TARGET POINTING OF THE BIRD SPACECRAFT VIA GROUND IN THE LOOP ATTITUDE CONTROL

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***BIRD**, a **B**i-spectral **I**nfra-**R**ed **D**etector is located on a micro-satellite mission launched on Oct. 22, 2001 on a PSLV–C3 from Sriharikota, India, into a sun-synchronous circular orbit with a semi-major axis of 6946 km and an inclination of 97.772º. The major attitude control modes during nominal operations are Sun pointing for battery charging (satellite -z-axis points towards the Sun), and target pointing for data-takes and for down-linking of high rate data to the ground (satellite +z-axis points towards a ground observation target). Since launch attitude determination, prediction and attitude maneuver design is performed on-ground filling in for an incomplete onboard attitude control system not yet implemented to its full extent.*
Continuous development of the on-ground attitude software and procedures has made it possible to achieve an accuracy in target pointing of less than two degrees. Special effort has been spent on the development of the maneuver design software to keep it user friendly in an operational environment.

KEYWORDS: attitude control, attitude prediction, target pointing, ground support, autonomy

INTRODUCTION

The micro-satellite for Bi-spectral Infrared Detection (BIRD) is a demonstrator of innovative remote sensing technology dedicated to fire recognition by small satellites. BIRD was developed, manufactured, and tested by the German Aerospace Center (DLR). It was piggy-back launched together with the Indian satellite TES and the ESA micro-satellite PROBA on October 22, 2001.

The primary BIRD mission objective is the test of a new generation of space based infrared sensors for the detection and scientific investigation of hot spots (forest fires, volcanic activities, burning oil wells, or coal seams) as well as the demonstration of new micro-satellite technologies in space.

The project management and science coordination is done at the Institute of Space Sensor Technology and Planetary Exploration (DLR Berlin-Adlershof), while the responsibility for operations was allocated to the GSOC (German Space Operations Center, DLR Oberpfaffenhofen).

The scientific instrumentation consists of a newly developed Hot Spot Recognition System (HSRS) - a dual-channel instrument for middle and thermal infrared detection. The Wide-Angle Optoelectronic Stereo Scanner (WAOSS-B) is the visual / near infrared-sensor of the BIRD payload. Actually developed for the MARS-96 mission a flight spare model was modified slightly for the application on BIRD.

BIRD is equipped with a set of 4 pairs of sun sensors, a three-axis magnetometer, a three-axis gyroscope assembly, two newly developed ASTRO 5 star sensors (Jena-Optronik GmbH, Germany), and a GPS receiver. Attitude maneuvers are executed using four reaction wheels, which are autonomously desaturated utilizing three magnetic torquers. Its sun synchronous orbit with a semi-major axis of 6946 km, eccentricity 0.001299 and an inclination of 97.772º is in accordance with the operational requirements of ground illumination, swath width and minimum life time of one year, which could already be clearly extended by now.

This paper will mainly deal with the attitude dynamics of the BIRD spacecraft, putting a focus on the ground support of attitude maneuvers for target observations. Ground support at its given extent is necessary to fill in for a more autonomous onboard attitude control system, which not yet became operational.

Anyhow between launch and April 2002, over 250 targets on ground have been successfully recorded. These include the bushfire near Sydney in January 2002, the burning of coal seams in China and the eruption of the volcano Etna in Sicily (Oct. 26, 2002).

BIRD ATTITUDE CONTROL SYSTEM

BIRD has been designed as a three axis stabilized satellite with its main attitude modes "sun pointing" and "earth pointing". For a complete listing of the control modes see Table 1.

Table 1. Characteristics of attitude control modes [1]

Mode	Name	Characteristics
SPM	Suspend Mode	initial state of control system, all actuators are disabled
AAM	Auto Acquisition Mode	attitude safe mode, solar arrays are pointing to the Sun
SPF	Sun Pointing Mode Fix	solar arrays are pointing to the Sun, attitude is inertial fixed
SPR	Sun Pointing Mode Rotate	solar arrays pointing to the Sun, satellite rotates around z-axis
EPM	Earth Pointing Mode	earth pointing of instruments and high gain antenna for remote sensing operations and for high-bit-rate down-link
IPG	Inertial Pointing Mode	Attitude is inertial fixed
LAM	Large Angle Maneuver	turns the satellite from one inertial fixed orientation to the next
DAM	Damping Mode	to stop any rotation of the satellite, to de-tumble the spacecraft

The associated spacecraft orientation for each control mode is illustrated in Fig. 1:

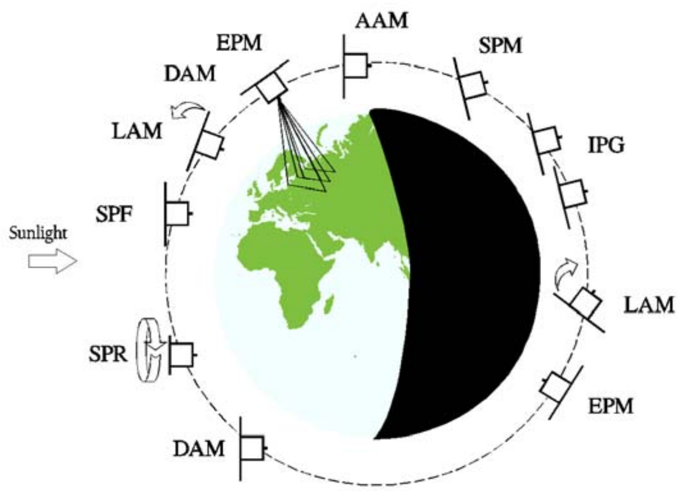

Fig. 1. BIRD Attitude Modes with reference to the Earth

The spacecraft orientation during earth pointing is described and illustrated in Table 2 and Fig. 2:

Table 2. Characteristics of attitude control mode EPM

Spacecraft axis	Earth pointing orientation	Axis definition
X	along flight direction	roll axis
Y	across flight direction	pitch axis
Z	viewing direction	yaw axis

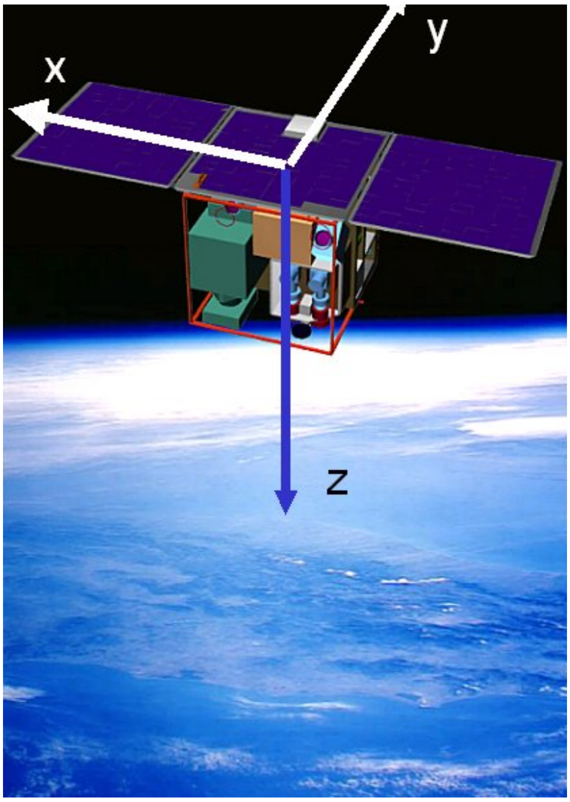

Fig. 2. BIRD body coordinate system (z-axis is earth pointing)

Up to now only part of the originally envisioned spacecraft control modes and functions have been implemented onboard: any orientation is established via the Auto Acquisition Mode (AAM) with the Coarse Sun Sensors (CSS), the magnetometer (Magnetic Field Sensor, MFS) and the laser gyroscope (Inertial Measurement Unit, IMU) involved (see Fig. 3). This simple mode has not been designed for definite pointing of the spacecraft.

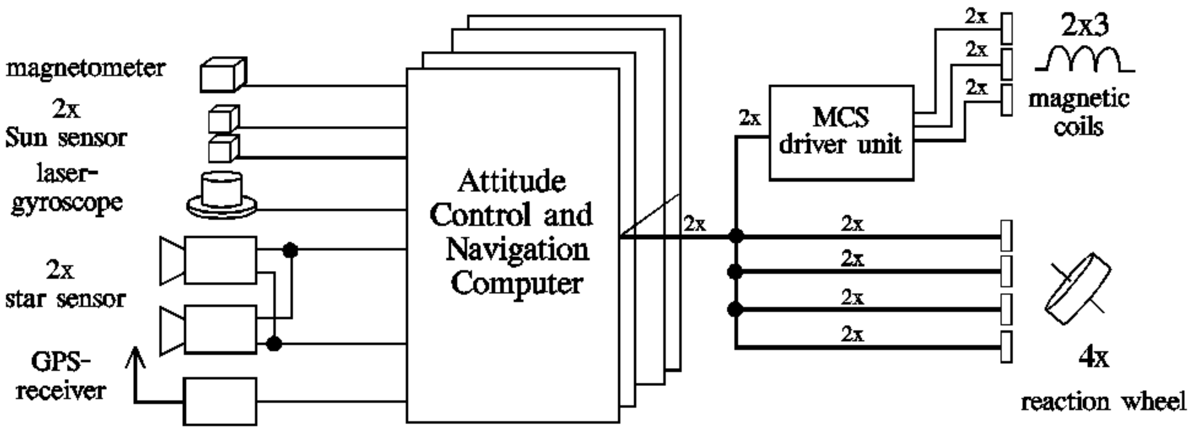

Fig. 3. Block scheme of the ACS components

Star sensors provide attitude information with respect to the inertial frame, but they are not involved in the attitude control. In particular control mode EPM foreseen for onboard-autonomous target pointing is not operational.

Successful target pointing requires a turn from sun pointing to earth pointing - an accurate knowledge of the spacecraft orientation prior to the start of the attitude maneuver is necessary to determine the rotation angles about the spacecraft main axes roll, pitch and yaw on-ground. For a turn from sun to the desired target these rotation angles are used as AAM bias angles.

BIRD ATTITUDE PERFORMANCE

Attitude determination performed on ground can be based on a set of 4 pairs of sun sensors and a three-axis magnetometer providing the sun vector and magnetic field vector in spacecraft coordinates. The reference coordinate system is the nominal orientation for "sun pointing mode fix", for which all three angles (roll, pitch, yaw) are 0. Whenever star camera data are available, the provided quaternions can also be used to calculate the offset angles. The same is true also for the onboard quaternion. Indeed it provides relative attitude information based on integrated gyro measurements. It has to be calibrated on ground, preferably with star sensor measurements.

The AAM mode has not been designed for three-axis stabilization of the satellite. While sun pointing BIRD rotates slowly about the axis pointing to the sun (yaw-axis, see Fig. 4). This axis is only controlled by the yaw-gyro - the gyro-drift of about 1 deg/hour can be observed in the yaw angle determination based on the onboard quaternion after 13:18 UTC (see Fig. 4, parameter Yaw_OBQ). The yaw angle deduced from the calibrated onboard quaternion deviates more and more from the true value since no star camera data (yielding Yaw_SC1 in Fig. 4) have been available for further calibration.

Three axis stabilized SPF mode, respectively controlled SPR mode, requires attitude control by the star camera, which also would assure space view of its optical axis. Instead the uncontrolled satellite motion about the sun vector causes star camera outages when pointing its optical axis towards the earth.

After an upload of the spacecraft board computer software in March 2002 star camera data became available for attitude determination. They showed that the yaw-axis moves up to 18 degrees away from the sun during transients from eclipse to sunlit phases (see Fig. 5). Magnetic torquer activity strongly influences the magnetic field measurement on-board, causing errors in the magnetometer based yaw angle determination of up to 40 degrees. This can be seen in Fig. 4 between 00:00 and 04:00 UTC (parameter Yaw_mag). As the star camera can only be used for attitude determination but not for attitude control operational steps had to be taken to increase attitude prediction accuracy.

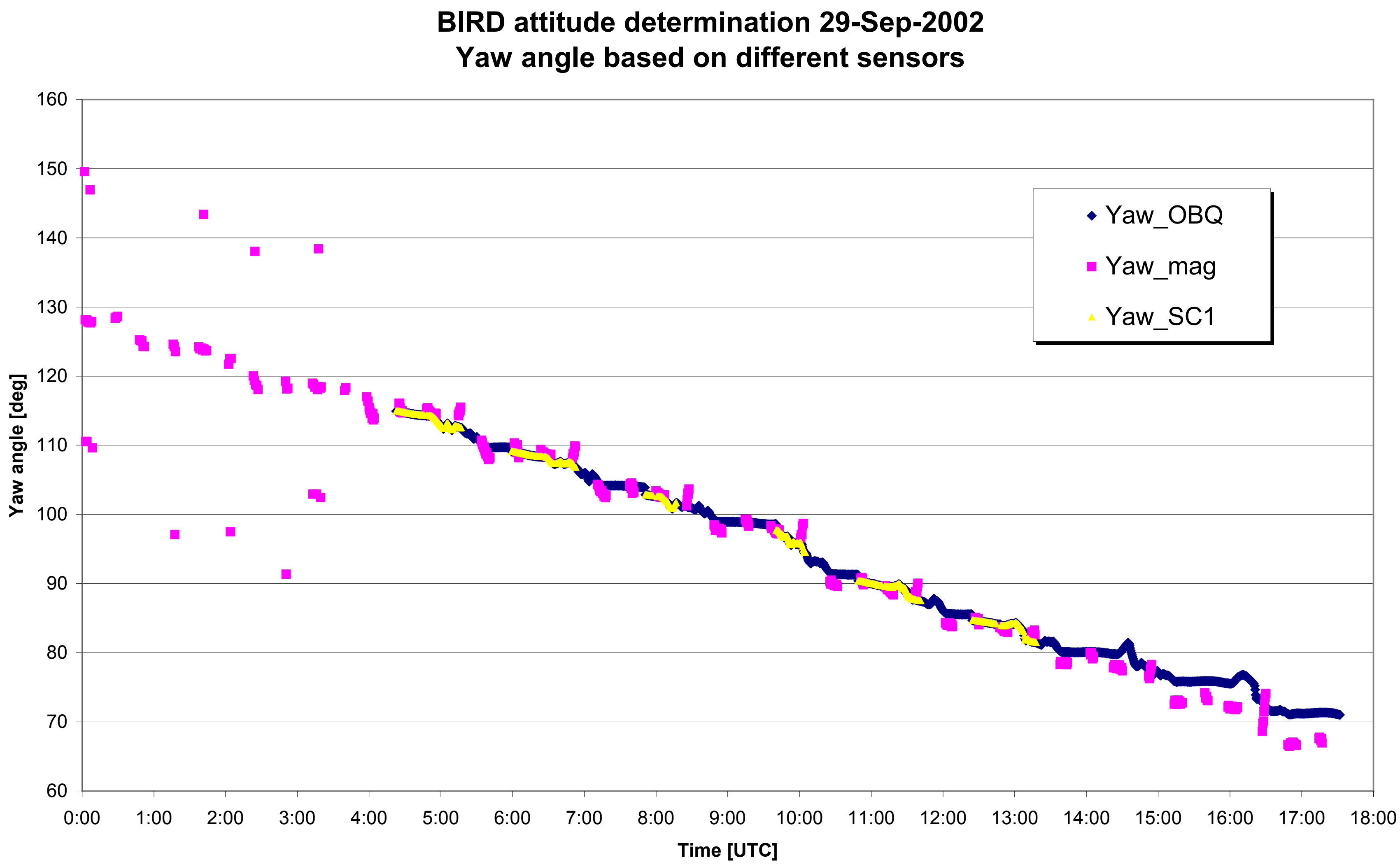

Fig. 4. Yaw angle determination 29-Sep-2002 showing rotation about sun vector

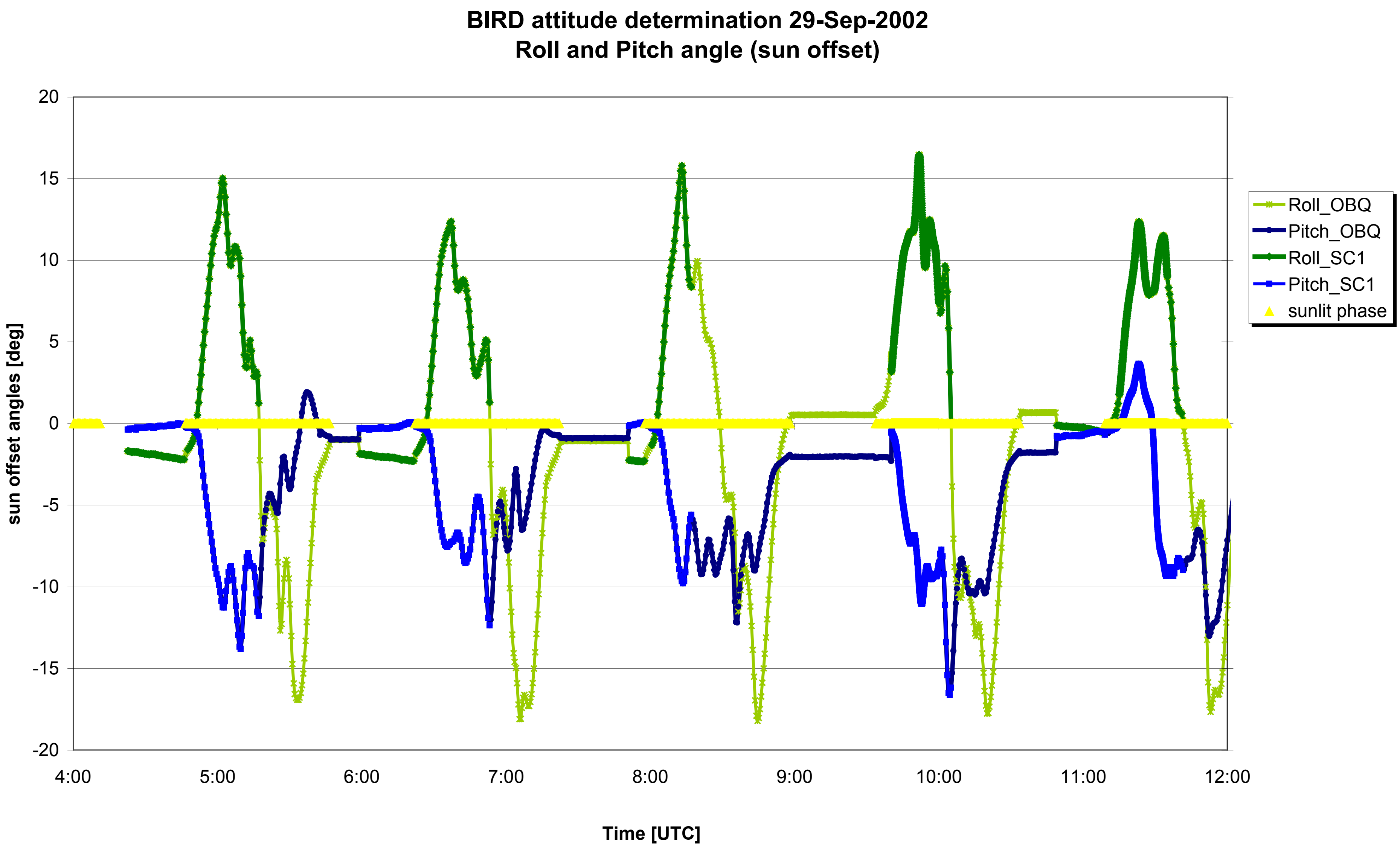

Fig. 5. Attitude determination 29-Sep-2002 showing offset from sun orientation during sunlit phases

PREPARATION OF TARGET ORIENTATIONS

To support science operations from ground first the basis had to be established:

1. Upgrade of the attitude determination software to support extended operational needs, especially attitude prediction and maneuver planning. This includes special sensor data filtering and design of attitude maneuvers as well as the generation of spacecraft specific commands
2. Step by step development and improvement of an operational process that imposes certain restrictions on spacecraft activities onboard while preparing a data-take

Each data-take is preceded by a time period when the spacecraft is in sun pointing mode. During this time period telemetry data are collected for subsequent attitude determination and prediction on ground. At least four hours are necessary to determine a reliable yaw rate for yaw angle prediction. No command activities are permitted that might influence attitude control, especially no attitude maneuver, no high rate reaction wheel unload and no redistribution of angular momentum between redundant reaction wheels until the end of the data-take.

Two contacts with a ground station are required for maneuver execution: During the first contact the collected attitude telemetry data are down-linked and then processed on ground, in the second pass the command file for target orientation is up-linked together with additional spacecraft commands.

To avoid roll and pitch offsets while sun pointing (see Fig. 5) the sun sensors are disabled at the beginning of the eclipse phase previous to the nadir turn. During this orbital phase typically only small deviations from sun pointing were observed. The turn from sun pointing to target pointing is described by Euler 3-1-2 rotations about the spacecraft main axes. Due to operational restrictions the yaw rotation must be replaced by a set of rotations perpendicular to the sun vector. A roll and pitch rotation completes the desired orientation. As a result the science instruments attitude is inertially fixed and points to the target at the pre-processed target time. At the end of the data-take the sun sensors are set in use and sun pointing is resumed. Table 3 gives an overview of the whole procedure of planning and executing a data-take.

Table 3. Procedure to perform a data-take

Progress	Description
Target selection	Science Coordinator provides target longitude and latitude and rough target observation time
Setup preparation	Operator runs maneuver scheduling task - observation time will be fixed
1. ground station contact	Receipt of attitude telemetry data for software analysis
Maneuver processing	Analysis of telemetry data including detailed schedule of the maneuver and generation of attitude commands
2. ground station contact	Uplink of commands for data-take and routine commands
Eclipse begin before target	Sun sensor is set out of use by time tagged command
Target time -25 min.	Start of turn from sun pointing to target pointing
Target time -10 min.	Target orientation is established
Target time -5 min. (max)	Start of data-take – science instruments are switched on
Target time +5 min. (max)	End of data-take – science instruments are switched off
Target time +10 min.	Sun sensor is set in use, sun orientation is re-established
Next ground station contact	Downlink of science data and housekeeping telemetry data

It is also possible to perform a data-take and receive housekeeping telemetry data and science data at the same time.

ATTITUDE DETERMINATION AND PREDICTION ON GROUND

Basically BIRD attitude determination on ground can be based on the analysis of three independent sensors:

1. DET: Sun sensor and magnetic field sensor (MFS)
2. SC1: Star camera (1 or 2)
3. OBQ: Onboard quaternion

Method 1 described as algebraic method [2] uses two vectors known in two reference coordinate systems to calculate the spacecraft attitude. The star camera provides directly a quaternion representing the spacecraft attitude in the star camera coordinate system. This can easily be transformed into the spacecraft coordinate system applying the alignment matrix between both coordinate systems. The onboard quaternion provides relative attitude information mainly based on integrated gyro rates. Table 4 contains a summary of pros and cons of each method.

Table 4. Pros and cons of attitude sensors for yaw angle determination

sensor	pros	cons
Sun sensor and MFS	High availability of reliable data	Low determination accuracy Result affected by magnetic torquer activity
Star camera	High determination accuracy	Sufficient availability not secured
Onboard quaternion	Continuous availability since first calibration with star camera	Calibration opportunity required Increasing yaw deviation after last calibration

Attitude prediction always presumes sun orientation of the spacecraft –z-axis while the angle about this axis is determined and predicted assuming a linear rate. Even when actual deviations from sun pointing can be determined using star camera data it is not possible to predict them as they follow no strict scheme. Therefore they have to be avoided setting the sun sensors during eclipse “inactive”.

The result of the different methods can be compared to the true yaw angle determined after the data-take. Table 5 shows typical results for six different data-takes. The star camera provides high attitude determination accuracy; anyhow it does not yield better attitude predictions. For Sydney, Turkey and Kalimantan no valid onboard quaternions have been available.

Table 5. Propagated yaw angles for different sensors

Target / Method	Australia 27.Sep.02	Andes 28.Sep.02	Colima 29.Sep.02	Sydney 02.Oct.02	Turkey 04.Oct.02	Kalimantan 05.Oct.02
yaw prop (DET)	-151.2	148.4	67.8	13.1	65.8	130.4
yaw prop (OBQ)	-149.6	147.0	69.0	n/a	n/a	n/a
yaw prop (SC1)	-151.2	148.2	68.5	14.9	69.4	130.9
yaw true	-146.6	147.2	66.5	14.9	62.5	131.5

Taking precision and availability considerations into account the combination of sun sensor and magnetic field sensor was selected as preferred sensor for attitude prediction.

Until January, 13 2003 wheel unload was disabled while collecting attitude data. That way interfering magnetic torquer activity was suppressed. After wheel 3 failed in February 2003, wheel unload had to be active all the time. Its influence on the yaw angle determination could be minimized exceeding the time interval for attitude determination. As an illustration Fig. 6 shows a graphical representation of the yaw angle determination for the target Colima.

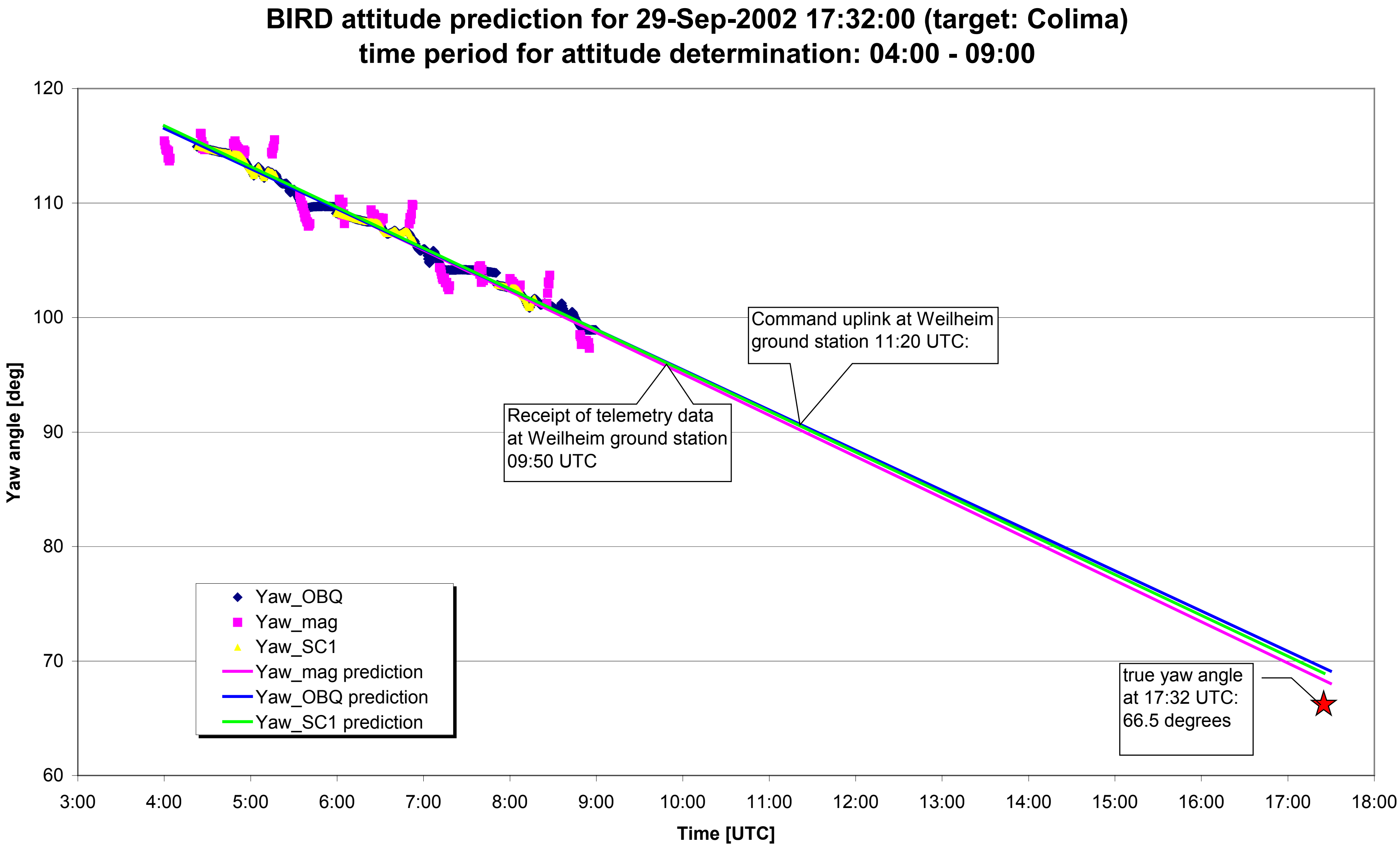

Fig. 6. Attitude prediction 29-Sep-2002 based on different sensors

TARGET POINTING ACCURACY

After receipt of the science data precise attitude determination can be performed to subsequently assess the target orientation accuracy. The different determination methods mentioned in the previous chapter can now be applied to determine the deviation angles with respect to the target.

Naturally star camera measurements yield the most accurate precision of measurements. Unfortunately in most cases star camera will discontinue providing data at least at the beginning of the attitude maneuver: the insensitivity of the star camera software against spacecraft accelerations has been improved only in a later version from which Bird could not benefit anymore. Furthermore there is a high probability that during the sequence of attitude maneuvers the optical sensor will be exposed to view the earth and loose star reference.

As mentioned already attitude determination accuracy based on the OBQ decreases with increasing time since last calibration with star camera data. The deviation level is in the order of 1 degree/hour. The spacecraft axis which is most effected depends on the actual attitude and the maneuvers performed before.

Even though – regarding one data point only – attitude determination with sun sensor and magnetic field sensor provides the lowest precision, the average of a great number of data points yields reasonable results.

An example for the target pointing accuracy based on the combination of sun sensor / MFS and onboard quaternion can be seen in Fig. 7. It shows the target deviations based on the onboard quaternion and the sun sensor / magnetic field sensor as described in Table 2. The last calibration of the onboard quaternion could be performed at 13:00 UTC, about 1 hour 40 minutes prior to earth orientation. Sun sensor / MFS data are available from 14:43 until 14:47 UTC.

In general the true pointing accuracy depends on

- the stability of the spacecraft yaw rate during sun pointing
- a stable sun pointing of the -yaw axis
- the epoch for attitude determination
- the forecasting horizon of the yaw angle
- the execution quality of the commanded attitude maneuvers

For most of the target observations the primary mission objective could be achieved: target observations could be performed with a reasonable pointing accuracy of better than two degrees.

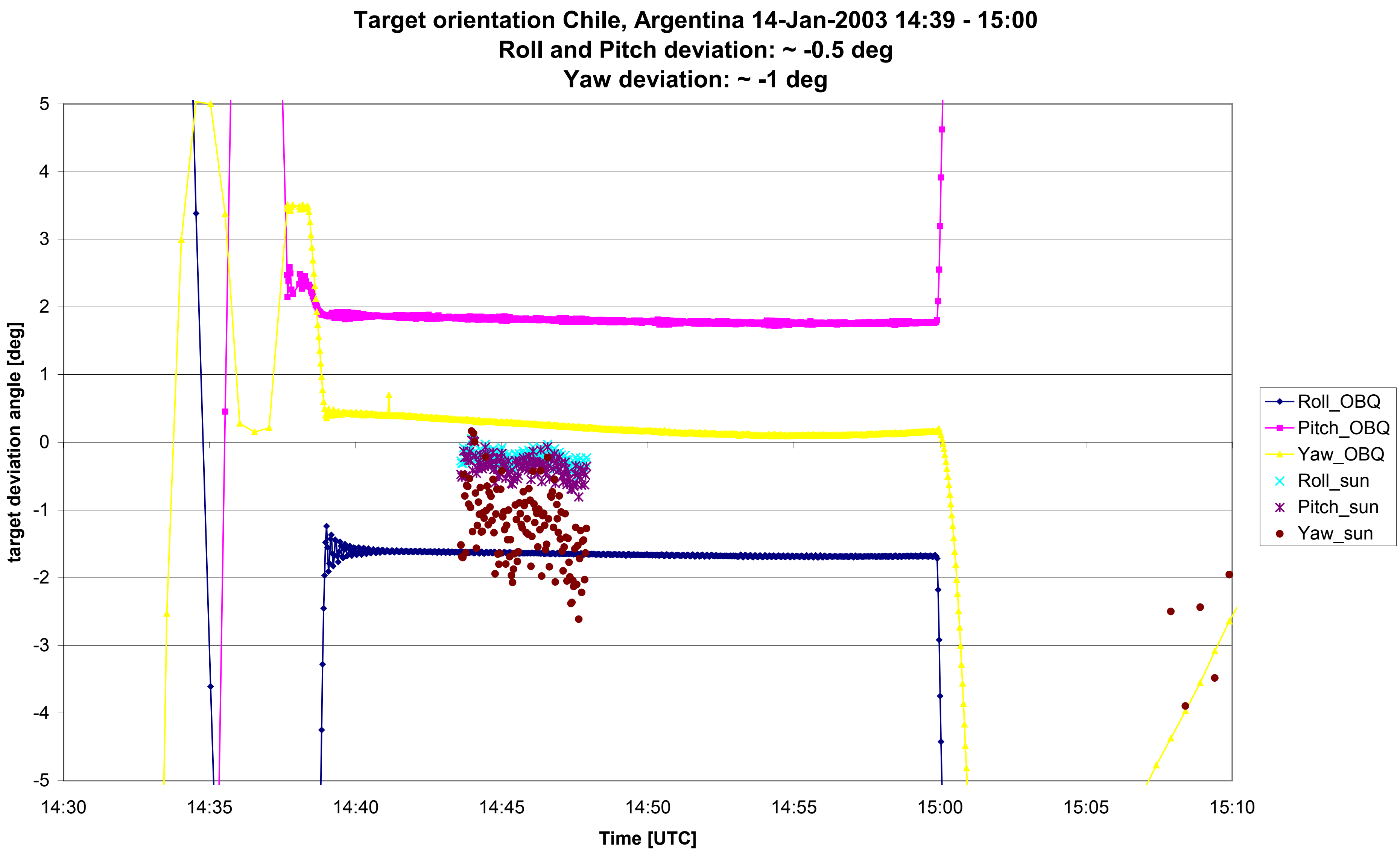

Fig. 7. Target pointing accuracy 14-Jan-2003 (target Chile)

SCIENTIFIC RESULTS

An overall scientific objective of the BIRD mission is the detection and investigation of hot spots caused by

- vegetation fires,
- volcanic activities,
- industrial hazards, burning oil wells, burning coal seams a.s.o.

To fulfill the scientific requirements under the conditions of a micro-satellite the payload consists of the following main parts:

- the bi-spectral infrared Hot Spot Recognition System (HSRS incl. MIR and TIR-Sensor)
- the Wide-Angle Optoelectronic Stereo Sensor (WAOSS-B, VNIR-Sensor) for vegetation analysis and fire classification,
- the Payload Data Handling system (PDH) with a mass memory,
- a neural network classificator for an on-board classification experiment.

The IR-sensors for medium (MIR) and thermal (TIR) infrared have a field of view of 18,8°, which corresponds to a swath width of 190 km, the field of view of the WAOSS-B stereo scanner is 50°. An observation time of 10 minutes corresponds to a ground track of more than 4000 km. A detailed description of the scientific instrumentation and data handling can be found in chapter 3 of the BIRD homepage from DLR [3].

Accompanied by earthquakes a great eruption of the volcano Etna (Sicily) occurred in the evening of Oct. 26, 2002, which lasted until November 1. At Nov. 2, at 10:15 UTC Bird observed the Etna region in three spectral channels.

As an example Fig. 8 shows a fragment of an image of the WAOSS camera in the 0.84 – 0.90 µm spectral channel (Italy and Sicily). In the corresponding false color composite image (Fig. 9) achieved from the infrared channels, meteorological steam clouds are represented blue. The warm ash clouds (red) can easily be identified. Hot lava appears yellow while sea and land with normal temperature appear green. The zoomed figure shows the effective lava temperature.

SUMMARY

For routine operations and the execution of data-takes Bird has been designed with several attitude modes supporting three-axis stabilized orientation. These attitude modes never became operational. Development of additional ground software after the Bird launch, accompanied by extended ground support during routine operations have made it possible to achieve a major mission objective: successful execution of data-takes for selected targets.

OUTLOOK

The Onboard Navigation System (ONS) [4], which is fully operational since launch, supports the BIRD attitude control system with real-time attitude information to allow for nadir pointing independent from ground based attitude determination and prediction. Precise GPS data processed by the ONS already provide a real-time position accuracy of a few meters onboard the BIRD spacecraft. An additional update of the onboard software to involve star camera measurements in attitude control could extend onboard autonomy as well as target pointing accuracy.

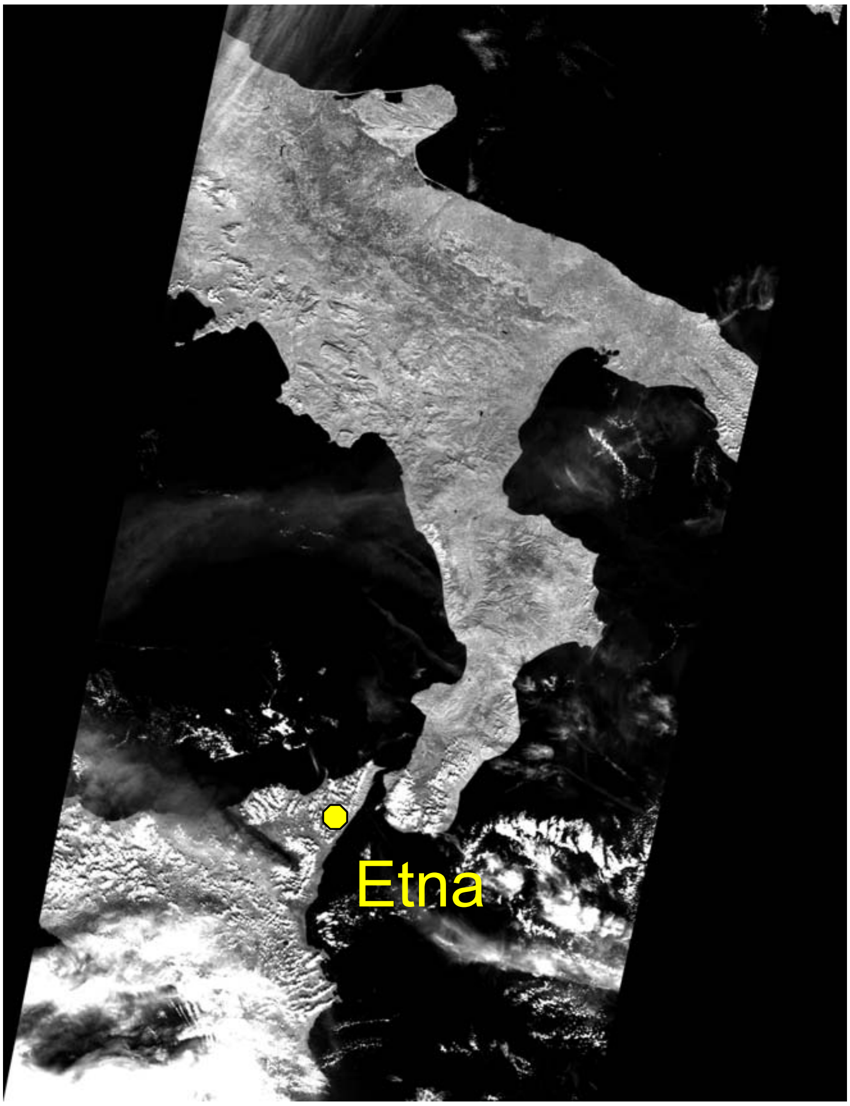

Fig. 8. Fragment of a WAOSS image 02-Nov-2002 (Italy and Sicily)

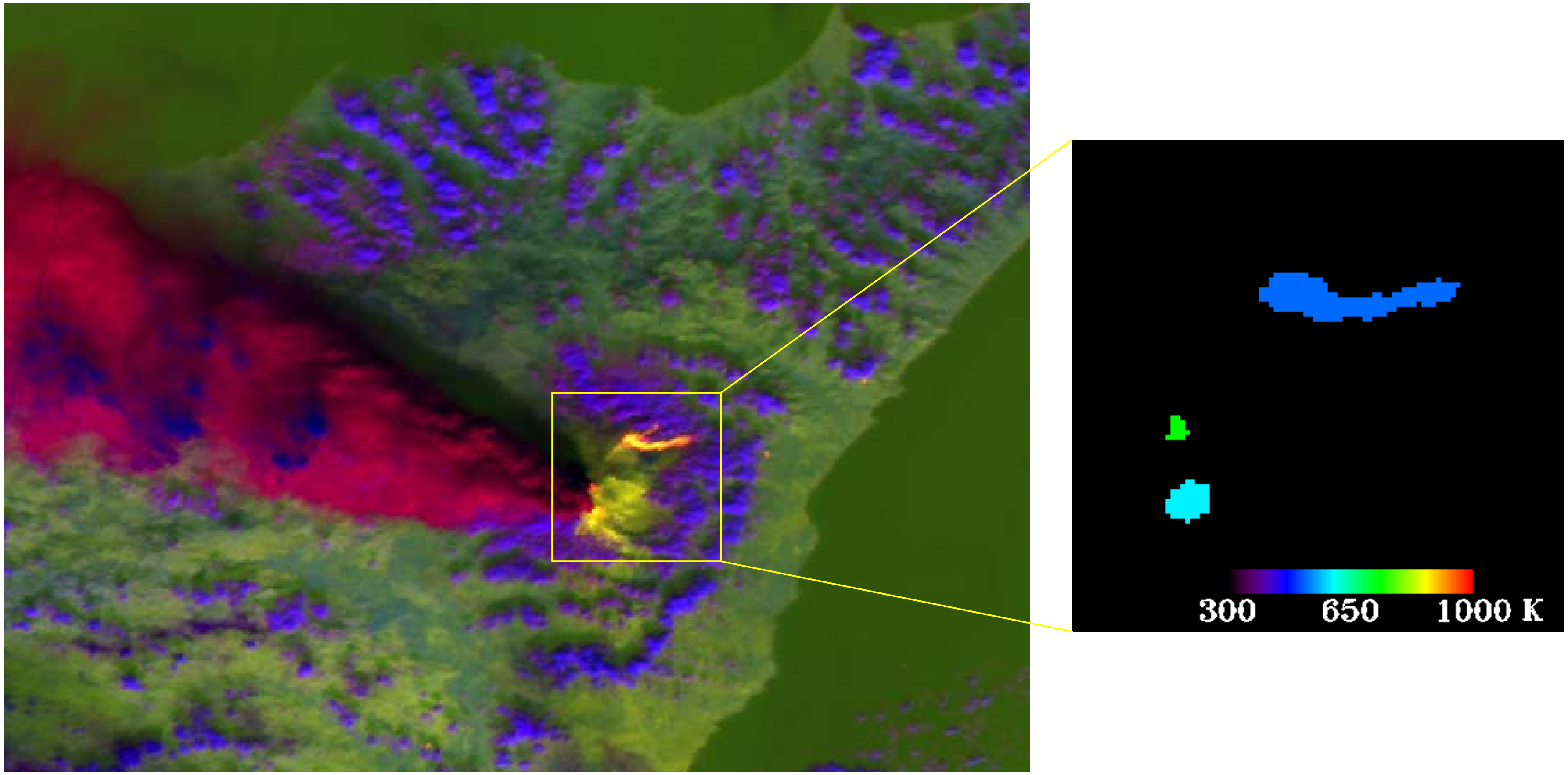

Fig. 9. Volcano Etna 02-Nov-2002: IR channels (Red: MIR, Green: TIR, Blue: NIR) and effective lava temperature

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