IEP-1000270

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Reference:

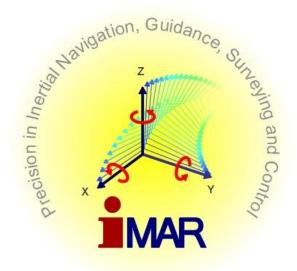
#### Report for iNAT-M200/SLN Evaluation on Aerobatic Aircraft (RedBull Ascot 2016) DOC160902193



# iNAT-M200/SLN on an Aerobatic Aircraft at RedBull 2016

- Performance Analysis of INS / GNSS & Interruption Behavior -

Company Confidential □ Commercial-in-Confidence ⊠



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I = Issued; C = Checked

Document No.: Reference:

DOC160902193 IEP-1000270

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DOCUMENT CHANGE RECORD		AI = Approved (iMAR) AC = Approved (Customer)				
Rev.	Paragraph	Comments		Date	Name	Function
1.00	All	Document created	I/C/AI	02.09.16	EvH	CEO

# **DOCUMENT CHECK & APPROVAL REQUIREMENTS**

CHECK required	APPROVAL by iMAR required	APPROVAL by Customer required
No	No	No

#### **Acronyms of Functions**

Industrial/	MIL Projects / Industrie- & MIL-Projekte	Aviation &	Space Projects / Luft- und Raumfahrtprojekte
CEO	Chief Executive Officer (Geschäftsführer)	AM	Accountable Manager
CUST	Customer (Kunde)	CUST	Customer (Kunde)
DE	Design Engineer / Development Engineer (Entwicklungsingenieur)	DE	Design Engineer / Development Engineer (Entwicklungsingenieur)
HD	Head of Development (Entwicklungsleiter)	HD	Head of Design (Entwicklungsleiter)
PGM	Program Manager (Projektmanager)	HoA	Head of Office of Airworthiness (Leiter Musterprüfleitstelle)
PJM	Project Manager (Projektleiter)	HoD	Head of Design Organisation
PM	Production Manager (Fertigungsleiter)	PGM	Program Manager (Projektmanager)
QA	Quality Assurance (Qualitätssicherung)	PJM	Project Manager (Projektleiter)
QM	Quality Manager (Qualitätsmanagementbeauftragter)	PM	Production Manager (Fertigungsleiter)
		CVE	Compliance Verification Engineer (Musterprüfingenieur)
		QA	Quality Assurance (Qualitätssicherung)
		QM	Quality Manager (Qualitätsmanagementbeauftragter)

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# **RELATED DOCUMENTS**

## **Table 1: Related Documents**

Name	Content	DocNumber
iNAT-M200 datasheet	Technical Product Specification	several
ICD iXCOM Protocol	iXCOM Protocol Specification	DOC141126064
MAN_iXCOM-CMD	iXCOM-CMD description for iXCOM systems (GUI)	DOC151211010
iMAR ARINC825 ICD	ARINC825 CAN iMAR Implementation	DOC141106133
ICD iNAT-M200	ICD iNAT-M200 Systems for MEMS based systems	DOC140301006
MAN_Introduction-into-Inertial- Measuring-Technology	Overview to coordinate systems etc.	DOC151228003
MAN_User-Manual_iNAT-Systems	General User Manual for iNAT Systems	DOC151228001
ICD iNAT-RxFxHx	ICD for RLG/FOG/HRG based systems	DOC141203029

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### Report for iNAT-M200/SLN Evaluation on Aerobatic Aircraft (RedBull Ascot 2016)



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# 1 INTRODUCTION

The iNAT-M200 INS/GNSS systems are designed for navigation, localization and attitude / heading measurement and control. The are equipped with an integrated MEMS based inertial sensor assembly (several classes of performance available), an integrated GNSS receiver (up to L1L2)



GPS+GLONASS+GALILEO RTK), an integrated wheel sensor (odometer) interface (A/B RS422 level), an integrated powerful miniaturized strapdown computer with data fusion (27+ state Kalman filter) and all required interfaces (Ethernet, UART RS422/RS232, CAN, USB) to communicate with external systems. Supported data protocols are TCP/IP, UDP, NMEA183 and many others as well as customized communication layers.

<u>Details</u> can be found in the related Interface Control Documents (ICD) and the manuals for hardware and software.

The systems can be directly integrated into the user's application or they ca be operated via the provided iXCOM-CMD user software (GUI), which is available under MS Windows<sup>TM</sup> as well as under LINUX.

Figure 1: iNAT-M200/SLN (INS/GNSS based navigation, surveying and control system)

The following report summarizes the results of the qualification flights during RedBull AirRace 2016 in Ascot / UK in the Master's Class. The iNAT-M200/SLN had been mounted on the aerobatic aircraft of Matthias Dolderer, the German's participant in the Master's League and the current field leader (rank 1 world list). He performed the shortest tie on the parcour and hence this aircraft with this pilot s the best base to demonstrate iNATM200/SLN performance under most challenging environment.

The following videos of the RedBull AirRace World Championship give an impression:

https://www.youtube.com/watch?v=AcpXAX00BHU

https://www.youtube.com/watch?v=UuD6\_QfkwOo

https://www.youtube.com/watch?v=9jQNxPObYMA

#### Note:

The same system is also available as iNAT-M200-FLAT/SLN or even as OEM card for direct integration into customer's measurement rack.



Figure 2: iNAT-M200-FLAT/SLN (INS/GNSS/ODO system)

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# **2 EVALUATION SETUP**

The iNAT-M200/SLN had been mounted inside Matthias Dolderer's racing aircraft. The y-direction of the INS iNAT-M200 was oriented in forward aircraft direction, the z axis had been directed downwards, the x axis was oriented sideward. For the integrated GNSS receiver a L1L2 GPS+GLONASS setup had been chosen, RTK corrections intentionally had not been available. EGNOS capability of the GNSS receiver had been activated and used where accessible.



Figure 3: Aircraft of Matthias Dolderer at RedBull AirRace

The data output rate had been 500 Hz, the iNAT-M200/SLN-30 was manufactured with

- Part Number: P/N 00190-00001-5101
- Serial Number S/N: 0001 (30 g version)
- Project Number: KFP-I000675.001

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The GNSS antenna had been of type ANTCOM L1L2 GPS/GLONASS with 4 mounting threads and SMB connector for temporarily mounting.

Our iNAT-M200/SLN had been operated stand-alone as a data logger, and collected data had been downloaded post-mission using our iXCOM-CMD configuration & visualization software. The iXCOM-CMD software is available on MS Windows as well as on LINUX machines.

In parallel a data link is available to display via iXCOM-CMD the artificial horizon, angular rate, speed, moving map as well as g-force (load factor) in real-time if desired.



#### Figure 4: iXCOM-CMD software for iNAT INS/GNSS system operation, data visualization and command

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# **3 DATA VISUALIZATION / ANALYSIS**

In the following chapter several plots of the 2<sup>nd</sup> qualifying on RedBull AirRace in Ascot at August 13 2016 at 16:24 UTC are shown (Master's Class of World Championship).

The following plot shows the configurable flight and supervision display of the iXCOM-CMD software. A configurable speed meter, heading instruments as well as artificial horizons, G Force Meter, time charts (here shown is the altitude as an example) or position plots (in local coordinates or in Lon/Lat) are available.

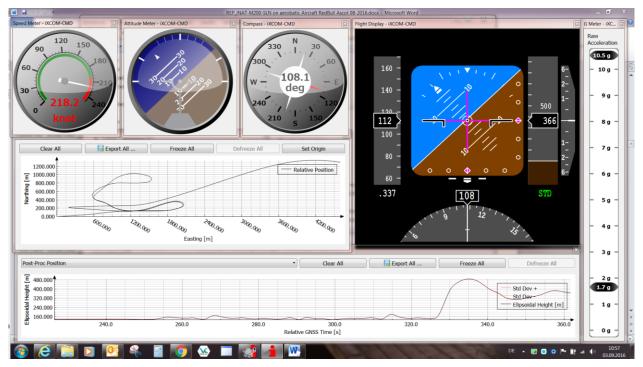


Figure 5: Display configuration example with iXCOM-CMD software

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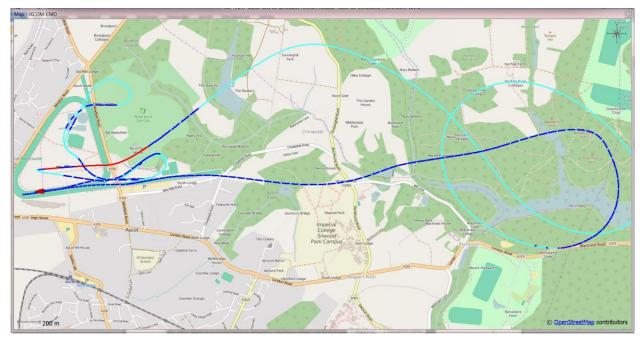


Figure 6: Travelled trajectory, shown on the moving map inside iXCOM-CMD software

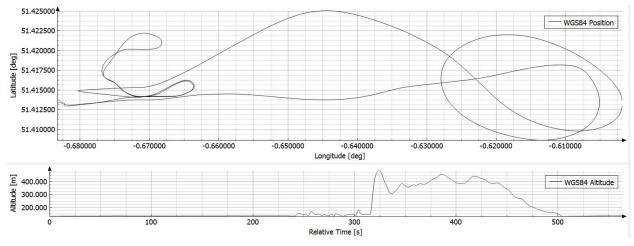


Figure 7: Travelled trajectory and altitude, shown inside iXCOM-CMD software

The following plot shows the travelled velocity as well as roll, pitch and yaw (heading) of the aerobatic aircraft as obtained from the real-time INS/GNSS solution.

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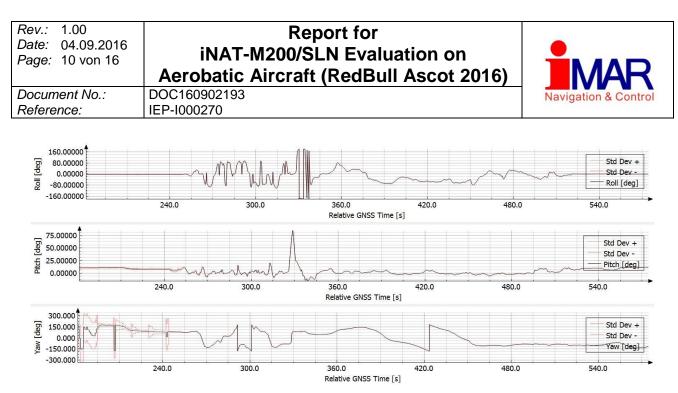


Figure 8: Aerobatic aircraft roll / pitch / yaw over time

It can be clearly identified that the 80 deg pitch at 325 sec relative time occurs when the altitude changes with very high change rate.

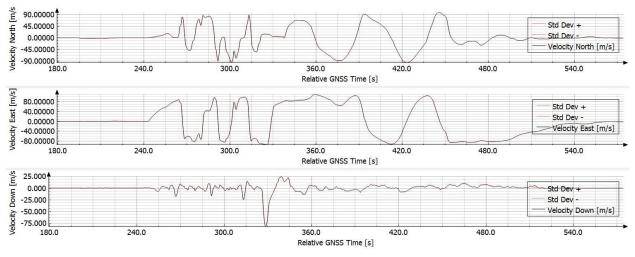
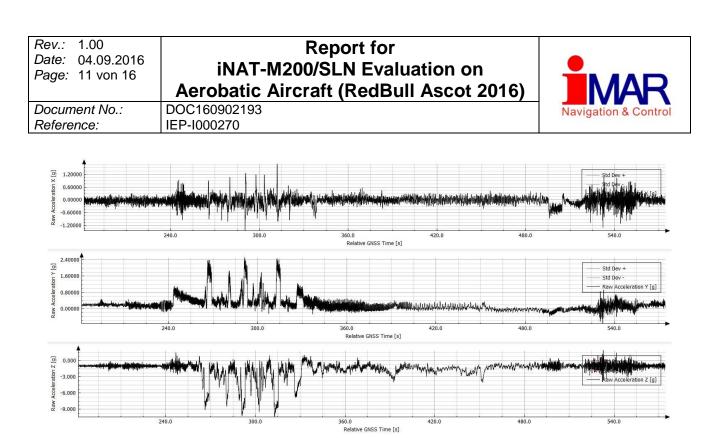


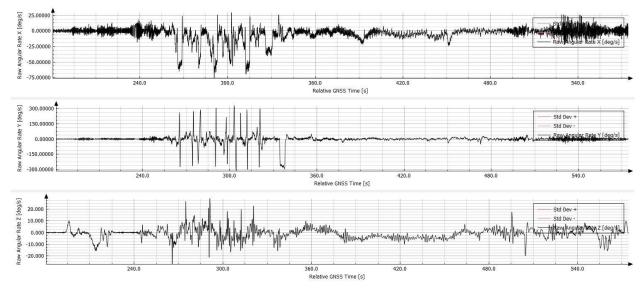
Figure 9: Aerobatic aircraft velocity over time

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#### Figure 10: Aerobatic aircraft acceleration (incl. gravity) over time

The aircraft had suffered up to 10 g acceleration in z direction (the RedBull AirRace regulations limit the acceleration to 10 g).



#### Figure 11: Aerobatic aircraft angular rate over time

Angular rates of up to 300 deg/s are present around the roll axis (y axis of INS). Remember that the "IMU raw y axis" is oriented along the aircraft roll axis and the "IMU raw x axis" is oriented along the aircraft transversal axis – the iNAT-M200 also provides the "corrected IMU data" (coordinate system rotated to aircraft body coordinate system) as well as "compensated IMU data" (additional compensated by gravity and earth rotation rate).

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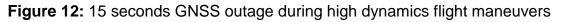
# 3.1 Example: GNSS Interruption for 15 Seconds

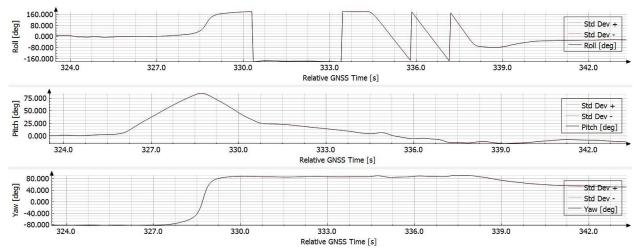
DOC160902193

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The following figures show the behaviour of the real-time data fusion when GNSS data are not available for aiding for about 15 seconds due to over-head flight maneuvers.







In the above figure the GNSS signal was interrupted for about 15 sec, after the pilot changed from headup flight (epoch 327 sec) to head-down flight (epoch 330 sec). The position deviation during GNSS loss keeps within better than 3 m. The following plots show the status at certain times (before, during and after GNSS outage).

Before GNSS outage the roll/pitch uncertainties are about 0.03 deg and heading uncertainty is about 0.05 deg. Position uncertainty is less than 1 m (remember, that the iNAT-M200 had been operated without any RTK aiding, only EGNOS correction data had been used if available).

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INS/GNSS Solution	GNSS Solution Odometer			
INS/GNSS Solution				5
Position WGS84		Position Standard Devi	ation	
Latitude	51.414'555'84 deg	Latitude	0.852 m	
Longitude	-0.677'598'63 deg	Longitude	0.464 m	
Ellipsoidal Height	144.580 m	Altitude	0.928 m	
Velocity NED		Velocity Standard Devi	ation	
North	14.089 m/s	North	0.090 m/s	
East	-95.048 m/s	East	0.064 m/s	
Down	-2.921 m/s	Down	0.069 m/s	
Attitude		Attitude Standard Devi	ation	
Roll	-0.483 deg	Tilt-North	0.037 deg	
Pitch	3.395 deg	Tilt-East	0.034 deg	
Yaw	-81.666 deg	Yaw	0.051 deg	
Raw Acceleration		Raw Angular Rate		
X-Axis	-0.304 g	X-Axis	-10.292 deg/s	
Y-Axis	0.034 g	Y-Axis	13.416 deg/s	
Z-Axis	-1.387 g	Z-Axis	-0.635 deg/s	

### Figure 13: Accuracy before GNSS outage

The next screenshot shows the data about 2 sec after head-down flight (roll about 180 deg) began.

INS/GNSS Solution	GNSS Solution Odometer		
INS/GNSS Solution			4
Position WGS84		Position Standard Devi	ation
Latitude	51.415'025'15 deg	Latitude	0.957 m
Longitude	-0.678'814'07 deg	Longitude	0.613 m
Ellipsoidal Height	439.228 m	Altitude	0.921 m
Velocity NED		Velocity Standard Devi	ation
North	5.674 m/s	North	0.147 m/s
East	65.671 m/s	East	0.076 m/s
Down	-26.526 m/s	Down	0.091 m/s
Attitude		Attitude Standard Devi	ation
Roll	-176.140 deg	Tilt-North	0.041 deg
Pitch	23.294 deg	Tilt-East	0.032 deg
Yaw	86.140 deg	Yaw	0.050 deg
Raw Acceleration		Raw Angular Rate	
X-Axis	-0.023 g	X-Axis	1.498 deg/s
Y-Axis	0.597 g	Y-Axis	-11.494 deg/s
Z-Axis	-0.237 g	Z-Axis	2.124 deg/s
Low Pass	Cut-Off Frequency 0.100 Hz	Low Pass	Cut-Off Frequency 50.000 Hz

Figure 14: Accuracy during GNSS outage at 180 deg roll

The next figure shows the estimated position and attitude deviation at the end of the GNSS outage period, i.e. 15 sec after loss of GNSS aiding. The position error had been increased to only 2.5 m in latitude (totally 3.5 m).

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	SNSS Solution Odometer		
INS/GNSS Solution			5
Position WGS84		Position Standard Devi	ation
Latitude	51.416'932'12 deg	Latitude	2.484 m
Longitude	-0.665'643'85 deg	Longitude	1.542 m
Ellipsoidal Height	357.784 m	Altitude	1.951 m
Velocity NED		Velocity Standard Devi	ation
North	55.993 m/s	North	0.253 m/s
East	83.260 m/s	East	0.143 m/s
Down	18.705 m/s	Down	0.202 m/s
Attitude		Attitude Standard Devi	iation
Roll	-23.152 deg	Tilt-North	0.051 deg
Pitch	-11.343 deg	Tilt-East	0.220 deg
Yaw	51.475 deg	Yaw	0.059 deg
Raw Acceleration		Raw Angular Rate	
X-Axis	0.091 g	X-Axis	5.723 deg/s
Y-Axis	0.349 g	Y-Axis	-3.159 deg/s
Z-Axis	-1.124 g	Z-Axis	-1.254 deg/s
Low Pass	Cut-Off Frequency 0.100 Hz	Low Pass	Cut-Off Frequency 50.000 Hz

#### Figure 15: Accuracy at the end of GNSS outage phase (maximum deviations)

The next figure shows the INS/GNSS performance 3 sec after GNSS had been recovered again. The roll/pitch uncertainties are well below 0.1 deg and heading uncertainty is about 0.05 deg again. Position uncertainty is less than 2 m (remember, that the iNAT-M200 had been operated without any RTK aiding, only EGNOS correction had been active).

IS/GNSS Solution							
Position WGS84			Position Standard Devia	ation			
Latitude 51.419'338'02 deg			Latitude	Latitude 0.986 m			
Longitude	-0.660'513'92	deg	Longitude	0.483 m			
Ellipsoidal Height	308.276 m		Altitude	1.022 m			
Velocity NED			Velocity Standard Devia	ation			
North	67.606 m/s		North	0.102 m/s			
East	85.772 m/s		East	0.053 m/s			
Down	1.149 m/s		Down	0.068 m/s			
Attitude			Attitude Standard Devia	ation			
Roll	2.289 deg		Tilt-North	0.038 deg			
Pitch	0.948 deg		Tilt-East	0.071 deg			
Yaw	48.161 deg		Yaw	0.047 deg			
Raw Acceleration			Raw Angular Rate				
X-Axis	0.061 g		X-Axis	-1.936	i deg/s		
Y-Axis	0.031 g		Y-Axis	-4.572	deg/s		
Z-Axis	-1.168 g		Z-Axis	-0.850	deg/s		
Low Pass		Cut-Off Frequency 0.100 Hz	Low Pass 🗸	7	Cut-Off Frequency 50.000 Hz		

#### Figure 16: Accuracy 3 sec after recovery from GNSS outage

The following figure shows the smooth correction of the sophisticated Kalman filter based data fusion inside the iNAT-M200.

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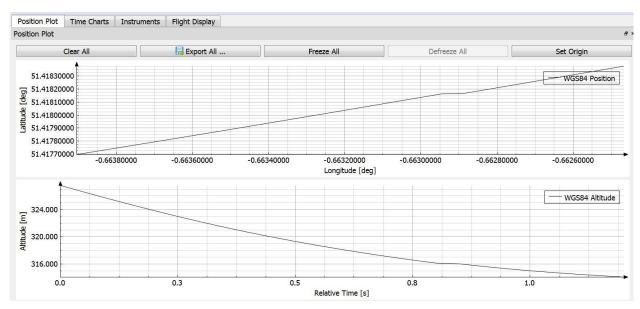


Figure 17: Position correction with new GNSS update after GNSS outage

#### Validation of Accuracy:

With an assumed accelerometer bias of about 1 mg (0.01 m/s<sup>2</sup>) the expected position error after 15 sec of free inertial (unaided) navigation will be in the range of 1.1 m in each direction, i.e. totally about sqrt(3) x 1.1 m = 1.9 m, assuming that the attitude determination had been free of any deviations at the beginning of the period of GNSS outage. Considering additionally an initial heading deviation of 0.05 deg and a roll and pitch deviation of each 0.03 deg at the beginning of the GNSS outage, just by such angle deviation the lateral position error after 10 seconds flight with a speed of about 100 m/s resp. 200 knots (i.e. during 10 sec the aircraft travels about 1 km!) will be additionally sqrt( $[1 m]^2 + [0.5 m]^2 + [0.5 m]^2$ ) = 1.2 m, so the estimated total position error will be in the area of sqrt( $[1.9 m]^2 + [1.2 m]^2$ ) = 2.3 m (1 sigma) or 4.6 m (2 sigma).

# **4 CONCLUSION**

The given report showed the challenging application to install a MEMS based INS on an aerobatic airplane. The race plane had to fulfil extreme dynamics conditions with up to 10 g acceleration and 300 deg/s angular rate. This lead to high requirements regarding the inertial sensor bias stability, scale factor accuracy and time stamping to perform an most accurate signal processing inside the INS in real-time. To be able to handle also the significant GNSS outages with high accuracy, the integrated INS/GNSS data fusion contains a 27+ state model which is also able to estimate – beside of other values – also the scale factors of the inertial sensors.

The above presented data of the iNAT-M200 show, that a high accuracy is achieved even under challenging dynamic requirements. Under standard flight dynamics the results are even more accurate as long as the flight dynamics is sufficient for a reasonable state observability of the data fusion algorithms.

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# **5 SUPPORT**

### 5.1 Asking for Support

For our support management system, we need to know the project number (Proj.No.) or alternatively P/N and S/N of the system you are speaking about.

These numbers are for example provided on the type plate (example shown in the Fig. on the right side).

www.imar-na	avigation.de
Nato CageCode	DN401
Туре:	IMADC
Proj.No.:	SYS-1000507.001.3
P/N; S/N:	00130-00001-0001; 00001
Customer P/N:	148L0630-01
Power:	9-36V / <2.5W
Manuf. Date:	04.2013 - ABCDE

Figure 18: Example of iMAR type plate

#### 5.2 Contact

You can find general information about our products, used technologies, and about inertial navigation, and GNSS based navigation at <u>www.imar-navigation.de</u>.

You can reach iMAR Customer Support as follows:

- support@imar-navigation.de
- **\*** +49-6894-9657-0
- iMAR Navigation GmbH Customer Support Im Reihersbruch 3 D-66386 St. Ingbert Germany

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