raw IMU data can be created from files .bin, .prm created by INS Demo Program. Use “Convert to IMU data” item in the “Convert” menu – see the Tersus INS Demo Program User’s Manual, section “12.2. Raw IMU data generation”.

For more details about post-processing see Section “12. INS and GNSS data post-processing” in the INS Demo Program User’s Manual.

### 6.10.1. Raw GNSS receiver data

The Tersus INS uses the COM2 port for output the raw GNSS receiver data. The INS starts output of these data after power on and completing of the receiver initialization (when the INS LED indicator switches from yellow to red).

Raw GNSS data consist of necessary logs for post-processing. There are synchronous and asynchronous logs. The data for synchronous logs are generated with set frequency. In order to output the most current data as soon as they are available, asynchronous data are generated at irregular intervals. List of generated logs is shown in the Table 6.54.

**Table 6.54. Logs of raw GNSS data**

Log	Description
<b>Asynchronous</b>	
CLOCKSTEERING	Clock steering status
GLOCLOCK	GLONASS clock information
ALMANAC	Decoded GPS Almanac
GPSEPHEM	Decoded GPS ephemerides
RAWALM	Raw Almanac data
RAWEPHEM	Raw ephemeris
RAWGPSSUBFRAME	Raw subframe data
RAWCNAVFRAME	Raw CNAV frame data
RAWGPSWORD	Raw navigation word
GLOALMANAC	Decoded GLONASS Almanac
GLOEPHEMERIS	Decoded GLONASS ephemeris
GLORAWALM	Raw GLONASS Almanac data
GLORAWEPHEM	Raw GLONASS Ephemeris data
GLORAWFRAME	Raw GLONASS frame data
GLORAWSTRING	Raw GLONASS string
<b>Synchronous</b>	
CLOCKMODEL	Current clock model status
TIMESYNC	Synchronize time between GNSS receivers
TIME	Time data
RANGE	Satellite range information
RANGEGPSL1	L1 version of the RANGE log
TRACKSTAT	Tracking status

## 6.11. Synchronization of INS data with LiDAR and other devices

Synchronization of the Tersus INS measurements with data from other devices is very important in many applications. The INS can trigger other devices, or an external device can trigger the INS measurements.

### 6.11.1. Synchronization pulses issued by INS

To trigger external devices the Tersus INS outputs accurate pulse per second (PPS) signal generated by on-board GNSS receiver. The PPS signal is provided by appropriate pin of the INS main connector (see Table 5.1 and Table 5.2). See section “5.3. PPS description” for details.

Adjustment of the PPS signal (pulse polarity, period, width) can be done using the Tersus INS Demo Program – see User’s Manual, section “13.1.1. Control of PPS output signal” for details.

### **6.11.2. Triggering of INS by external devices**

The Tersus INS output data can be get on request by two ways.

At the first, the INS can operate in the “On Request” (on demand) mode when the INS sends one data block after each Request command issued from the host computer. See section “6.3.2. SetOnRequestMode command – getting INS data on request (on demand)” for details.

The second way of the INS data synchronization is using of General Purpose Input Output (GPIO) line to trigger the INS output data by external devices. GPIO line is connected to appropriate pin of the INS main connector (see Table 5.1 and Table 5.2). Also, see section “5.4. GPIO description”. Currently the GPIO is used to trigger GNSS raw data in INS.

### **6.11.3. Synchronization of INS data with LiDAR**

For Tersus INS operation with LiDAR it is necessary to make the next connections:

- use INS COM1 port for output of the main INS data;
- use INS COM2 port for output of GNSS raw data or NMEA data set generated by INS onboard GNSS receiver;
- connect INS COM3 port for output of \$GPRMC messages issued by INS onboard GNSS receiver to LiDAR;
- connect pulse-per-second (PPS) signal generated by INS onboard GNSS receiver to LiDAR;
- optionally, for camera synchronization – connect General Purpose Input Output (GPIO) line for input signal from camera to trigger specific GNSS receiver data (MARK2POS and MARK2TIME logs)

All these data and signals are available on the main INS connector – see section “5. Electrical interface”. For adjustment of INS data and signals use INS Demo Program. See INS Demo Program User’s Manual, section “13.3. INS operation with LiDAR” for details.

## 6.12. Change of the main COM port baud rate

COM1 is the main COM port. It is used for commands and data transfer between the Tersus INS and the host computer.

The default baud rate for the INS COM1 port is set to 115200 bps (maximum for the standard COM-port). Since firmware version 2.2.0.0 the INS supports different baud rates: 4800, 9600, 14400, 19200, 38400, 57600, 115200, 230400 and 460800 bps.

Change of the INS COM1 port baud rate can be done using INS Demo Program since version 2.0.19.78 from 03/18/2016. See INS Demo Program User's Manual, section "4.2.4. Change of the main COM port baud rate" for details.

Note the same baud rate must be set for COM port of the host computer.

## 6.13. Limitation of the INS maximum output data rate

When setting of the output data rate for the INS unit using LoadAHRSIIPar command (see section 6.3.4) or using the Tersus INS Demo Program it is essential to ensure the chosen baud rate of the main COM port is capable of handling the data throughput with desirable data rate. The maximum data rate (Hz) can be calculated using the baud rate and data package length:

$$\text{max\_data\_rate} = \frac{\text{COM\_baud\_rate}}{\text{bits\_per\_byte} * \text{package\_length}}, \quad (6.1)$$

where COM\_baud\_rate is COM port baud rate (bits/s); bits\_per\_byte = 11 bits per one transferred byte of data; package\_length for binary data = payload length plus 8 bytes of overhead. See Tables 6.4, 6.7, 6.8, 6.9, 6.10, 6.11 and 6.17 for payload length of binary output data formats. The package\_length of the text output data formats correspond to their structure shown in sections 6.2.1 to 6.2.7.

Below Table 6.55 contains data package length for each output data format and also maximum data rate calculated using formula (6.1), with some spare. Note the maximum measurement rate of INS data is limited by 200 Hz.

**Table 6.55. INS maximum measurement rate for different output data formats**

Output data format	Data package length, bytes	COM-port baud rate, bps					
		9600	19200	38400	<b>115200</b>	230400	460800
		Maximum measurement rate, Hz					
INS Sensors Data	84+8	9	10	30	<b>100</b>	200	200
INS Full Output Data	94+8	8	10	30	<b>100</b>	200	200
INS OPVT	92+8	8	10	30	<b>100</b>	200	200
INS QPVT	94+8	8	10	30	<b>100</b>	200	200
INS OPVT2A	101+8	8	10	30	<b>90</b>	190	200
INS OPVT2AW	103+8	7	10	30	<b>90</b>	180	200
INS OPVT2Ahr	129+8	6	10	20	<b>70</b>	150	200
INS Minimal Data	50	10	30	60	<b>200</b>	200	200
INS NMEA	93	9	10	30	<b>100</b>	200	200
INS Sensors NMEA	141	6	10	20	<b>80</b>	140	200

Note INS unit controls correctness of the data rate setting. If user sets data rate which exceeds limit shown in Table 6.55, then its value is corrected. True data rate is given out in the byte #3 of INS message after completing of the initial alignment procedure (see Table 6.28, Table 6.29).

## APPENDIX A. The Tersus INS Calibration

The Tersus INS software allows to take into account influence of the carrier object soft and hard iron on the heading determination. For this purpose, field calibration of the INS magnetometers on hard and soft iron is provided. This calibration does not require any additional equipment, but it requires setting of the carrier object, where the INS is mounted, in specified positions.

There are several types of the calibration implemented onboard the INS:

- 3D calibration;
- 2D-2T calibration;
- 2D calibration;
- VG3D calibration;
- on-the-fly VG3D calibration.

Other types of hard/soft iron calibration can be fulfilled with Tersus INS Demo software.

**3D calibration** is designed for carrier objects that can operate in full heading, pitch and roll ranges. For this calibration the carrier object is rotated in the horizon plane (the Z-axis is up) with periodical stops about each 90 degrees for tilting in pitch and roll. After full 360° rotation the carrier object with the INS is turned over (the Z-axis is down) and the procedure described above should be repeated. During this calibration the range of pitch and roll angles changing must be as much as possible.

**VG3D calibration** is similar to 3D calibration but allows performing simpler rotation than it is necessary for 3D calibration.

**2D-2T calibration** is designed for carrier objects that operate in full heading range but with limited range of pitch and roll angles. This calibration procedure involves a few full 360° rotations of the carrier object with installed INS in heading with different pitch angles. During each rotation, pitch and roll angles should be as constant as possible.

**2D calibration** is designed for carrier objects that operate in full azimuth range but with small pitch and roll angles (not more than a few degrees). This calibration procedure involves full 360° rotation of the carrier object with

installed INS in the horizon plane. During this rotation pitch and roll angles must be as close to zero as possible.

**On-the-fly VG3D calibration** allows to calibrate INS unit during INS ordinary operation without interruption of INS navigation data calculation and output.

If place of the INS mounting on the carrier object is changed, or if the carrier object is changed, then the INS should be re-calibrated on the hard and soft iron of the carrier object.

See section 6.7 for detailed description of embedded calibration procedures.

## APPENDIX B.

### Variants of the Tersus INS mounting relative to the object axes

The Tersus INS can be mounted on the object in any known position (up to upside-down, upright etc.) relative to the object axes. Such mounting doesn't change right determination of the object orientation if angles of the INS mounting are correctly stored in the INS nonvolatile memory.

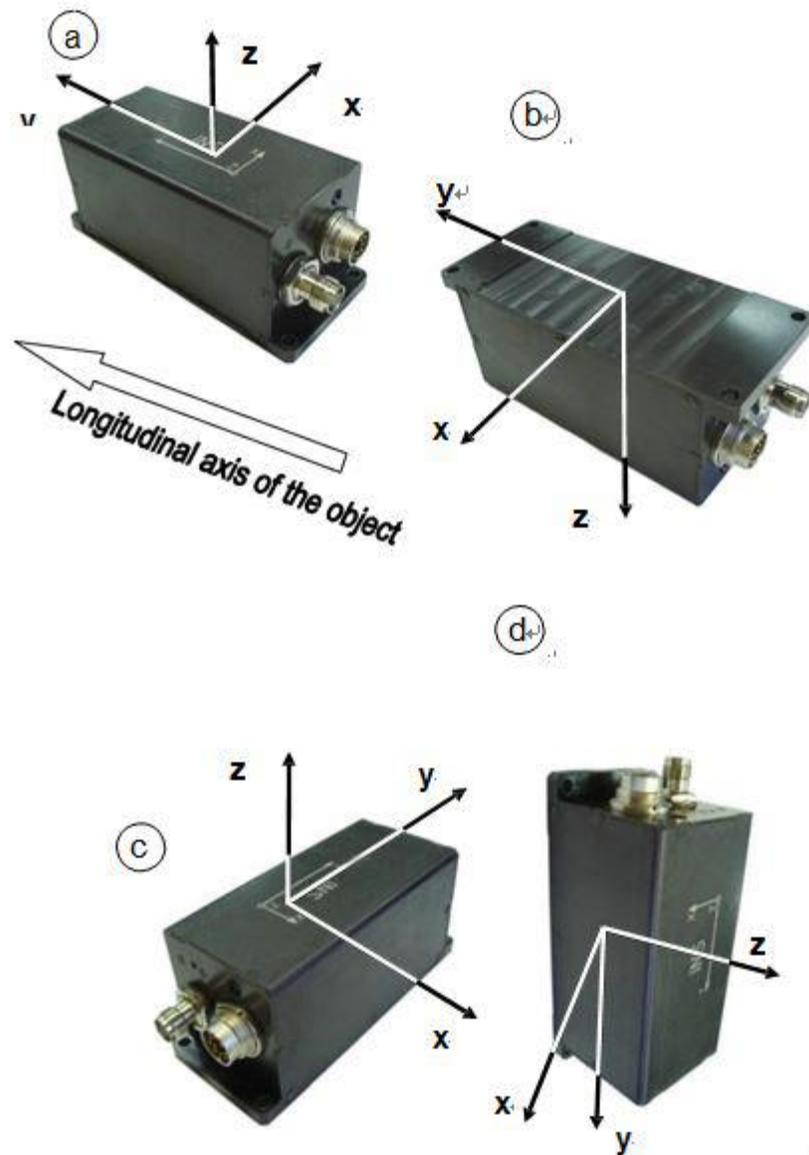
To store angles of the INS mounting to its nonvolatile memory please use the Tersus INS Demo Program (item «Device option ...» from the «Options» menu) or send LoadINSPar command to the INS directly (see structure of the message following after the LoadINSPar command in the Table 6.22). In both cases these angles are denoted as “Alignment angles”.

Angles of the INS position (alignment angles) are set in next order (like heading, pitch and roll setting):

- first alignment angle sets position of the INS longitudinal axis Y relative to longitudinal axes of the object measured in the horizontal plane of the object. Clockwise rotation is positive;
- second alignment angle is equal to angle of inclination of the INS longitudinal axis Y relative to the horizontal plane of the object. Positive direction is up;
- third alignment angle is equal to inclination angle of the INS lateral axis X measured around INS' longitudinal axis. Positive rotation is X axis moving down.

All angles are set in degrees. Some examples of the Tersus INS mounting relative the carrier object are shown on Fig.B.1.

To check correctness of the alignment angles please run the INS using the Tersus INS Demo program. Default values of the INS alignment angles are all zero.



**Fig.B.1. Examples of the Tersus INS mounting on the carrier object**

- a – alignment angles are 0, 0, 0 (degrees);
- b – alignment angles are 0, 0, 180 (degrees);
- c – alignment angles are 90, 0, 0 (degrees);
- d – alignment angles are 180, -90, 0 (degrees);

## APPENDIX C. Full list of the Tersus INS commands

All the INS commands have the byte structure shown in the Table 6.2. Payload for all commands has length 1 byte and contains code of the command. Below Table C.1 lists all commands with their exact structure in hexadecimal numbers.

**Table C.1. List of the INS commands with exact structure**

Command name	Code	Exact structure (hex)
<b>Commands for Tersus INS control</b>		
INS_SensorsData	0x50	AA 55 00 00 07 00 50 57 00
INS_FullData	0x51	AA 55 00 00 07 00 51 58 00
INS_OPVTdata	0x52	AA 55 00 00 07 00 52 59 00
INS_QPVTdata	0x56	AA 55 00 00 07 00 56 5D 00
INS_OPVT2Adata	0x57	AA 55 00 00 07 00 57 5E 00
INS_OPVT2AWdata	0x59	AA 55 00 00 07 00 59 60 00
INS_OPVT2Ahrdata	0x58	AA 55 00 00 07 00 58 5F 00
INS_minData	0x53	AA 55 00 00 07 00 53 5A 00
INS_NMEA	0x54	AA 55 00 00 07 00 54 5B 00
INS_Sensors_NMEA	0x55	AA 55 00 00 07 00 55 5C 00
SetOnRequestMode	0xC1	AA 55 00 00 07 00 C1 C8 00
Stop	0xFE	AA 55 00 00 07 00 FE 05 01
LoadINSpar	0x40	AA 55 00 00 07 00 40 47 00
ReadINSpar	0x41	AA 55 00 00 07 00 41 48 00
GetBIT	0x1A	AA 55 00 00 07 00 1A 21 00
<b>Commands for Tersus INS calibration</b>		
Start2DCIb	0x21	AA 55 00 00 07 00 21 28 00
Start2D2TCIb	0x22	AA 55 00 00 07 00 22 29 00
Start3DCIb	0x23	AA 55 00 00 07 00 23 2A 00
StartVG3DCIb	0x25	AA 55 00 00 07 00 25 2C 00
StartVG3Dclb_flight	0x26	AA 55 00 00 07 00 26 2D 00
StopVG3Dclb_flight	0x27	AA 55 00 00 07 00 27 2E 00
StartClbRun	0x2B	AA 55 00 00 07 00 2B 32 00
StopClbRun	0x20	AA 55 00 00 07 00 20 27 00
FinishClb	0x2C	AA 55 00 00 07 00 2C 33 00
AcceptClb	0x2E	AA 55 00 00 07 00 2E 35 00
ExitClb	0xFE	AA 55 00 00 07 00 FE 05 01
ClearClb	0x2F	AA 55 00 00 07 00 2F 36 00
GetClbRes	0x2A	AA 55 00 00 07 00 2A 31 00

## APPENDIX D. Forms of the Tersus INS orientation presentation

Define coordinate system  $Ox_0y_0z_0$  to be fixed to the carrier object where  $Ox_0$  axis is lateral and directed to the right,  $Oy_0$  axis is longitudinal and directed forward,  $Oz_0$  axis is normal and directed vertical. At usual installation of the INS on carrier object the INS appropriate axes should be parallel to the axes as above Fig.1.3 shows. Also, it is possible to install the INS in any known position relative to the object with known alignment angles (see APPENDIX B for details).

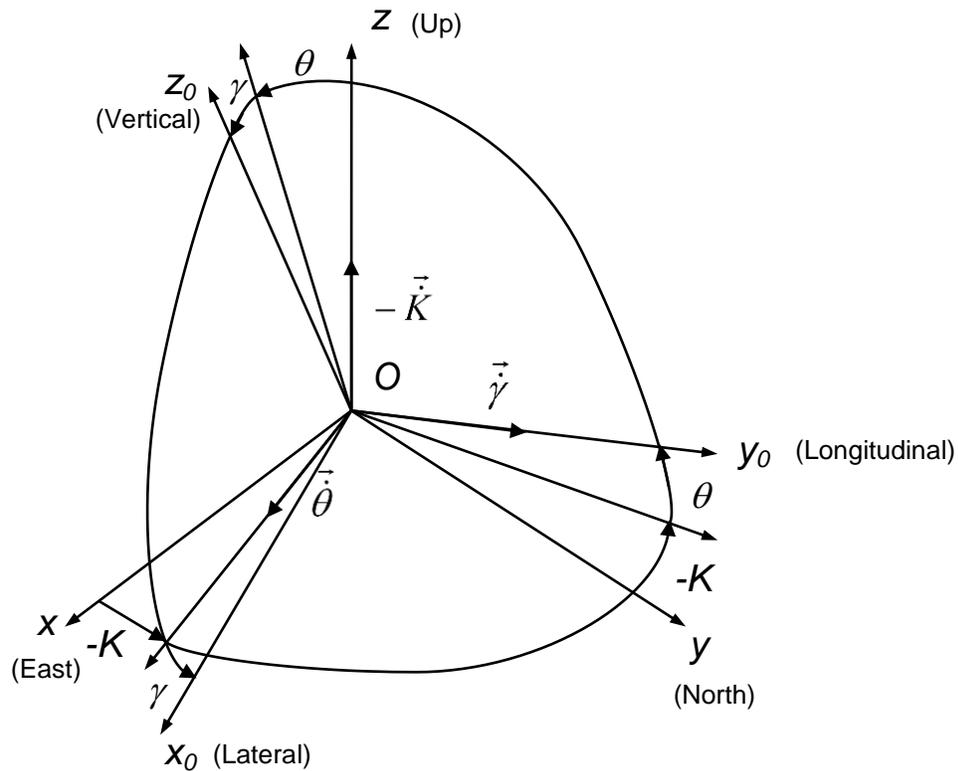
The Tersus INS calculates orientation of the coordinate system  $Ox_0y_0z_0$  fixed to the carrier object with respect to Cartesian geographical reference frame  $Oxyz$  where axes  $Ox$  and  $Oy$  are in the level and directed to the East and North, and  $Oz$  axis is directed up. Such reference frame is also known as ENU (East-North-Up) Earth-level frame.

Measured angles are the standard Euler angles of rotation from the Earth-level frame to the object frame: heading  $K$  is first, then pitch  $\theta$ , and then roll  $\gamma$  -- see Fig.D.1.

### **Notes:**

1. Positive direction of heading is clock-wise. So heading  $K$  is shown with minus sign on Fig.D.1.
2. In different applications "heading" is also known as "azimuth" or "yaw"; "pitch" is also known as "elevation" or "tilt"; "roll" is also known as "bank".

Due to the definition of Euler angles there is a mathematical singularity when the object longitudinal  $y_0$ -axis is pointed up or down (i.e. pitch approaches  $\pm 90^\circ$ ). This singularity is not present in the quaternion or directional cosine matrix (rotation matrix) presentation.



**Fig.D.1. Transformation of coordinate systems**

Directional cosine matrix (DCM) is the rotation matrix  $\mathbf{C}$  from the object body reference frame  $Ox_oy_oz_0$  to the geographical reference frame  $Oxyz$ . According to Fig.D.1, DCM can be represented through Euler angles as

$$\mathbf{C} = \begin{bmatrix} \cos K \cos \gamma + \sin K \sin \gamma \sin \theta & \sin K \cos \theta & \cos K \sin \gamma - \sin K \cos \gamma \sin \theta \\ -\sin K \cos \gamma + \cos K \sin \gamma \sin \theta & \cos K \cos \theta & -\sin K \sin \gamma - \cos K \cos \gamma \sin \theta \\ -\cos \theta \sin \gamma & \sin \theta & \cos \theta \cos \gamma \end{bmatrix}. \quad (\text{D.1})$$

Or, Euler angles can be calculated from elements  $c_{ij}$  of directional cosine matrix  $\mathbf{C}$ :

$$K = \arctan \frac{c_{12}}{c_{22}}; \theta = \arcsin c_{32}; \gamma = -\arctan \frac{c_{31}}{c_{33}}. \quad (\text{D.2})$$

Also the Tersus INS provides orientation output in quaternion  $\mathbf{Q}$  form which is a hyper-complex number with four components

$$\mathbf{Q} = (q_0, q_1, q_2, q_3), \quad (\text{D.3})$$

where  $q_0$  is real part,  $q_1, q_2, q_3$  are vector part. In other words,  $q_0$  represents the magnitude of the rotation, and the other three components represent the axis about which that rotation takes place.

With only four components, quaternion representation of orientation is computationally efficient. However, manipulation of quaternions is not intuitive, so their use in place of directional cosine matrices may increase the chances of mistakes being made.

Quaternion  $\mathbf{Q}$  is converted to directional cosine matrix  $\mathbf{C}$  using the next expressions:

$$\mathbf{C} = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 + q_0q_2) \\ 2(q_1q_2 + q_0q_3) & q_0^2 + q_2^2 - q_1^2 - q_3^2 & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & 2(q_2q_3 + q_0q_1) & q_0^2 + q_3^2 - q_1^2 - q_2^2 \end{bmatrix}. \quad (\text{D.4})$$

The reverse conversation from directional cosine matrix  $\mathbf{C}$  to quaternion  $\mathbf{Q}$  is following:

$$q_0 = \frac{1}{2} \sqrt{1 + c_{11} + c_{22} + c_{33}}; \quad (\text{D.5})$$

$$q_1 = \frac{c_{32} - c_{23}}{4q_0}; \quad q_2 = \frac{c_{13} - c_{31}}{4q_0}; \quad q_3 = \frac{c_{21} - c_{12}}{4q_0}.$$

Expressions (D.5) are wide used but they have singularity at  $q_0 = 0$ . Therefore the Tersus INS uses other expressions that have no singularity:

$$q_0 = \frac{1}{2} \sqrt{1 + c_{11} + c_{22} + c_{33}}; \quad q_1 = \frac{1}{2} \sqrt{1 + c_{11} - c_{22} - c_{33}} \cdot \text{sign}(c_{32} - c_{23}); \quad (\text{D.6})$$

$$q_2 = \frac{1}{2} \sqrt{1 - c_{11} + c_{22} - c_{33}} \cdot \text{sign}(c_{13} - c_{31}); \quad q_3 = \frac{1}{2} \sqrt{1 - c_{11} - c_{22} + c_{33}} \cdot \text{sign}(c_{21} - c_{12}).$$

At necessity to calculate Euler angles from quaternion, calculate elements  $c_{12}, c_{22}, c_{31}, c_{32}, c_{33}$ , according to (D.6), and then use formulas (D.2):

$$K = \arctan \frac{2(q_1 q_2 - q_0 q_3)}{q_0^2 + q_2^2 - q_1^2 - q_3^2}; \quad \theta = \arcsin(2q_2 q_3 + 2q_0 q_1); \quad (\text{D.7})$$
$$\gamma = -\arctan \frac{2(q_1 q_3 - q_0 q_2)}{q_0^2 + q_3^2 - q_1^2 - q_2^2},$$

where arctan is four-quadrant inverse tangent.

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