GPS aided INS - Integration and Application in the Croatian Sky

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Sound title actually notes the utilization of hyperspectral imaging using airborne platform for the first time in Croatia. Specific application requirements highlited the need for Position and Orientation system capable to measure and record inertial orientation and GPS position data at high frequency, according to general requirement for line imaging mode utilization of airborne hyperspectral imaging scanner, which states that at least one set of position and orientation data should be available for each scan line. GPS proved as critical throughout few different tasks it has in: velocity and heading aiding for IMU (drift correction), time synchronization, trigerring and navigation. Furthermore, several electro-optical sensors were integrated in airborne sensor pod, with hyperspectral puhbroom scanner and hybrid IMU/GPS system (serving as Position and Orientation System) in its core. Complete airborne multisensor system is built off-the-shelf, integrated by using PC running under Windows OS and aimed to different applications, such as spectral detection of oil polution spill at sea, quality monitoring of water in lakes and rivers and explosives polution detection at military fire range, etc. Good understanding of different application requirements, along with the characteristics and design specification of state of the art sensors, led to system integration, which has proved as operational during first flight tests and has already scheduled for airborne mapping campaignes over mine contaminated area in Croatia.

KEY WORDS
Inertial Measurement Unit GPS Hyperspectral Scanner Direct Georeferencing

1. INTRODUCTION. For the first time in Croatia an airborne application of hyperspectral imaging was introduced under recent technologic project “System for the Multisensor Airborne Reconnaissance and Surveillance in the Crisis Situations and the Environment Protection“, supported by Croatian Ministry of Science, Education and Sports. Such airborne use of various digital electro-optic sensors, and esspecially the hyperspectral pushbroom scanner, with its precision imaging spatial and spectral resolution led to definition of Position and Orientation System (POS) capable to deliver required precision exterior orientation (attitude and position) data needed to perform Direct Georeferencing (DG) of produced scanner lines. Altough the INS is by definition selfcontained IMU with onboard navigation processing capability, specific case of forming the INS from hybrid IMU/GPS system during post-processing is used. Furthermore, the application required system integration which was comprised of pushbroom scanner as core sensor and other sensors (multispectral frame camera DunchanTech MS3100, thermal imaging camera Photon, video camera Sony FCB-IX11AP), and POS gathered in a fully functional and self powered multisensor pod controled by PC based acquisition system.

The application highlited the need for position orientation system capable to measure and record inertial orientation and GPS position data at high frequency, according to general requirement for line imaging mode utilization of hyperspectral imaging scanner, which states that read-out IMU frequency should be at least of those of scanner imaging frequency. Position and Orientation System, is built around chosen tactical-grade MEMS iMAR iVRU-RSSC, so-called Vertical Reference Unit, with integrated internal

GPS unit and strap-down processor, rather then full integrated INS/GPS since there is no need for real-time navigation procesing for the POS.

Integration of hyperspectral imaging scanner, acquistion PC system and Position and Orientation System (POS) has been achieved by sharing reference PC clock time as common platform, in relation to other possible ways which also have been cosidered (Ding et al., 2008). In this digital interface configuration, PC clock is continuously updated and corrected by GPS UTC time externally provided. Such synchronization allows the control and acquistion timinig of hyperspectral imaging sensor and POS are referenced to PC GPS time. The impact of time synchronisation on imaging capabilities and spatial accuracy of such system is of huge importance. Furthermore, transformation of mentioned hybrid IMU/GPS system into an INS, in post-processing phase and additional techniques of interpolation and filtering of GPS using inertial data are used in lieu of real-time in-flight operations. Possibility to make utilization of presented high-performance IMU/GPS system for other aplications, including land and sea environment, is planned.

2. SUBSYSTEMS. The Multisensor System comprises of few subsystems: Position and Orientation System, Sensors System and Acquisition/Control System.

2.1. *Position and Orientation System.* In case of core sensor, the pushbroom scanner, the application highlited the need for position orientation system capable to measure and record inertial orientation and GPS position data at high frequency, according to general requirement for line imaging mode utilization of hyperspectral imaging scanner, which states that read-out IMU frequency should be at least of those of scanner imaging frequency. Position and Orientation System is built around chosen tactical-grade MEMS iMAR iVRU-RSSC, so-called Vertical Reference Unit, with integrated internal GPS unit and strap-down processor, providing: amongst other data (gravity/earth rate compensated and raw acceleration and angular rates), Roll, Pitch, Yaw (or relative heading), GPS Latitude, GPS Longitude, GPS Altitude and GPS Velocity data, at maximum frequency of 200Hz, interfaced with PC based acquisition system.

2.1.1. *GPS aiding*. To achieve best performance under high dynamic conditions, the iVRU uses velocity aiding provided via a GPS GPVTG NMEA message. The GPS velocity aiding is used to compensate the drift of the roll gyro using the longitudinal velocity and the measured angular rate. However, if the iVRU is configured for GPS velocity or acceleration aiding and in case if there is no velocity or acceleration aiding information available (no valid GPS solution), the iVRU will start aiding without GPS aiding (only accelerometer aiding will be used). As soon as the iVRU gets valid velocity/acceleration, this information is used for aiding and corresponding aiding mode is switched on. If hereafter this information become invalid again, then GPS aiding is switched off as long as GPS data are invalid.
Furthermore, also for the best performance under high dynamic conditions and to compensate the gyro induced heading drift, the iVRU uses a track angle information provided via an GPS based NMEA sequence of the format GPVTG. If the GPVTG contains also a velocity information, those is also used for aiding. It is assumed that the vehicle moves in positive x direction of the iVRU. The course over ground of the GPVTG message will only be used under two terms: the velocity itself is higher than a certain threshold (detected from the GPS signals, typically 3m/s), afterwards the GPS heading is used with a certain damping to correct the IMU heading (time constant is set to several minutes to eliminate incertainties and distorsions of GPS data) and the angular rate is smaller than a certain threshold to avoid mismeasurements on dynamic trajectories (due to the low sampling frequency of e.g. 1 Hz the GPS measures the secant and not the tangent on a driven circle). POS has provided seamless data during flight testing campaigne overhead Jarun lake in Zagreb, shown in Figure 5. and 6.

2.1.2. *POS Trigger Time Synchronisation*. Via RS232 interface (Figure 2.) the GPS NMEA sequence GPGGA is provided with the leading ‘$’ allowing the iVRU to detect this data sentence to extract the UTC time of the recent Pulse per Second (PPS) rising edge. Then the trigger time is set to this UTC time (seconds of week) from the recent PPS (taken from the NMEA sequences). To use this feature the availability of the NMEA sequence as well as the PPS trigger was provided by external 5Hz GPS receiver.

2.2. *Airborne Pushbroom Scanner.* Hyperspectral imaging pushbroom scanner shown in Figure 1. (modified after Rochester Institute of Technology's Digital Imaging and Remote Sensing Laboratory - overview of pushbroom concept, 2006) is a powerfull tool since it delivers imaging spectroscopy data which allows clasification and change detection of an object matter, measuring its unique spectral characteristics. Today the pushbroom scanners are becoming widely used and often replacing the older whiskbroom scanners. Airborne use of pusbroom scanning, along with its space use, reveals the full power of imaging spectroscopy. To utilize the pushbroom scanner in full imaging mode, means acquiring contigous scan lines (without gaps between them), it is necesarry to find the optimum ground speed of the aircraft, which is function of desired Ground Sampling Distance (GSD) and scanner imaging frequency, according to simple equation (1), used to arrive at optimum distance per second:

$$GS = \frac{GSD}{f_i} \tag{1}$$

, where: *GS = Ground Speed of the aircraft [m/s]*
GSD = Ground Sampling Distance [m]
f_i *= Imaging frequency(scan period) [s]*

Additional constraint for finding the optimum ground speed is spatial resolution along the aircraft track which is determined by the line width and integration time per one scene line (=one detector frame). Actual configuration of ImSpector V9 pushbroom scanner, depending on used vertical binning of CCD operation (x1 or x2), provides the integration time per scene line of 79.8ms or 40.3ms, respectivelly. Thus, predicted spatial resolution along track for Zagreb/Jarun Lake campaign was 1.34m. Above mapping geometry depends on height of the aircraft above ground level (pixel scale factor) which could be obtaied from an Digital Elevation Model (DEM). Entire previous mapping flight planning is done by using TopoFlight 3D flight planning software (by Flotron AG, Klaus Budmiger). Finally, high imaging resolution of pushbroom scanners, both spectral and spatial, as in case of ImSpector V9 (i.e. Zagreb/Jarun Lake flight campaign using Bell B206 helicopter had produced, in average, the lines with length of 218m and 1.63m wide, with accros track pixel size of 19cm at altitude of 750m; in spectral range of 80 channels and with spectral resolution of 4.4nm), requires additional technology and metods for final exploatation of their produced data, by using mentioned POS and performing the DG.

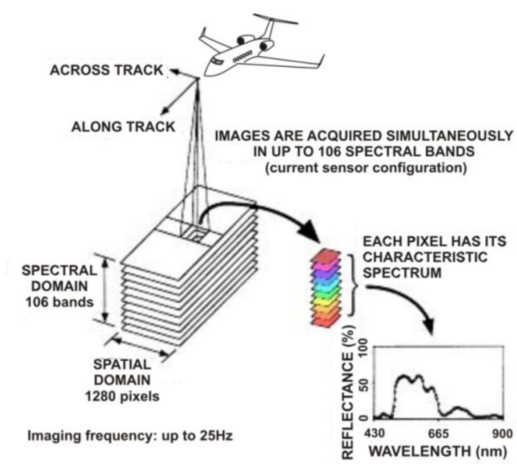

Figure 1. Pushbroom Scanner concept
(Including basic specifications of used ImSpector V9)

3. INTEGRATION ARCHITECTURE. Figure 2. shows schematic overview of integrated POS-Sensors-Acquisition System. Integration of hyperspectral imaging scanner, acquistion PC system and Position and Orientation System (POS) has been achieved by sharing reference PC clock time as common platform. In this digital interface configuration, PC clock is continuously updated and corrected by GPS UTC time externally provided by 5Hz 1PPS signal extracted from NMEA 0183 GGA and/or ZDA sentences. This process of PC clock synchronization is achieved by use of precizion timing software „TAC32Plus“ (by Communications, Navigation and Surveilance Systems Inc.) Thereafter, both the control and acquistion timinigs of hyperspectral imaging sensor and POS are referenced to PC GPS time. The impact of time synchronisation on imaging capabilities and spatial accuracy of such system is of vital importance.

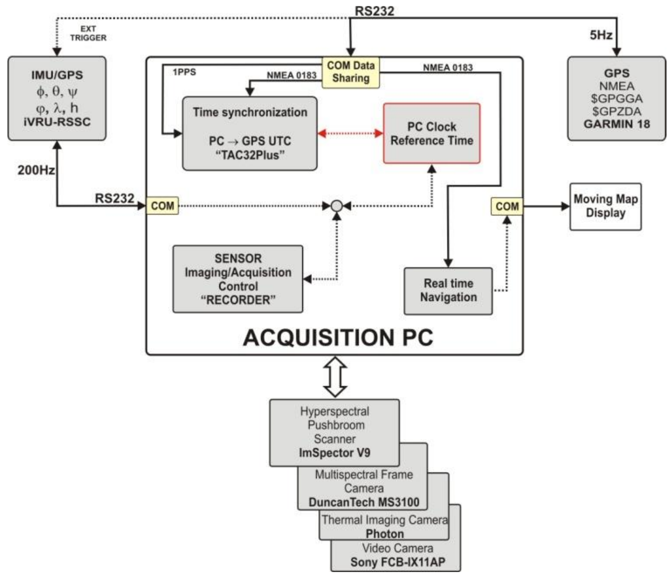

Figure 2. Scheme of integration architecture used in flight tests and Zagreb/Jarun Lake flight campaign

4. NAVIGATION POST-PROCESSING. The navigation solution was derived from iVRU-RSSC's inertial measurements of gravity compensated accelerations and earth rate compensated angular velocity, where GPS measurements were accounted for drift correction through velocity and track angle aiding. Navigation processor is based on Matlab/Simulink model where INS Block from AeroSim Simulink Blockset (by Unmanned Dynamics, LLC) represents the core computation engine for accelerations and angular rates integration to obtain the aircraft position, velocity, and attitude. Model also allows for axes sorting transformation (raw IMU data in navigation East-North-Up (ENU) coordinate system to North-East-Down (NED) coordinate system required by INS Block), forming the time series format of raw IMU data, setting up of initial parameters, etc.

However, by integrating the IMU measurements with the INS algorithm, the errors will accumulate, leading to significant drift in the position and velocity outputs. Although the iVRU-RSSC's inertial measurements are corrupted by noise (< 0.25 °/s), scale factor (< 0.2 %) and bias variations with temperature (< 0.1 °/s), one advantage of the IMU is that it can be sampled at high-rates, therefore it is capable to capture the fast dynamics of the aircraft and the mentioned drift in position and velocity outputs can be compensated by GPS/INS integration, in conjunction with a navigation Kalman filter.

Used AeroSim's INS Simulink Block, which implements the nonlinear 6-DOF INS equations of motion and includes a WGS84 Earth geoid model, integrates inertial measurements provided by the IMU to return the PVA (position / velocity / attitude) solution. The INS block is planned to be used for GPS/INS integration in conjunction with navigation Kalman filter, according to future application requirements. The Block characteristics are listed in Table 1. along with real simulation setup:

Table 1. AeroSim INS Block parameters with actual setup to produce navigation solution based on GPS aided IMU measurements

Parameters	**Real setup values**	**Notes**
Initial position = the 3 x 1 vector of initial aircraft location $[Lat\ Lon\ Alt]^T$.	Latitude: 45.7686N Longitude: 15.8511E Altitude: 125.10m	$[rad\ rad\ m]^T$ Transformation *degrees to radians* required.
Initial velocities = the 3 x 1 vector of initial aircraft velocity components in geodetic frame $[V_N\ V_E\ V_D]^T$.	V_N = 3.201m/s V_E = -0.381 m/s V_D = 0 m/s	GPS Velocity of 3.225 m/s transformed to velocity components in geodetic frame (used velocity threshold >3m/s).
Initial attitude = the 4 x 1 vector of initial aircraft attitude provided as Euler-Rodrigues quaternions $[e_0\ e_x\ e_y\ e_z]^T$.	ϕ = -0.0321° θ = 4.6582° ψ = -6.7920°	*Euler angles to Quaternions* transformation is required. ENU to NED axes transformation is required.
Sample time = the sample time at which the INS will run.	0.033s	30Hz according to iVRU-RSSC actual sampling setup (up to 200Hz possible).
Inputs		
IMU = the 6 x 1 vector of inertial measurements (3 accelerations + 3 angular rates) in body axes $[a_x\ a_y\ a_z\ p\ q\ r]^T$.	(Time series object with uniform time length 0-2611s; 79113 value entries.)	Gravity compensated accelerations. Earth rate compensated angular velocity. Data are formed as time series (previously prepared using Matlab Time Series Tool).
RST = the INS integrator reset flag	0	(Reset on rising edge).
Outputs		
PVA = the INS states $[Lat\ Lon\ Alt\ V_N\ V_E\ V_D\ e_0\ e_x\ e_y\ e_z]^T$.	(Graph in Figure 3.)	

Final results (shown in Figure 3.) showed justifiability of using navigation post-processing of raw IMU data to produce high frequency positioning, up to 200Hz, according to future application's requirements.

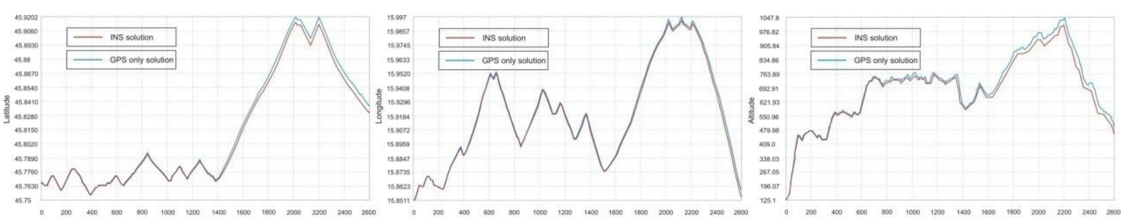

Figure 3. INS derived positions at 30Hz compared to GPS only solution for Zagreb/Jarun Lake flight campaign

5. DIRECT GEOREFERNCING. Amongst numerous definitions of Direct Georeferencing concept, one is adopted here as International Society for Photogrammetry and Remote Sensing (ISPRS) is defining it mathematically by a transformation between the image coordinates specified in the sensor frame and the geodetic (mapping) reference frame, whose model requires the knowledge of the sensor interior and exterior orientation parameters. Combined IMU/GPS observation offers a direct in real-time platform exterior orientation needed for DG. The utilization of direct measurements of the image exterior orientation parameters by a GPS/IMU system for image rectification is called Direct Georeferencing and allows a fast automatic ortho-rectification of the sensor data, in conjunction with Digital Elevation Model (DEM). The concept of a Direct Georeferencing system is illustrated in Figure 4. (Müller et al., 2002)

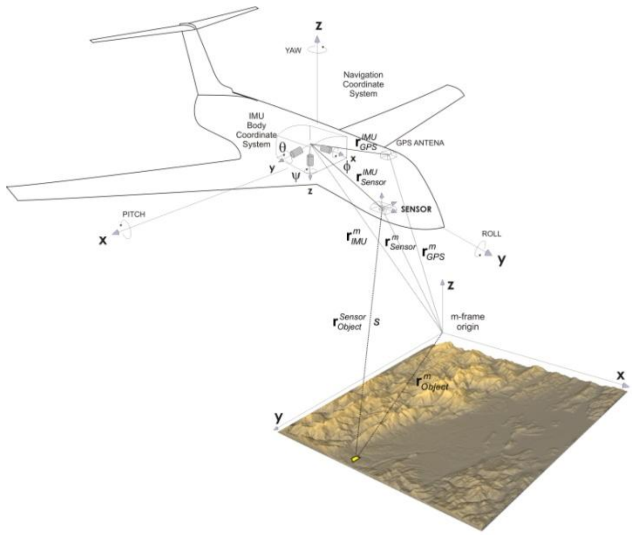

Figure 4. Direct Georeferencing Concept – different vector definitions along with different coordinate systems and their orientation

Direct georeferencing equation (2) based on co-linearity concept, where the coordinates of an object point r_{Object}^{Sensor} measured in the imaging sensor's coordinate frame are related to the coordinates r_{Object}^{m} in the mapping coordinate frame (Müller et al., 2002):

$$r_{Object}^{m} = r_{Sensor}^{m} + s_i \cdot R_{IMU}^{m} R_{Sensor}^{IMU} \cdot r_{Object}^{Sensor} \quad (2)$$

With the actual position of projection centre of sensor (3):

$$r_{Sensor}^{m} = r_{GPS}^{m} - R_{IMU}^{m} \cdot r_{GPS}^{IMU} + R_{IMU}^{m} \cdot r_{Sensor}^{IMU} \quad (3)$$

In the above equations, the lower indices of the vectors ***r*** indicate the placement of the points, whereas the upper indices denote the coordinate frame in which the vector is measured. The notation of the indices of the rotation matrices ***R*** indicates the transformation direction where the lower index represents the source coordinate system and the upper index the destination coordinate system. Time dependent variables in the above equation are: vector r_{Sensor}^{m} , actual GPS measurements, and transformation matrix R_{IMU}^{m} , actual roll/pitch/yaw measurements represented by Euler angles. Other vectors are usually determined in pre-processing, called calibration phase (measuring of boresight misalignment angles between IMU and sensor, lever arm determination between IMU and GPS antenna, etc.) and in post-processing, called geocoding phase.

Direct georeferencing of acquired hyperspectral pushbroom data is done by using Parametric Geocoding & Orthorectification for Airborne Optical Scanner Data (PARGE) software (by ReSe Applications Schläpfer & RSL, University of Zurich). Required high spatial accuracy of position and orientation data used for DG in PARGE software is performed in pre-processing by several utilities provided extrapolation of the attitude data (shown in Figure 5.), interpolation and coordinate re-projection of the GPS data (sampled by 1Hz) and synchronization of attitude and GPS data with scanner lines. After such pre-processing, the data are imported in PARGE and their further processing is made by using PARGE proprietary filters and tools.

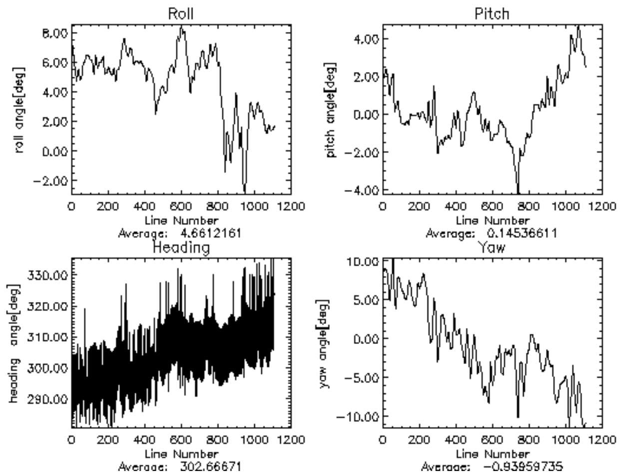

Figure 5. Raw Attitude Data provided by iVRU-RSSC at 30Hz during Zagreb/Jarun Lake flight campaign

5.1.*Navigation data use for roll compensation.* Deeply investigated for DG purpose, use of navigation data for attitude induced distortions and their compensations is presented by (Schläpfer, 2006; Schläpfer et al., 2002). Since the roll distortions have significant effects in airborne image data (Figure 5.), the separate procedure for roll compensation of raw image data is performed. This procedure allows correction for artifacts by shifting each scanned line by an estimate of numbers of pixels, using the height above ground and roll information from the image data, result of which is shown in Figure 7. In addition, this procedure allows for use of original navigation data-airplane height to calculate roll compensation more exactly (shown in Figure 6.).

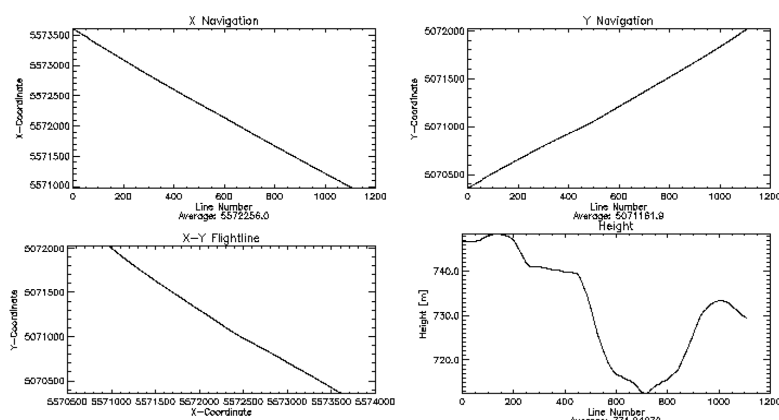

Figure 6. Plot of iVRU-RSSC provided navigation GPS Data; Zagreb/Jarun Lake flight campaign (Projection: Transverse Mercator; Datum: Hermannskögel)

Pixel size is estimated from average altitudes and Instantaneous Field of View (IFOV), after changing average height of airplane or ground. The roll compensation pixel shift is calculated from the simple equation (4):

$$n(pixel\ shift) = \frac{\tan\phi \times h}{p_y} \tag{4}$$

, where: ϕ = roll angle around the x-axis of body system
h = vertical distance (height AGL) of aircraft from the ground
p_y = across track pixel size

In situation when no heading data are available, the heading can be calculated as first derivative of the flight path (shown in Figure 5.; lower left graph). This PARGE function requires the navigation data (shown in Figure 6.) to be already transformed to Cartesian coordinates. Additionally, if there is also a yaw available at this point, it will be added to the flight direction.

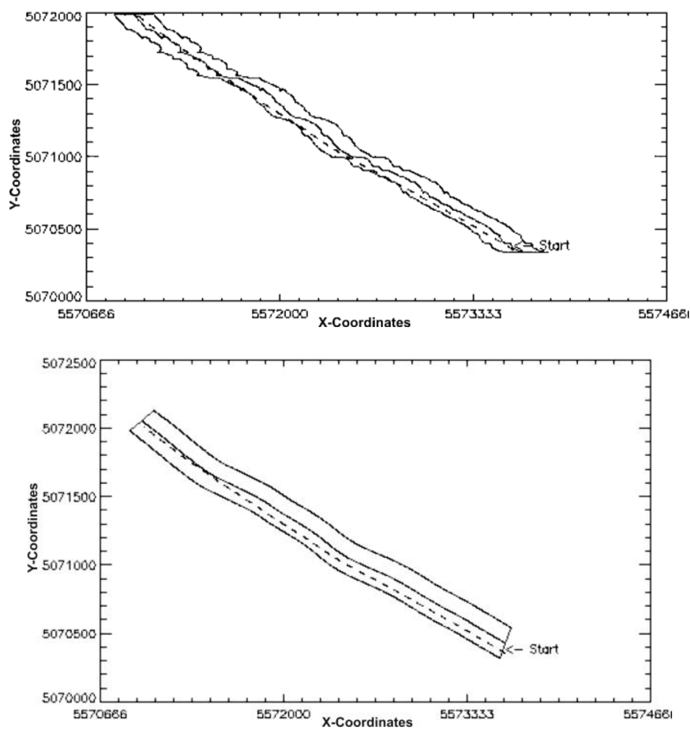

Figure 7. Raw data image coverage compared to image area after applying Roll Distortion Compensation and data filtering data along 3 axes (Projection: Transverse Mercator; Datum: Hermannskögel)

When heading and flight direction differ by a large amount (i.e. more than 45degrees), what could be caused by three possible reasons: heading data have factor of 2π offset or have negative values, heading is not correctly defined inside the navigation data or sensor head was not aligned to the aircraft principal axes; PARGE allows for simple correction of values. However, a yaw data are not required by PARGE for rectification process and it only may be used for mentioned derivation of the heading when necessary.
Finally, in case of GPS data acquisition fail but IMU provided useful data, PARGE allows reconstruction of a flight path using Ground Control Points (GCPs).

Previous interpolation and filtering of raw attitude and navigation data in PARGE, having produced the values acceptable for final geocoding of raw data cube, are shown in Figure 8.

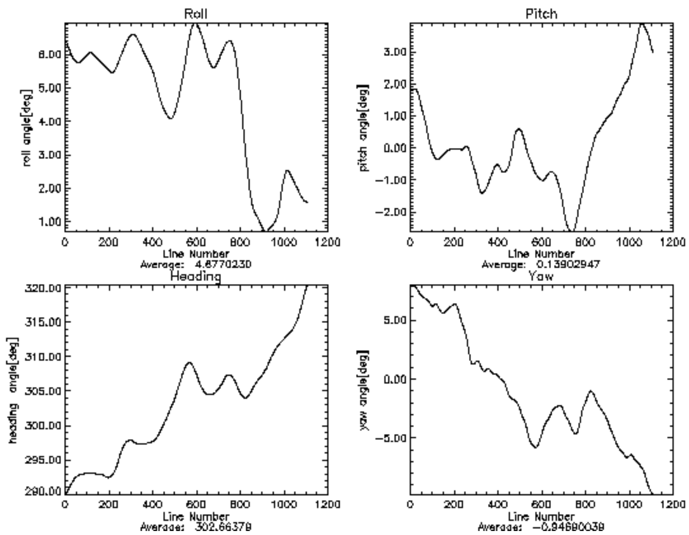

Figure 8. Attitude data after filtering in PARGE;
Zagreb/Jarun Lake flight campaign

Finally, geocoded data cube, (shown in Figure 9.) has been produced successfully and spectral readings become available for further exploitations.

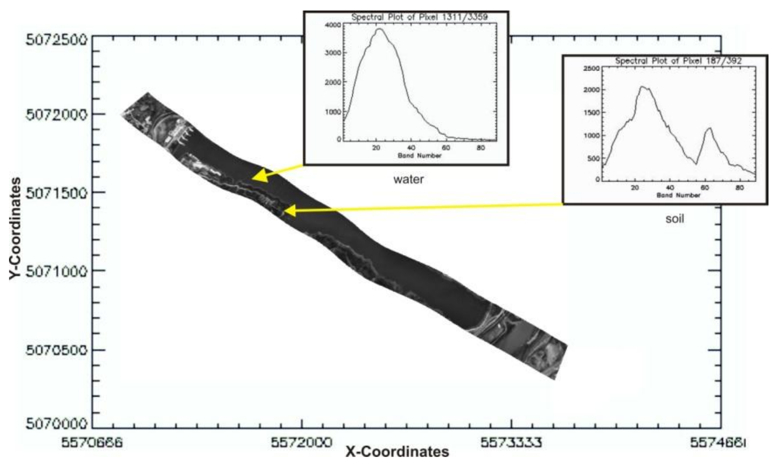

Figure 9. Geocube of Jarun Lake produced after Zagreb/Jarun Lake flight campaign with ImSpector V9 in full imaging mode
(Projection: Transverse Mercator; Datum: Hermannskögel)

6. CONLUSION. Although hyperspectral mapping for water quality inspection purpose, as it was during first campaign and flight tests, does not require absolute positioning accuracy more than 2m 2D RMS, the differential mode of GPS was not utilized at the time for the same reasons. INS solution building showed that positioning based only on GPS aided inertial measurement proved as sufficient and that further complete GPS/INS integration by Kalman filter will be utilized if application accuracy demand would go beyond the post-processing positioning accuracy with GCP usage or real-time high frequency positioning will be demanded. Full imaging mode utilization of pushbroom scanner resulted in geocube for exploratory actions. Furthermore, Position and Orientation System along with Multisensor System, proved as efficient tool even with present low demanded positioning accuracy.

GPS proved as essential technology in Multisensor Airborne System, since it is accomplishing vital tasks as: precise timing/synchronization, aiding the INS, positioning measurements, sensor triggering and real-time navigation. Overall, the GNSS various vulnerabilities had no immediate implications on Project real-time flight application (except for the real-time navigation purpose), but reflected through achieved absolute positioning accuracy and were compensated by using both real time techniques such are GPS aiding to INS, and post processing techniques which include: GPS and IMU data filtering and interpolation, usage of Ground Control Points (GCPs) and forming of an navigation solution by using INS.

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